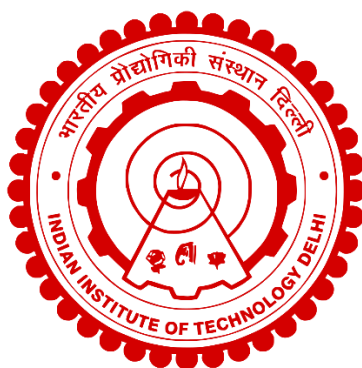


**DESIGN AND CONTROL OF PV-WIND ENERGY
BASED MICROGRIDS WITH ISLANDING AND
RESYNCHRONIZATION**

FARHEEN CHISHTI



DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
DECEMBER 2022

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RESYNCHRONIZATION**

by

FARHEEN CHISHTI

Department of Electrical Engineering

Submitted

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

to the



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CERTIFICATE

It is certified that the thesis entitled “**Design and Control of PV-Wind Energy Based Microgrids with Islanding and Resynchronization,**” being submitted by **Mrs. Farheen Chishti** 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 her under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma

Dated:

(Prof. Bhim Singh)

Electrical Engineering Department

Indian Institute of Technology Delhi

Hauz Khas, New Delhi-110016, India

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ABSTRACT

This thesis presents the design and control of solar photovoltaic array and wind energy generation based microgrids with seamless transfer of operating modes for the electrification of rural communities as the prime motive. The combination of solar energy and wind energy generation increases the power reliability and provides energy surety as both the resources complement each other and cut down the reserve or storage requirements. The challenge is imposed as the renewable resources are dominated by their intermittency and geographic location availability. The variability of the energy supply is overcome by the use of energy storage systems, like battery energy storage (BES) or utility interconnection of the microgrid. The rural electrification is carried out either by grid interconnection or by incorporating the storage battery with the renewables to fulfill the community load demand. The first option is not viable for rural areas as site affordability acts as the key barrier. Secondly, the battery energy storage (BES) is worthwhile when specific conditions are fulfilled, which in return makes the value proposition of storage greater than the cost of installing it. BES is an expensive option but it meets all the aspects of integration challenges such as the uncertainty during demand rise and power sufficiency.

Here, in this work, BES control is deployed either connected directly at the DC link or through a bidirectional DC-DC converter. It controls the discharging and charging of the battery. The wind conversion systems also suffer from harmonics injection, degradation of minimum fault current and sudden voltage disruptions due to wind speed intermittency. These encountered challenges are resolved by utilizing full rated voltage source converters (VSCs) as an interface between the machine and the utility grid. Two back-to-back connected VSCs, i.e., AC/DC converter, named as machine side VSC (MSC), a DC link, and a DC/AC inverter named as load side VSC (LSC) are implemented for variable speed operation of the system. The MSC regulates the synchronous

generator (SG) output power. It adjusts the current and torque of the SG. The LSC upholds the DC link voltage and synchronizes the AC generated power by the wind turbine driven SG with the power of the utility grid. The encoder-less field oriented control (FOC) with speed and position estimation is utilized for the SG. Depending upon the requirement, the solar PV array is configured as single stage or two stage configurations utilizing a boost converter. This work focuses upon the development and implementation of the advance control techniques for the successful operation of the microgrids during grid-connected mode or standalone operating mode. Even under adverse grid conditions, these improved approaches assess the amplitude, frequency, and phase of grid phase voltages quickly and accurately. All of the microgrid configurations have efficient control algorithms for the load side converter, which improve power quality at the PCC while maintaining unity power factor, provides harmonics elimination, grid currents balancing, reactive power compensation, neutral current compensation and power factor correction. The continuity of supply to the local consumer loads is ensured. The solar PV array and wind energy feed-forward terms express the power sharing mechanism to the utility and provides fast tracking under dynamic condition. The maximum power point extraction schemes for wind generation and solar PV array track the optimal power even under adverse solar insolation and wind speed conditions. The core objective is also to provide continuous supply to the critical loads even under grid outage scenarios. However, renewable generation loss and battery with low state of charge are also the conditions that need to be addressed for the continuity of supply during standalone operating mode. To overcome this shortcoming, the diesel generator set is brought into action for a short period of time and operated under maximum fuel efficiency zone to cater to the emergency load demand. All microgrid configurations are categorized in accordance to single phase, three phase three wire and three phase four wire distribution networks. The consumer requirement decides the type of the

microgrid to be selected for specific applications. For investigating the performance, these microgrids are modelled and simulated using the MATLAB®/ Simulink platform, and experimental validations are carried out using developed laboratory prototypes. This study is intended to contribute significantly to existing knowledge on the design, development, and control of PV-wind energy based microgrids with islanding and resynchronization capabilities.

सार

यह थीसिस मुख्य उद्देश्य के रूप में ग्रामीण समुदायों के विद्युतीकरण के लिए ऑपरेटिंग मोड के निर्बाध हस्तांतरण के साथ सौर फोटोवोल्टिक पैनल और पवन ऊर्जा उत्पादन आधारित माइक्रोग्रिड के डिजाइन और नियंत्रण को प्रस्तुत करता है। सौर ऊर्जा और पवन ऊर्जा उत्पादन का संयोजन बिजली की विश्वसनीयता बढ़ाता है और ऊर्जा सुनिश्चितता प्रदान करता है क्योंकि दोनों संसाधन एक दूसरे के पूरक हैं और रिजर्व या भंडारण आवश्यकताओं को कम करते हैं। चुनौती इसलिए लगाई गई है क्योंकि अक्षय संसाधनों पर भौगोलिक स्थिति की उपलब्धता का बोलबाला है। ऊर्जा भंडारण प्रणालियों के उपयोग से ऊर्जा आपूर्ति की परिवर्तनशीलता को दूर किया जाता है, जैसे बैटरी ऊर्जा भंडारण (BES) या माइक्रोग्रिड इंटरकनेक्शन। ग्रामीण विद्युतीकरण या तो ग्रिड इंटरकनेक्शन द्वारा किया जाता है या सामुदायिक भार की मांग को पूरा करने के लिए नवीकरणीय ऊर्जा के साथ भंडारण बैटरी को शामिल करके किया जाता है। पहला विकल्प ग्रामीण क्षेत्रों के लिए व्यवहार्य नहीं है क्योंकि साइट की सामर्थ्य प्रमुख बाधा के रूप में कार्य करती है। दूसरे, बैटरी ऊर्जा भंडारण तब सार्थक होता है जब विशिष्ट शर्तें पूरी होती हैं, जो बदले में भंडारण के मूल्य प्रस्ताव को इसे स्थापित करने की लागत से अधिक बनाता है। BES एक महंगा विकल्प है लेकिन यह एकीकरण चुनौतियों के सभी पहलुओं जैसे मांग वृद्धि और बिजली की पर्याप्तता के दौरान अनिश्चितता को पूरा करता है।

यहां, इस कार्य में, BES नियंत्रण या तो सीधे डीसी लिंक पर या एक द्विदिश डीसी-डीसी कनवर्टर के माध्यम से जुड़ा हुआ है। यह बैटरी की डिस्चार्जिंग और चार्जिंग को नियंत्रित करता है। पवन रूपांतरण प्रणालियां भी हार्मोनिक इंजेक्शन, न्यूनतम फॉल्ट करंट की गिरावट और हवा की गति रुक-रुक कर होने के कारण अचानक वोल्टेज व्यवधान से ग्रस्त हैं। इन चुनौतियों का समाधान मशीन और उपयोगिता ग्रिड के बीच इंटरफेस के रूप में पूर्ण रेटेड वोल्टेज स्रोत कन्वर्टर (VSC) का उपयोग करके किया जाता है। दो बैक टू बैक कनेक्टेड VSC, यानी AC/DC कन्वर्टर, जिसे मशीन साइड वीएससी (MSC), एक डीसी लिंक और एक DC/AC इन्वर्टर को लोड साइड वीएससी (LSC) के रूप में नामित किया गया है, को चर गति संचालन के लिए लागू किया गया है। MSC सिंक्रोनस जनरेटर (SG) आउटपुट पावर को नियंत्रित करता है। यह SG के करंट और टॉर्क को एडजस्ट करता है। LSC डीसी लिंक वोल्टेज को बनाए रखता है और उपयोगिता ग्रिड की शक्ति के साथ पवन टरबाइन संचालित SG द्वारा AC उत्पन्न बिजली को सिंक्रनाइज़ करता

है। गति और स्थिति अनुमान के साथ एन्कोडर-रहित क्षेत्र उन्मुख नियंत्रण (FOC) का उपयोग SG के लिए किया जाता है। आवश्यकता के आधार पर, सोलर पीवी ऐरे को बूस्ट कन्वर्टर का उपयोग करते हुए सिंगल स्टेज या टू स्टेज कॉन्फ़िगरेशन के रूप में कॉन्फ़िगर किया गया है। यह कार्य ग्रिड से जुड़े मोड या स्टैंडअलोन ऑपरेटिंग मोड के दौरान माइक्रोग्रिड के सफल संचालन के लिए अग्रिम नियंत्रण तकनीकों के विकास और कार्यान्वयन पर केंद्रित है। प्रतिकूल ग्रिड परिस्थितियों में भी, ये बेहतर दृष्टिकोण ग्रिड चरण वोल्टेज के आयाम, आवृत्ति और चरण का जल्दी और सटीक आकलन करते हैं। सभी माइक्रोग्रिड कॉन्फ़िगरेशन में लोड साइड कन्वर्टर के लिए कुशल नियंत्रण एल्गोरिदम होते हैं, जो यूनिटी पावर फैक्टर को बनाए रखते हुए PCC में पावर क्वालिटी में सुधार करते हैं, हार्मोनिक्स एलिमिनेशन, ग्रिड करंट बैलेंसिंग, रिएक्टिव पावर, न्यूट्रल करंट और पावर फैक्टर करेक्शन प्रदान करते हैं। स्थानीय उपभोक्ता भार की आपूर्ति की निरंतरता सुनिश्चित की जाती है। सौर पीवी ऐरे और पवन ऊर्जा फीड-फॉरवर्ड, उपयोगिता के लिए बिजली साझाकरण तंत्र को व्यक्त करते हैं और गतिशील स्थिति के तहत तेजी से ट्रेकिंग प्रदान करते हैं। पवन उत्पादन और सौर पीवी ऐरे के लिए अधिकतम बिजली निष्कर्षण योजनाएं प्रतिकूल सौर सूर्यातप और हवा की गति की स्थिति के तहत भी इष्टतम शक्ति को ट्रैक करती हैं। मुख्य उद्देश्य ग्रिड आउटेज परिदृश्यों के तहत भी महत्वपूर्ण भार को निरंतर आपूर्ति प्रदान करना है। हालांकि, अक्षय उत्पादन हानि और कम चार्ज वाली बैटरी भी ऐसी स्थितियां हैं जिन्हें स्टैंडअलोन ऑपरेटिंग मोड के दौरान आपूर्ति की निरंतरता के लिए संबोधित करने की आवश्यकता है। इस कमी को दूर करने के लिए, डीजल जनरेटर सेट को थोड़े समय के लिए चालू किया जाता है और आपातकालीन भार की मांग को पूरा करने के लिए अधिकतम ईंधन दक्षता क्षेत्र के तहत संचालित किया जाता है। सभी माइक्रोग्रिड कॉन्फ़िगरेशन को सिंगल फेज, थ्री फेज थ्री वायर और थ्री फेज फोर वायर डिस्ट्रीब्यूशन नेटवर्क के अनुसार वर्गीकृत किया गया है। उपभोक्ता की आवश्यकता विशिष्ट अनुप्रयोगों के लिए चुने जाने वाले माइक्रोग्रिड के प्रकार को तय करती है। प्रदर्शन की जांच के लिए, इन माइक्रोग्रिड को MATLAB® / सिमुलिक प्लेटफॉर्म का उपयोग करके मॉडलिंग और सिमुलेटेड किया जाता है, और विकसित प्रयोगशाला प्रोटोटाइप का उपयोग करके प्रयोगात्मक सत्यापन किया जाता है। इस अध्ययन का उद्देश्य पीवी-पवन ऊर्जा आधारित माइक्रोग्रिड के डिजाइन, विकास और नियंत्रण पर मौजूदा ज्ञान में महत्वपूर्ण योगदान देना है, जिसमें द्वीपीय और पुनः सिंक्रनाइज़ेशन क्षमताएं हैं।

TABLE OF CONTENTS

	Page No.
Certificate	I
Acknowledgement	II
Abstract	V
Table of Contents	X
List of Figures	XLIX
List of Tables	LXXVI
List of Abbreviations	LXXXIII
List of Symbols	LXXXVI
 CHAPTER I INTRODUCTION	 1-15
1.1 General	1
1.2 State of Art on Microgrids	3
1.3 Objectives and Scope of Work	8
1.3.1 Wind Energy Generation Based Grid Interactive Microgrid with Islanding and Resynchronization	10
1.3.2 Battery Supported Wind Energy Generation Based Grid Interactive Microgrid for Islanding and Resynchronization	10
1.3.3 Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrid for Islanding and Resynchronization	11
1.3.4 Battery Supported Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrid for Islanding and Resynchronization	11
1.3.5 Wind Energy Generation Based Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	12
1.3.6 Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	12
1.4 Outline of Chapters	12
 CHAPTER II LITERATURE REVIEW	 16-37
2.1 General	16
2.2 Historical Development of Solar PV Technology	17
2.3 Historical Development of Wind Energy Technology	17
2.4 Standards, Testing and Quality Certification for Solar PV Systems	18
2.5 Certification Schemes for Wind Turbines	20
2.6 Literature Survey	21
2.6.1 Review on Solar PV Energy Harnessing Techniques	22
2.6.2 Review on the Wind Energy Harnessing Techniques	22

2.6.3	Review of MPPT Techniques for Solar PV Generation based Microgrids	24
2.6.4	Review of MPPT Techniques for Wind Energy Generation based Microgrids	25
2.6.5	Review on Sensorless Schemes for Wind Turbine Generators	26
2.6.6	Review on Renewable Energy based Microgrids with Diesel Generator (DG)	27
2.6.7	Review of Energy Storage System Technologies in Microgrid	28
2.6.8	Review of Hybrid Renewable Energy based Microgrid	29
2.6.9	Review on Converter Control Techniques for Microgrid	31
2.6.10	Review of Synchronization Techniques for Microgrid	34
2.7	Identified Research Areas	36
2.8	Conclusions	37
CHAPTER III WIND ENERGY GENERATION BASED GRID INTERACTIVE MICROGRIDS WITH ISLANDING AND RESYNCHRONIZATION		38-114
3.1	General	38
3.2	Configurations of Wind Energy Generation Based Grid Interactive Microgrids With Islanding and Resynchronization	39
3.2.1	Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	40
3.2.2	Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	41
3.2.3	Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	42
3.3	Design of Wind Energy Generation Based Grid Interactive Microgrids	44
3.3.1	Design and Selection of Wind Turbine	44
3.3.2	Selection of Synchronous Generator (SG)	45
3.3.3	Selection of DC link Voltage	45
3.3.4	Design of DC Bus Capacitor	46
3.3.5	Design of Converter Switching Devices	46
3.3.6	Design of Machine side VSC (MSC)	47
3.3.7	Design of Load side VSC (LSC)	48
3.3.8	Design of Interfacing Inductor	48
3.3.9	Design of Ripple Filter	48
3.4	Control of Wind Energy Generation Based Grid Interactive Microgrids	51
3.4.1	Control of Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	51

3.4.1.1	Current Control of LSC for Grid Connected Mode of Operation	52
3.4.1.2	Voltage Control of LSC for Standalone Mode of Operation	57
3.4.1.3	Islanding and Resynchronization Detection Control	58
3.4.1.4	MSC Switching Pulse Control	61
3.4.2	Control of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	65
3.4.2.1	Current Control of LSC for Grid Connected Mode of Operation	66
3.4.2.2	Voltage Control of LSC for Islanded Mode of Operation	69
3.4.2.3	Mode Transfer Control	70
3.4.2.4	MSC Control	72
3.4.3	Control of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	72
3.4.3.1	Current Control for Grid Synchronized Operating Mode	73
3.4.3.2	Standalone Voltage Control	76
3.4.3.3	Mechanism of MSC Control	77
3.5	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Grid Interactive Microgrids	79
3.5.1	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	80
3.5.2	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	80
3.5.3	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	81
3.6	Hardware Implementation of Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	81
3.6.1	Development of Hall Effect Voltage Sensor Circuit with Signal Conditioning Unit	82
3.6.2	Development of Hall Effect Current Sensor Circuit with Signal Conditioning Unit	83
3.6.3	Development of Gate Driver Amplification and Isolation Circuit	84
3.6.4	Execution of Control Schemes on DSP-dSPACE 1202 Microlab-Box	84
3.7	Results and Discussion	86

3.7.1	Simulated Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	87
3.7.1.1	Steady State and Dynamic Performances	87
3.7.1.2	Power Quality Performance	89
3.7.2	Experimental Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	91
3.7.2.1	Grid Connected Operating Mode and Power Quality Indices	91
3.7.2.2	Seamless Transition Mode	94
3.7.2.3	Islanded Operating Mode	95
3.7.3	Simulated Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	97
3.7.3.1	Steady State and Dynamic Performances	97
3.7.3.2	Power Quality Performance	100
3.7.4	Experimental Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	100
3.7.4.1	Grid Connected Operating Mode and Power Quality Indices	101
3.7.4.2	Mode Transition	103
3.7.4.3	Islanded Operating Mode	104
3.7.5	Simulated Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	105
3.7.5.1	Steady State and Dynamic Performances	106
3.7.5.2	Power Quality Performance	108
3.7.6	Experimental Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	109
3.7.6.1	Grid Connected Operating Mode and Power Quality Indices	109
3.7.6.2	Mode Transition	111
3.7.6.3	Islanded Operating Mode	112
3.8	Conclusions	114

CHAPTER IV	BATTERY SUPPORTED WIND ENERGY GENERATION BASED GRID INTERACTIVE MICROGRIDS FOR ISLANDING AND RESYNCHRONIZATION	115-217
4.1	General	115
4.2	Configuration of Battery Supported Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	116
4.2.1	Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	117
4.2.2	Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	118
4.2.3	Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	118
4.2.4	Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	120
4.2.5	Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	121
4.2.6	Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	122
4.3	Design of Battery Supported Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	123
4.3.1	Design and Selection of Battery Energy Storage	124
4.3.2	Design and Selection of Inductor of Bidirectional DC-DC Converter	125
4.3.3	Design of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	126
4.3.4	Design of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	127
4.3.5	Design of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	128
4.3.6	Design of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	129
4.3.7	Design of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	130
4.3.8	Design of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	131

4.4	Control of Battery Supported Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	132
4.4.1	Control of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	133
4.4.1.1	Current Control of LSC for Grid Connected Mode of Operation	133
4.4.1.2	Voltage Control of LSC for Standalone Mode of Operation	135
4.4.1.3	Islanding and Resynchronization Detection Control	137
4.4.1.4	MSC Switching Pulse Control	140
4.4.2	Control of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	142
4.4.2.1	Current Control of LSC for Grid Connected Mode of Operation	142
4.4.2.2	Voltage Control of LSC for Standalone Mode of Operation	143
4.4.2.3	Control of Bidirectional DC-DC Converter	143
4.4.2.4	Islanding and Resynchronization Detection Control	145
4.4.2.5	MSC Switching Pulse Control	145
4.4.3	Control of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	146
4.4.3.1	Current Control of LSC for Grid Connected Mode of Operation	146
4.4.3.2	Voltage Control of LSC for Standalone Mode of Operation	149
4.4.3.3	Islanding and Resynchronization Detection Control	151
4.4.3.4	MSC Switching Pulse Control	152
4.4.4	Control of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	153
4.4.4.1	Current Control of LSC for Grid Connected Mode of Operation	154
4.4.4.2	Voltage Control of LSC for Standalone Mode of Operation	155
4.4.4.3	Control of Bidirectional DC-DC Converter	155
4.4.4.4	Islanding and Resynchronization Detection Control	156
4.4.4.5	MSC Switching Pulse Control	157
4.4.5	Control of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	157
4.4.5.1	Current Control of LSC for Grid Connected Mode of Operation	158

	4.4.5.2	Voltage Control of LSC for Standalone Mode of Operation	160
	4.4.5.3	Islanding and Resynchronization Detection Control	161
	4.4.5.4	MSC Switching Pulse Control	163
4.4.6		Control of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	164
	4.4.6.1	Current Control of LSC for Grid Connected Mode of Operation	164
	4.4.6.2	Voltage Control of LSC for Standalone Mode of Operation	165
	4.4.6.3	Control of Bidirectional DC-DC Converter	167
	4.4.6.4	Islanding and Resynchronization Detection Control	167
	4.4.6.5	MSC Switching Pulse Control	168
4.5		MATLAB Based Modelling and Simulation of Battery Supported Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	169
	4.5.1	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	169
	4.5.2	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	169
	4.5.3	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	170
	4.5.4	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	170
	4.5.5	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	171
	4.5.6	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	172
4.6		Hardware Implementation of Battery Supported Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	172
4.7		Results and Discussion	173
	4.7.1	Simulated Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	173
	4.7.1.1	Steady State and Dynamic Performances	174
	4.7.1.2	Power Quality Performance	175
	4.7.2	Experimental Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	177

4.7.2.1	Grid Connected Operating Mode and Power Quality Indices	177
4.7.2.2	Seamless Transition Mode	178
4.7.2.3	Islanded Operating Mode	179
4.7.3	Simulated Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	181
4.7.3.1	Steady State and Dynamic Performances	181
4.7.3.2	Power Quality Performance	183
4.7.4	Experimental Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	183
4.7.4.1	Grid Connected Operating Mode and Power Quality Indices	183
4.7.4.2	Seamless Transition Mode	185
4.7.4.3	Islanded Operating Mode	186
4.7.5	Simulated Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	188
4.7.5.1	Steady State and Dynamic Performances	189
4.7.5.2	Power Quality Performance	190
4.7.6	Experimental Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	191
4.7.6.1	Grid Connected Operating Mode and Power Quality Indices	191
4.7.6.2	Seamless Transition Mode	193
4.7.6.3	Islanded Operating Mode	193
4.7.7	Simulated Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	195
4.7.7.1	Steady State and Dynamic Performances	196
4.7.7.2	Power Quality Performance	197
4.7.8	Experimental Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	198
4.7.8.1	Grid Connected Operating Mode and Power Quality Indices	198
4.7.8.2	Seamless Transition Mode	200
4.7.8.3	Islanded Operating Mode	201
4.7.9	Simulated Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	203
4.7.9.1	Steady State and Dynamic Performances	204
4.7.9.2	Power Quality Performance	206

4.7.10	Experimental Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	206
4.7.10.1	Grid Connected Operating Mode and Power Quality Indices	206
4.7.10.2	Seamless Transition Mode	208
4.7.10.3	Islanded Operating Mode	209
4.7.11	Simulated Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	209
4.7.11.1	Steady State and Dynamic Performances	210
4.7.11.2	Power Quality Performance	211
4.7.12	Experimental Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	213
4.7.12.1	Grid Connected Operating Mode and Power Quality Indices	213
4.7.12.2	Seamless Transition Mode	214
4.7.12.3	Islanded Operating Mode	215
4.8	Conclusions	216
CHAPTER V HYBRID SOLAR PV ARRAY AND WIND ENERGY GENERATION BASED GRID INTERACTIVE MICROGRIDS FOR ISLANDING AND RESYNCHRONIZATION		218-326
5.1	General	218
5.2	Configuration of Hybrid Solar PV Array and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	220
5.2.1	Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	220
5.2.2	Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	222
5.2.3	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	223
5.2.4	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	224
5.2.5	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	225
5.2.6	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	226

5.3	Design of Hybrid Solar PV Array and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	227
5.3.1	Design and Selection of Solar PV Array	228
5.3.2	Design of Boost Converter	229
5.3.3	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	230
5.3.4	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	230
5.3.5	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	232
5.3.6	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	232
5.3.7	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	233
5.3.8	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	234
5.4	Control of Hybrid Solar PV Array and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	236
5.4.1	Control of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	237
5.4.1.1	Current Control of LSC for Grid Connected Mode of Operation	238
5.4.1.2	Voltage Control of LSC for Standalone Mode of Operation	242
5.4.1.3	Islanding and Resynchronization Detection Control	243
5.4.1.4	MSC Switching Pulse Control	244
5.4.2	Control of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	245
5.4.2.1	Current Control of LSC for Grid Connected Mode of Operation	245
5.4.2.2	Voltage Control of LSC for Standalone Mode of Operation	247
5.4.2.3	Control of Boost Converter	247
5.4.2.4	Islanding and Resynchronization Detection Control	248
5.4.2.5	MSC Switching Pulse Control	248
5.4.3	Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	249

	5.4.3.1	Current Control of LSC for Grid Connected Mode of Operation	249
	5.4.3.2	Voltage Control of LSC for Standalone Mode of Operation	252
	5.4.3.3	Islanding and Resynchronization Detection Control	254
	5.4.3.4	MSC Switching Pulse Control	256
5.4.4		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	257
	5.4.4.1	Current Control of LSC for Grid Connected Mode of Operation	258
	5.4.4.2	Voltage Control of LSC for Standalone Mode of Operation	258
	5.4.4.3	Control of Boost Converter	259
	5.4.4.4	Islanding and Resynchronization Detection Control	260
	5.4.4.5	MSC Switching Pulse Control	261
5.4.5		Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	262
	5.4.5.1	Current Control of LSC for Grid Connected Mode of Operation	262
	5.4.5.2	Voltage Control of LSC for Standalone Mode of Operation	265
	5.4.5.3	Islanding and Resynchronization Detection Control	266
	5.4.5.4	MSC Switching Pulse Control	268
5.4.6		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	269
	5.4.6.1	Current Control of LSC for Grid Connected Mode of Operation	270
	5.4.6.2	Voltage Control of LSC for Standalone Mode of Operation	271
	5.4.6.3	Control of Boost Converter	271
	5.4.6.4	Islanding and Resynchronization Detection Control	271
	5.4.6.5	MSC Switching Pulse Control	272
5.5		MATLAB Based Modelling and Simulation of Hybrid Solar PV Array and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	272
	5.5.1	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	273
	5.5.2	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	273

5.5.3	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	274
5.5.4	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	274
5.5.5	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	275
5.5.6	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	275
5.6	Hardware Implementation of Hybrid Solar PV Array and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	276
5.7	Results and Discussion	277
5.7.1	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	277
5.7.1.1	Steady State and Dynamic Performances	278
5.7.1.2	Power Quality Performance	279
5.7.2	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	281
5.7.2.1	Grid Connected Operating Mode and Power Quality Indices	281
5.7.2.2	Seamless Transition Mode	283
5.7.2.3	Islanded Operating Mode	285
5.7.3	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	286
5.7.3.1	Steady State and Dynamic Performances	286
5.7.3.2	Power Quality Performance	288
5.7.4	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Islanding and Resynchronization	289
5.7.4.1	Grid Connected Operating Mode and Power Quality Indices	289
5.7.4.2	Seamless Transition Mode	292
5.7.4.3	Islanded Operating Mode	293
5.7.5	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	293
5.7.5.1	Steady State and Dynamic Performances	295
5.7.5.2	Power Quality Performance	297

5.7.6	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	298
5.7.6.1	Grid Connected Operating Mode and Power Quality Indices	298
5.7.6.2	Seamless Transition Mode	300
5.7.6.3	Islanded Operating Mode	302
5.7.7	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	303
5.7.7.1	Steady State and Dynamic Performances	303
5.7.7.2	Power Quality Performance	305
5.7.8	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Islanding and Resynchronization	306
5.7.8.1	Grid Connected Operating Mode and Power Quality Indices	306
5.7.8.2	Seamless Transition Mode	308
5.7.8.3	Islanded Operating Mode	309
5.7.9	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	310
5.7.9.1	Steady State and Dynamic Performances	311
5.7.9.2	Power Quality Performance	312
5.7.10	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	313
5.7.10.1	Grid Connected Operating Mode and Power Quality Indices	313
5.7.10.2	Seamless Transition Mode	315
5.7.10.3	Islanded Operating Mode	316
5.7.11	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	317
5.7.11.1	Steady State and Dynamic Performances	318
5.7.11.2	Power Quality Performance	319
5.7.12	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Islanding and Resynchronization	321
5.7.12.1	Grid Connected Operating Mode and Power Quality Indices	321
5.7.12.2	Seamless Transition Mode	323
5.7.12.3	Islanded Operating Mode	324
5.8	Conclusions	325

CHAPTER VI	BATTERY SUPPORTED HYBRID SOLAR PV AND WIND ENERGY GENERATION BASED GRID INTERACTIVE MICROGRIDS FOR ISLANDING AND RESYNCHRONIZATION	327-478
6.1	General	327
6.2	Configuration of Battery Supported Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	329
6.2.1	Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	329
6.2.2	Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	331
6.2.3	Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	332
6.2.4	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	333
6.2.5	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	334
6.2.6	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	336
6.2.7	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	337
6.2.8	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	338
6.2.9	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	339
6.3	Design of Battery Supported Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	340
6.3.1	Design and Selection of Solar PV Array	340
6.3.2	Design of Boost Converter	342
6.3.3	Design and Selection of Battery Energy Storage	343
6.3.4	Design and Selection of Inductor of Bidirectional DC-DC Converter	344
6.3.5	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	345

6.3.6	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	346
6.3.7	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	347
6.3.8	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	348
6.3.9	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	349
6.3.10	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	350
6.3.11	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	351
6.3.12	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	353
6.3.13	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	354
6.4	Control of Battery Supported Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	355
6.4.1	Control of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	356
6.4.1.1	Current Control of LSC for Grid Connected Mode of Operation	356
6.4.1.2	Voltage Control of LSC for Standalone Mode of Operation	360
6.4.1.3	Control of Bidirectional DC-DC Converter	361
6.4.1.4	Islanding and Resynchronization Detection Control	362
6.4.1.5	MSC Switching Pulse Control	363
6.4.2	Control of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	365
6.4.2.1	Current Control of LSC for Grid Connected Mode of Operation	365
6.4.2.2	Voltage Control of LSC for Standalone Mode of Operation	365
6.4.2.3	Control of Boost Converter	367
6.4.2.4	Islanding and Resynchronization Detection Control	368
6.4.2.5	MSC Switching Pulse Control	368

6.4.3	Control of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	369
6.4.3.1	Current Control of LSC for Grid Connected Mode of Operation	369
6.4.3.2	Voltage Control of LSC for Standalone Mode of Operation	369
6.4.3.3	Control of Bidirectional DC-DC Converter	369
6.4.3.4	Control of Boost Converter	370
6.4.3.5	Islanding and Resynchronization Detection Control	371
6.4.3.6	MSC Switching Pulse Control	371
6.4.4	Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	371
6.4.4.1	Current Control of LSC for Grid Connected Mode of Operation	371
6.4.4.2	Voltage Control of LSC for Standalone Mode of Operation	375
6.4.4.3	Control of Bidirectional DC-DC Converter	376
6.4.4.4	Islanding and Resynchronization Detection Control	377
6.4.4.5	MSC Switching Pulse Control	379
6.4.5	Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	380
6.4.5.1	Current Control of LSC for Grid Connected Mode of Operation	381
6.4.5.2	Voltage Control of LSC for Standalone Mode of Operation	382
6.4.5.3	Control of Boost Converter	382
6.4.5.4	Islanding and Resynchronization Detection Control	382
6.4.5.5	MSC Switching Pulse Control	383
6.4.6	Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	383
6.4.6.1	Current Control of LSC for Grid Connected Mode of Operation	383
6.4.6.2	Voltage Control of LSC for Standalone Mode of Operation	384
6.4.6.3	Control of Bidirectional DC-DC Converter	385
6.4.6.4	Control of Boost Converter	385
6.4.6.5	Islanding and Resynchronization Detection Control	385
6.4.6.6	MSC Switching Pulse Control	386
6.4.7	Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	386

	6.4.7.1	Current Control of LSC for Grid Connected Mode of Operation	386
	6.4.7.2	Voltage Control of LSC for Standalone Mode of Operation	389
	6.4.7.3	Control of Bidirectional DC-DC Converter	391
	6.4.7.4	Islanding and Resynchronization Detection Control	392
	6.4.7.5	MSC Switching Pulse Control	393
6.4.8		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	394
	6.4.8.1	Current Control of LSC for Grid Connected Mode of Operation	394
	6.4.8.2	Voltage Control of LSC for Standalone Mode of Operation	394
	6.4.8.3	Control of Boost Converter	395
	6.4.8.4	Islanding and Resynchronization Detection Control	396
	6.4.8.5	MSC Switching Pulse Control	397
6.4.9		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	397
	6.4.9.1	Current Control of LSC for Grid Connected Mode of Operation	397
	6.4.9.2	Voltage Control of LSC for Standalone Mode of Operation	397
	6.4.9.3	Control of Bidirectional DC-DC Converter	398
	6.4.9.4	Control of Boost Converter	399
	6.4.9.5	Islanding and Resynchronization Detection Control	399
	6.4.9.6	MSC Switching Pulse Control	399
6.5		MATLAB Based Modelling and Simulation of Battery Supported Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	399
	6.5.1	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	400
	6.5.2	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	400
	6.5.3	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	401
	6.5.4	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire	401

	Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	
6.5.5	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	402
6.5.6	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	402
6.5.7	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	403
6.5.8	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	403
6.5.9	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	404
6.6	Hardware Implementation of Battery Supported Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids for Islanding and Resynchronization	404
6.7	Results and Discussion	405
6.7.1	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	406
	6.7.1.1 Steady State and Dynamic Performances	406
	6.7.1.2 Power Quality Performance	408
6.7.2	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	409
	6.7.2.1 Grid Connected Operating Mode and Power Quality Indices	409
	6.7.2.2 Seamless Transition Mode	411
	6.7.2.3 Islanded Operating Mode	412
6.7.3	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	413
	6.7.3.1 Steady State and Dynamic Performances	414
	6.7.3.2 Power Quality Performance	416
6.7.4	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Islanding and Resynchronization	417

6.7.4.1	Grid Connected Operating Mode and Power Quality Indices	417
6.7.4.2	Seamless Transition Mode	419
6.7.4.3	Islanded Operating Mode	420
6.7.5	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	422
6.7.5.1	Steady State and Dynamic Performances	423
6.7.5.2	Power Quality Performance	424
6.7.6	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	426
6.7.6.1	Grid Connected Operating Mode and Power Quality Indices	426
6.7.6.2	Seamless Transition Mode	428
6.7.6.3	Islanded Operating Mode	428
6.7.7	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	430
6.7.7.1	Steady State and Dynamic Performances	430
6.7.7.2	Power Quality Performance	433
6.7.8	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	433
6.7.8.1	Grid Connected Operating Mode and Power Quality Indices	434
6.7.8.2	Seamless Transition Mode	436
6.7.8.3	Islanded Operating Mode	436
6.7.9	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	438
6.7.9.1	Steady State and Dynamic Performances	438
6.7.9.2	Power Quality Performance	441
6.7.10	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	441
6.7.10.1	Grid Connected Operating Mode and Power Quality Indices	442
6.7.10.2	Seamless Transition Mode	444
6.7.10.3	Islanded Operating Mode	444
6.7.11	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	446

	6.7.11.1	Steady State and Dynamic Performances	447
	6.7.11.2	Power Quality Performance	448
6.7.12		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	450
	6.7.12.1	Grid Connected Operating Mode and Power Quality Indices	450
	6.7.12.2	Seamless Transition Mode	452
	6.7.12.3	Islanded Operating Mode	453
6.7.13		Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	455
	6.7.13.1	Steady State and Dynamic Performances	455
	6.7.13.2	Power Quality Performance	456
6.7.14		Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	458
	6.7.14.1	Grid Connected Operating Mode and Power Quality Indices	458
	6.7.14.2	Seamless Transition Mode	460
	6.7.14.3	Islanded Operating Mode	461
6.7.15		Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	462
	6.7.15.1	Steady State and Dynamic Performances	462
	6.7.15.2	Power Quality Performance	464
6.7.16		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Islanding and Resynchronization	465
	6.7.16.1	Grid Connected Operating Mode and Power Quality Indices	465
	6.7.16.2	Seamless Transition Mode	468
	6.7.16.3	Islanded Operating Mode	468
6.7.17		Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	470
	6.7.17.1	Steady State and Dynamic Performances	470
	6.7.17.2	Power Quality Performance	472
6.7.18		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Islanding and Resynchronization	473

	6.7.18.1	Grid Connected Operating Mode and Power Quality Indices	473
	6.7.18.2	Seamless Transition Mode	475
	6.7.18.3	Islanded Operating Mode	476
6.8	Conclusions		478
CHAPTER VII WIND ENERGY GENERATION BASED GRID INTERACTIVE MICROGRID WITH DIESEL GENERATOR FOR ISLANDING AND RESYNCHRONIZATION			479-604
7.1	General		479
7.2	Configuration of Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization		481
	7.2.1	Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	481
	7.2.2	Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	482
	7.2.3	BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	483
	7.2.4	Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	484
	7.2.5	Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	485
	7.2.6	BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	486
	7.2.7	Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	487
	7.2.8	Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	488
	7.2.9	BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	489
7.3	Design of Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization		490
	7.3.1	Design of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	491
	7.3.2	Design of Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	491

7.3.3	Design of BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	491
7.3.4	Design of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	493
7.3.5	Design of Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	493
7.3.6	Design of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	494
7.3.7	Design of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	496
7.3.8	Design of Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	497
7.3.9	Design of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	497
7.4	Control of Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	498
7.4.1	Control of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	499
7.4.1.1	Current Control of LSC for Grid/DG Connected Mode of Operation	499
7.4.1.2	Voltage Control of LSC for Standalone Mode of Operation	504
7.4.1.3	Islanding and Resynchronization Detection Control	505
7.4.1.4	MSC Switching Pulse Control	506
7.4.2	Control of Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	506
7.4.2.1	Current Control of LSC for Grid/DG Connected Mode of Operation	507
7.4.2.2	Voltage Control of LSC for Standalone Mode of Operation	507
7.4.2.3	Islanding and Resynchronization Detection Control	507
7.4.2.4	MSC Switching Pulse Control	510
7.4.3	Control of BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	511
7.4.3.1	Current Control of LSC for Grid/DG Connected Mode of Operation	512

	7.4.3.2	Voltage Control of LSC for Standalone Mode of Operation	512
	7.4.3.3	Control of Bidirectional DC-DC Converter	512
	7.4.3.4	Islanding and Resynchronization Detection Control	514
	7.4.3.5	MSC Switching Pulse Control	514
7.4.4		Control of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	515
	7.4.4.1	Current Control of LSC for Grid/DG Connected Mode of Operation	515
	7.4.4.2	Voltage Control of LSC for Standalone Mode of Operation	518
	7.4.4.3	Islanding and Resynchronization Detection Control	519
	7.4.4.4	MSC Switching Pulse Control	520
7.4.5		Control of Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	521
	7.4.5.1	Current Control of LSC for Grid/DG Connected Mode of Operation	521
	7.4.5.2	Voltage Control of LSC for Standalone Mode of Operation	521
	7.4.5.3	Islanding and Resynchronization Detection Control	523
	7.4.5.4	MSC Switching Pulse Control	524
7.4.6		Control of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	524
	7.4.6.1	Current Control of LSC for Grid/DG Connected Mode of Operation	524
	7.4.6.2	Voltage Control of LSC for Standalone Mode of Operation	524
	7.4.6.3	Control of Bidirectional DC-DC Converter	525
	7.4.6.4	Islanding and Resynchronization Detection Control	527
	7.4.6.5	MSC Switching Pulse Control	527
7.4.7		Control of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	527
	7.4.7.1	Current Control of LSC for Grid/DG Connected Mode of Operation	528
	7.4.7.2	Voltage Control of LSC for Standalone Mode of Operation	530
	7.4.7.3	Islanding and Resynchronization Detection Control	534
	7.4.7.4	MSC Switching Pulse Control	534
7.4.8		Control of Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	535

	7.4.8.1	Current Control of LSC for Grid/DG Connected Mode of Operation	536
	7.4.8.2	Voltage Control of LSC for Standalone Mode of Operation	536
	7.4.8.3	Islanding and Resynchronization Detection Control	536
	7.4.8.4	MSC Switching Pulse Control	538
7.4.9		Control of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	538
	7.4.9.1	Current Control of LSC for Grid/DG Connected Mode of Operation	538
	7.4.9.2	Voltage Control of LSC for Standalone Mode of Operation	538
	7.4.9.3	Control of Bidirectional DC-DC Converter	539
	7.4.9.4	Islanding and Resynchronization Detection Control	540
	7.4.9.5	MSC Switching Pulse Control	540
7.5		MATLAB Based Modelling and Simulation of Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	541
	7.5.1	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	541
	7.5.2	MATLAB Based Modelling and Simulation of Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	542
	7.5.3	MATLAB Based Modelling and Simulation of BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	542
	7.5.4	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	543
	7.5.5	MATLAB Based Modelling and Simulation of Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	543
	7.5.6	MATLAB Based Modelling and Simulation of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	544
	7.5.7	MATLAB Based Modelling and Simulation of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	544
	7.5.8	MATLAB Based Modelling and Simulation of Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid	545

	Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	
7.5.9	MATLAB Based Modelling and Simulation of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	545
7.6	Hardware Implementation of Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	546
7.7	Results and Discussion	547
7.7.1	Simulated Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	547
	7.7.1.1 Steady State and Dynamic Performances	548
	7.7.1.2 Power Quality Performance	549
7.7.2	Experimental Performance of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	550
	7.7.2.1 Grid/DG Connected Operating Mode and Power Quality Indices	550
	7.7.2.2 Seamless Transition Mode	550
	7.7.2.3 Islanded Operating Mode	552
7.7.3	Simulated Performance of Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	553
	7.7.3.1 Steady State and Dynamic Performances	553
	7.7.3.2 Power Quality Performance	554
7.7.4	Experimental Performance of Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	555
	7.7.4.1 Grid/DG Connected Operating Mode and Power Quality Indices	555
	7.7.4.2 Seamless Transition Mode	557
	7.7.4.3 Islanded Operating Mode	558
7.7.5	Simulated Performance of BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	559
	7.7.5.1 Steady State and Dynamic Performances	559
	7.7.5.2 Power Quality Performance	560
7.7.6	Experimental Performance of BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	560
	7.7.6.1 Grid/DG Connected Operating Mode and Power Quality Indices	561
	7.7.6.2 Seamless Transition Mode	563
	7.7.6.3 Islanded Operating Mode	564

7.7.7	Simulated Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	565
7.7.7.1	Steady State and Dynamic Performances	565
7.7.7.2	Power Quality Performance	567
7.7.8	Experimental Performance of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	568
7.7.8.1	Grid/DG Connected Operating Mode and Power Quality Indices	568
7.7.8.2	Seamless Transition Mode	569
7.7.8.3	Islanded Operating Mode	569
7.7.9	Simulated Performance of Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	570
7.7.9.1	Steady State and Dynamic Performances	571
7.7.9.2	Power Quality Performance	572
7.7.10	Experimental Performance of Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	572
7.7.10.1	Grid/DG Connected Operating Mode and Power Quality Indices	573
7.7.10.2	Seamless Transition Mode	574
7.7.10.3	Islanded Operating Mode	575
7.7.11	Simulated Performance of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	576
7.7.11.1	Steady State and Dynamic Performances	577
7.7.11.2	Power Quality Performance	577
7.7.12	Experimental Performance of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	579
7.7.12.1	Grid/DG Connected Operating Mode and Power Quality Indices	579
7.7.12.2	Seamless Transition Mode	580
7.7.12.3	Islanded Operating Mode	581
7.7.13	Simulated Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	582
7.7.13.1	Steady State and Dynamic Performances	583
7.7.13.2	Power Quality Performance	583
7.7.14	Experimental Performance of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	585

	7.7.14.1	Grid/DG Connected Operating Mode and Power Quality Indices	585
	7.7.14.2	Seamless Transition Mode	587
	7.7.14.3	Islanded Operating Mode	587
7.7.15		Simulated Performance of Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	589
	7.7.15.1	Steady State and Dynamic Performances	589
	7.7.15.2	Power Quality Performance	591
7.7.16		Experimental Performance of Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	591
	7.7.16.1	Grid/DG Connected Operating Mode and Power Quality Indices	592
	7.7.16.2	Seamless Transition Mode	594
	7.7.16.3	Islanded Operating Mode	595
7.7.17		Simulated Performance of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	596
	7.7.17.1	Steady State and Dynamic Performances	597
	7.7.17.2	Power Quality Performance	597
7.7.18		Experimental Performance of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	599
	7.7.18.1	Grid/DG Connected Operating Mode and Power Quality Indices	599
	7.7.18.2	Seamless Transition Mode	601
	7.7.18.3	Islanded Operating Mode	601
7.8		Conclusions	604
CHAPTER VIII HYBRID SOLAR PV AND WIND ENERGY GENERATION BASED GRID INTERACTIVE MICROGRID WITH DG FOR ISLANDING AND RESYNCHRONIZATION			605-793
8.1		General	605
8.2		Configuration of Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	606
	8.2.1	Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	607
	8.2.2	Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	608

8.2.3	Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	609
8.2.4	Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	610
8.2.5	Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	611
8.2.6	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	612
8.2.7	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	613
8.2.8	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	614
8.2.9	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	615
8.2.10	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	616
8.2.11	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	617
8.2.12	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	618
8.2.13	Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	619
8.2.14	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	620
8.2.15	Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	621
8.3	Design of Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	622

8.3.1	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	622
8.3.2	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	622
8.3.3	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	622
8.3.4	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	623
8.3.5	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	624
8.3.6	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	626
8.3.7	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	628
8.3.8	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	629
8.3.9	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	630
8.3.10	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	631
8.3.11	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	632
8.3.12	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	633
8.3.13	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	634
8.3.14	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	635

8.3.15	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	636
8.4	Control of Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	637
8.4.1	Control of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	638
8.4.1.1	Current Control of LSC for Grid/DG Connected Mode of Operation	638
8.4.1.2	Voltage Control of LSC for Standalone Mode of Operation	641
8.4.1.3	Islanding and Resynchronization Detection Control	643
8.4.1.4	MSC Switching Pulse Control	645
8.4.2	Control of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	645
8.4.2.1	Current Control of LSC for Grid/DG Connected Mode of Operation	645
8.4.2.2	Voltage Control of LSC for Standalone Mode of Operation	647
8.4.2.3	Control of Boost Converter	647
8.4.2.4	Islanding and Resynchronization Detection Control	647
8.4.2.5	MSC Switching Pulse Control	648
8.4.3	Control of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	648
8.4.3.1	Current Control of LSC for Grid/DG Connected Mode of Operation	648
8.4.3.2	Voltage Control of LSC for Standalone Mode of Operation	649
8.4.3.3	Control of Bidirectional DC-DC Converter	649
8.4.3.4	Islanding and Resynchronization Detection Control	650
8.4.3.5	MSC Switching Pulse Control	651
8.4.4	Control of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	651
8.4.4.1	Current Control of LSC for Grid/DG Connected Mode of Operation	651
8.4.4.2	Voltage Control of LSC for Standalone Mode of Operation	653
8.4.4.3	Control of Boost Converter	653
8.4.4.4	Islanding and Resynchronization Detection Control	653
8.4.4.5	MSC Switching Pulse Control	653

8.4.5	Control of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	655
8.4.5.1	Current Control of LSC for Grid/DG Connected Mode of Operation	655
8.4.5.2	Voltage Control of LSC for Standalone Mode of Operation	656
8.4.5.3	Control of Boost Converter	656
8.4.5.4	Control of Bidirectional DC-DC Converter	656
8.4.5.5	Islanding and Resynchronization Detection Control	656
8.4.5.6	MSC Switching Pulse Control	657
8.4.6	Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	658
8.4.6.1	Current Control of LSC for Grid/DG Connected Mode of Operation	658
8.4.6.2	Voltage Control of LSC for Standalone Mode of Operation	660
8.4.6.3	Islanding and Resynchronization Detection Control	662
8.4.6.4	MSC Switching Pulse Control	663
8.4.7	Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	663
8.4.7.1	Current Control of LSC for Grid/DG Connected Mode of Operation	663
8.4.7.2	Voltage Control of LSC for Standalone Mode of Operation	664
8.4.7.3	Control of Boost Converter	664
8.4.7.4	Islanding and Resynchronization Detection Control	664
8.4.7.5	MSC Switching Pulse Control	665
8.4.8	Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	665
8.4.8.1	Current Control of LSC for Grid/DG Connected Mode of Operation	665
8.4.8.2	Voltage Control of LSC for Standalone Mode of Operation	665
8.4.8.3	Control of Bidirectional DC-DC Converter	666
8.4.8.4	Islanding and Resynchronization Detection Control	667
8.4.8.5	MSC Switching Pulse Control	668
8.4.9	Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	668

	8.4.9.1	Current Control of LSC for Grid/DG Connected Mode of Operation	668
	8.4.9.2	Voltage Control of LSC for Standalone Mode of Operation	669
	8.4.9.3	Control of Boost Converter	669
	8.4.9.4	Islanding and Resynchronization Detection Control	669
	8.4.9.5	MSC Switching Pulse Control	670
8.4.10		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	670
	8.4.10.1	Current Control of LSC for Grid/DG Connected Mode of Operation	670
	8.4.10.2	Voltage Control of LSC for Standalone Mode of Operation	670
	8.4.10.3	Control of Boost Converter	671
	8.4.10.4	Control of Bidirectional DC-DC Converter	671
	8.4.10.5	Islanding and Resynchronization Detection Control	672
	8.4.10.6	MSC Switching Pulse Control	672
8.4.11		Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	672
	8.4.11.1	Current Control of LSC for Grid/DG Connected Mode of Operation	672
	8.4.11.2	Voltage Control of LSC for Standalone Mode of Operation	674
	8.4.11.3	Islanding and Resynchronization Detection Control	677
	8.4.11.4	MSC Switching Pulse Control	677
8.4.12		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	677
	8.4.12.1	Current Control of LSC for Grid/DG Connected Mode of Operation	678
	8.4.12.2	Voltage Control of LSC for Standalone Mode of Operation	678
	8.4.12.3	Control of Boost Converter	679
	8.4.12.4	Islanding and Resynchronization Detection Control	679
	8.4.12.5	MSC Switching Pulse Control	679
8.4.13		Control of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	679
	8.4.13.1	Current Control of LSC for Grid/DG Connected Mode of Operation	679
	8.4.13.2	Voltage Control of LSC for Standalone Mode of Operation	680

	8.4.13.3	Control of Bidirectional DC-DC Converter	680
	8.4.13.4	Islanding and Resynchronization Detection Control	681
	8.4.13.5	MSC Switching Pulse Control	681
8.4.14		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	682
	8.4.14.1	Current Control of LSC for Grid/DG Connected Mode of Operation	682
	8.4.14.2	Voltage Control of LSC for Standalone Mode of Operation	682
	8.4.14.3	Control of Boost Converter	682
	8.4.14.4	Islanding and Resynchronization Detection Control	682
	8.4.14.5	MSC Switching Pulse Control	682
8.4.15		Control of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	683
	8.4.15.1	Current Control of LSC for Grid/DG Connected Mode of Operation	684
	8.4.15.2	Voltage Control of LSC for Standalone Mode of Operation	685
	8.4.15.3	Control of Boost Converter	685
	8.4.15.4	Control of Bidirectional DC-DC Converter	685
	8.4.15.5	Islanding and Resynchronization Detection Control	685
	8.4.15.6	MSC Switching Pulse Control	685
8.5		MATLAB Based Modelling and Simulation of Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	685
	8.5.1	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	686
	8.5.2	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	686
	8.5.3	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	687
	8.5.4	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	688

8.5.5	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	688
8.5.6	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	689
8.5.7	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	689
8.5.8	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	690
8.5.9	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	690
8.5.10	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	691
8.5.11	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	691
8.5.12	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	692
8.5.13	MATLAB Based Modelling and Simulation of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	692
8.5.14	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	693
8.5.15	MATLAB Based Modelling and Simulation of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	693

8.6	Hardware Implementation of Hybrid Solar PV and Wind Energy Generation Based Grid Interactive Microgrids with Diesel Generator for Islanding and Resynchronization	694
8.7	Results and Discussion	695
8.7.1	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	695
8.7.1.1	Steady State and Dynamic Performances	695
8.7.1.2	Power Quality Performance	696
8.7.2	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	697
8.7.2.1	Grid/DG Connected Operating Mode and Power Quality Indices	697
8.7.2.2	Seamless Transition Mode	699
8.7.2.3	Islanded Operating Mode	700
8.7.3	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	701
8.7.3.1	Steady State and Dynamic Performances	701
8.7.3.2	Power Quality Performance	702
8.7.4	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	704
8.7.4.1	Grid/DG Connected Operating Mode and Power Quality Indices	704
8.7.4.2	Seamless Transition Mode	706
8.7.4.3	Islanded Operating Mode	706
8.7.5	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	708
8.7.5.1	Steady State and Dynamic Performances	708
8.7.5.2	Power Quality Performance	709
8.7.6	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	711
8.7.6.1	Grid/DG Connected Operating Mode and Power Quality Indices	711
8.7.6.2	Seamless Transition Mode	712
8.7.6.3	Islanded Operating Mode	713
8.7.7	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	715

	8.7.7.1	Steady State and Dynamic Performances	715
	8.7.7.2	Power Quality Performance	717
8.7.8		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	717
	8.7.8.1	Grid/DG Connected Operating Mode and Power Quality Indices	718
	8.7.8.2	Seamless Transition Mode	719
	8.7.8.3	Islanded Operating Mode	720
8.7.9		Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	721
	8.7.9.1	Steady State and Dynamic Performances	721
	8.7.9.2	Power Quality Performance	723
8.7.10		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	724
	8.7.10.1	Grid/DG Connected Operating Mode and Power Quality Indices	724
	8.7.10.2	Seamless Transition Mode	726
	8.7.10.3	Islanded Operating Mode	727
8.7.11		Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	728
	8.7.11.1	Steady State and Dynamic Performances	728
	8.7.11.2	Power Quality Performance	729
8.7.12		Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	731
	8.7.12.1	Grid/DG Connected Operating Mode and Power Quality Indices	731
	8.7.12.2	Seamless Transition Mode	732
	8.7.12.3	Islanded Operating Mode	733
8.7.13		Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	734
	8.7.13.1	Steady State and Dynamic Performances	734
	8.7.13.2	Power Quality Performance	735
8.7.14		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	736
	8.7.14.1	Grid/DG Connected Operating Mode and Power Quality Indices	736

	8.7.14.2	Seamless Transition Mode	737
	8.7.14.3	Islanded Operating Mode	739
8.7.15		Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	739
	8.7.15.1	Steady State and Dynamic Performances	739
	8.7.15.2	Power Quality Performance	741
8.7.16		Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	741
	8.7.16.1	Grid/DG Connected Operating Mode and Power Quality Indices	742
	8.7.16.2	Seamless Transition Mode	744
	8.7.16.3	Islanded Operating Mode	744
8.7.17		Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	746
	8.7.17.1	Steady State and Dynamic Performances	746
	8.7.17.2	Power Quality Performance	747
8.7.18		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	748
	8.7.18.1	Grid/DG Connected Operating Mode and Power Quality Indices	748
	8.7.18.2	Seamless Transition Mode	749
	8.7.18.3	Islanded Operating Mode	749
8.7.19		Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	752
	8.7.19.1	Steady State and Dynamic Performances	753
	8.7.19.2	Power Quality Performance	754
8.7.20		Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	754
	8.7.20.1	Grid/DG Connected Operating Mode and Power Quality Indices	755
	8.7.20.2	Seamless Transition Mode	756
	8.7.20.3	Islanded Operating Mode	757

8.7.21	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	759
8.7.21.1	Steady State and Dynamic Performances	759
8.7.21.2	Power Quality Performance	761
8.7.22	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	761
8.7.22.1	Grid/DG Connected Operating Mode and Power Quality Indices	761
8.7.22.2	Seamless Transition Mode	763
8.7.22.3	Islanded Operating Mode	764
8.7.23	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	765
8.7.23.1	Steady State and Dynamic Performances	766
8.7.23.2	Power Quality Performance	767
8.7.24	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Islanding and Resynchronization	767
8.7.24.1	Grid/DG Connected Operating Mode and Power Quality Indices	767
8.7.24.2	Seamless Transition Mode	769
8.7.24.3	Islanded Operating Mode	770
8.7.25	Simulated Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	771
8.7.25.1	Steady State and Dynamic Performances	771
8.7.25.2	Power Quality Performance	773
8.7.26	Experimental Performance of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	773
8.7.26.1	Grid/DG Connected Operating Mode and Power Quality Indices	774
8.7.26.2	Seamless Transition Mode	776
8.7.26.3	Islanded Operating Mode	777
8.7.27	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	778
8.7.27.1	Steady State and Dynamic Performances	779
8.7.27.2	Power Quality Performance	779
8.7.28	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive	780

	Microgrid with Battery and Diesel Generator for Islanding and Resynchronization	
	8.7.28.1 Grid/DG Connected Operating Mode and Power Quality Indices	780
	8.7.28.2 Seamless Transition Mode	781
	8.7.28.3 Islanded Operating Mode	783
8.7.29	Simulated Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	785
	8.7.29.1 Steady State and Dynamic Performances	785
	8.7.29.2 Power Quality Performance	786
8.7.30	Experimental Performance of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Islanding and Resynchronization	787
	8.7.30.1 Grid/DG Connected Operating Mode and Power Quality Indices	787
	8.7.30.2 Seamless Transition Mode	789
	8.7.30.3 Islanded Operating Mode	790
8.8	Conclusions	792
CHAPTER IX	MAIN CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK	794-799
9.1	General	794
9.2	Main Conclusions	795
9.3	Key Contributions	797
9.3	Suggestions for Further Work	798
	REFERENCES	800
	APPENDIX A	818
	LIST OF PUBLICATIONS	834
	BIO-DATA	838

LIST OF FIGURES

- Fig. 2.1 Classification of generators utilized in WEGS.
- Fig. 3.1 Wind energy generation based single phase grid interactive microgrid.
- Fig. 3.2 Wind energy generation based three phase three wire grid interactive microgrid.
- Fig. 3.3 Wind energy generation based three phase four wire grid interactive microgrid.
- Fig. 3.4 Structure of LSC current control.
- Fig. 3.5 Structure of LSC voltage control.
- Fig. 3.6 (a) Flowchart for islanding and resynchronization detection control, (b) grid synchronization control.
- Fig. 3.7 CGI-PLL structure and grid synchronization control.
- Fig. 3.8 Structure of MSC control.
- Fig. 3.9 LSC Current Control.
- Fig. 3.10 Voltage control of LSC.
- Fig. 3.11 Islanding and resynchronization detection control.
- Fig. 3.12 Structure of BGI-PLL.
- Fig. 3.13 Grid synchronized and standalone control of the LSC.
- Fig. 3.14 Structure of SOAP-FLL structure.
- Fig. 3.15 Detection control for grid synchronized and standalone operating mode.
- Fig. 3.16 MSC control Structure.
- Fig. 3.17 Matlab model of the WEGU based single phase grid interactive microgrid.
- Fig. 3.18 MATLAB model of wind energy generation based three phase three wire grid interactive microgrid.
- Fig. 3.19 MATLAB model of wind energy generation based three phase four wire grid interactive microgrid.
- Fig. 3.20 Photograph of the developed hardware prototype.
- Fig. 3.21 Signal conditioning circuit for voltage sensors (a) Schematic diagram (b) Photograph of voltage sensor board.
- Fig. 3.22 Signal conditioning circuit for current sensors (a) Schematic diagram (b) Photograph of current sensor board.
- Fig. 3.23 Isolation and amplification circuit for gate drivers (a) Schematic diagram (b) Photograph of opto-isolation and amplification board.
- Fig. 3.24 Architecture of dSPACE 1202 (a) Execution of control algorithm (b) image of dSPACE 1202.
- Fig. 3.25 Grid synchronization and islanded operating modes.
- Fig. 3.26 Transition between grid connected to islanded mode and resynchronized mode.
- Fig. 3.27 Performance of the islanded microgrid under variable wind speed condition.
- Fig. 3.28 (a-b) THD of utility current (i_g) (c-d) Load current (i_L) THD (e-f) THD of v_{PCC} .

- Fig. 3.29 Estimated wind generator speed along with SG currents (a) at 7.2m/s wind speed; (b) at 12m/s wind speed; (c) at wind speed variation.
- Fig. 3.30 SG rotor position and speed estimation behavior under wind speed variation (a) at wind speed of 7.2m/s; (b) at wind speed of 12m/s; (c) at wind speed variations.
- Fig. 3.31 Load profile parameters and DC link voltage.
- Fig. 3.32 (a) grid voltage and current, (b) power fed to the grid, P_{grid} , and (c-d) harmonic spectrum of the grid current and voltage.
- Fig. 3.33 Load profile parameters (a) v_L and i_L . (b) P_{Load} (c-d) harmonic spectrum of the load current and voltage.
- Fig. 3.34 (a-d) Microgrid parameters determining grid isolation and resynchronization.
- Fig. 3.35 Islanded microgrid operation under (a-b) load variation; (c-d) wind speed variation.
- Fig. 3.36 (a) Grid isolation; (b) microgrid reconnection to grid.
- Fig. 3.37 (a-b) Performance of the islanded microgrid under variable load conditions.
- Fig. 3.38 Performance of the grid connected microgrid under variable wind speed conditions.
- Fig. 3.39 (a-b) THD of utility current (i_{ga}) (c-d) Load current (i_{La}) THD (e-f) THD of v_{La} .
- Fig. 3.40 Wind generator currents with respect to change in wind speed.
- Fig. 3.41 Estimated rotor position and speed of the wind generator under cut-in and cut-out wind speeds.
- Fig. 3.42 Power variation during grid connected mode.
- Fig. 3.43 (a) grid voltage and current, (b) power fed to the grid, P_{grid} , and (c-d) harmonic spectrum of the grid current and voltage.
- Fig. 3.44 Load profile parameters (a) v_L and i_L . (b) P_{Load} (c-d) harmonic spectrum of the load current and voltage.
- Fig. 3.45 Mode transition parameters and their response during grid isolation and reconnection.
- Fig. 3.46 Performance of microgrid under islanded operating mode (a) constant generation and load demand; (c-d) change in load demand leading to change in wind generation.
- Fig. 3.47 Performance of microgrid under mode transition (a) Grid connected to islanded mode, (b) islanded mode to grid connected mode, (c) neutral current and power signals during grid connected to islanded mode, (d) neutral currents and power signals during islanded mode to grid connected mode.
- Fig. 3.48 Variation in microgrid performance at wind speed variation leading to generation change of WEGU during grid connected mode.
- Fig. 3.49 Harmonic spectrum of (a-b) utility current (i_{ga}) (c-d) Load current (i_{La}) THD (e-f) THD of v_{La} .
- Fig. 3.50 Generation variation of wind during wind speed variations during grid connected mode.

- Fig. 3.51 (a) grid voltage and current, (b) power fed to the grid, P_{grid} , and (c-d) harmonic spectrum of the grid current and voltage.
- Fig. 3.52 Load profile parameters (a) v_L and i_L . (b) P_{Load} (c-d) harmonic spectrum of the load current and voltage.
- Fig. 3.53 Seamless mode transfer response and its parameters.
- Fig. 3.54 Microgrid islanded mode of operation; (a-b) load demand rise and fall leading to WEGU generation variation; (c-d) one phase load disconnection leading to variation of wind generation.
- Fig. 4.1 Structure of wind energy generation based single phase grid interactive microgrid with battery.
- Fig. 4.2 Structure of wind energy generation based single phase grid interactive microgrid with BDC controlled battery.
- Fig. 4.3 Structure of wind energy generation based three phase three wire grid interactive microgrid with battery.
- Fig. 4.4 Structure of wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery.
- Fig. 4.5 Structure of wind energy generation based three phase four wire grid interactive microgrid with battery.
- Fig. 4.6 Structure of wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery.
- Fig. 4.7 Control architecture of the wind energy generation based single phase grid interactive microgrid with BES.
- Fig. 4.8 MSC control.
- Fig. 4.9 Control architecture of the wind energy generation based single phase grid interactive microgrid with BDC controlled BES.
- Fig. 4.10 Control architecture of the wind energy generation based three phase three wire grid interactive microgrid with battery for islanding and resynchronization.
- Fig. 4.11 Control Logic of MSC.
- Fig. 4.12 Control architecture of the wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 4.13 Control structure of wind energy generation based three phase four wire grid interactive microgrid with battery for islanding and resynchronization.
- Fig. 4.14 MSC control Structure.
- Fig. 4.15 Control of wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 4.16 MSC control Structure.
- Fig. 4.17 Matlab model of the wind energy generation based single phase grid interactive microgrid with battery.

- Fig. 4.18 Matlab model of the wind energy generation based single phase grid interactive microgrid with BDC controlled battery.
- Fig. 4.19 Matlab model of the WEGU based three phase three wire grid interactive microgrid with battery.
- Fig. 4.20 Matlab model of the wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery.
- Fig. 4.21 Matlab model of the wind energy generation based three phase four wire grid interactive microgrid with battery.
- Fig. 4.22 Matlab model of the wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery.
- Fig. 4.23 Hardware developed prototype of the battery supported microgrid.
- Fig. 4.24 Grid synchronization and islanded operating modes.
- Fig. 4.25 Microgrid mode transition under wind speed variation and load variation
- Fig. 4.26 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of v_{PCC} .
- Fig. 4.27 Performance of the microgrid under (a-d) v_{wind} of 7.2m/s and 12m/s, (e-f) effect of change in wind speeds.
- Fig. 4.28 Grid indices (a-b) grid voltage and current waveform; (c-d) harmonic spectrum of grid voltage and current.
- Fig. 4.29 Load response under steady state (a-b) load voltage and current waveform; (c-d) harmonic spectrum of load voltage and current.
- Fig. 4.30 (a-c) Microgrid performance during seamless transition between operating modes.
- Fig. 4.31 Islanded operation of the microgrid and its performance (a-b) under load disconnection (c-d) under wind speed change.
- Fig. 4.32 Response of the battery under (a-b) wind generator is feeding the load and battery; (c-d) load is removed and wind generator feeds the battery; (e-f) wind generator is off and battery feeds the load
- Fig. 4.33 Grid synchronization and islanded operating modes.
- Fig. 4.34 Microgrid mode transition and variations of load disconnection and wind speeds.
- Fig. 4.35 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of v_{PCC} .
- Fig. 4.36 (a-c) wind generation and its variations under wind speed change.
- Fig. 4.37 Grid indices (a-b) grid voltage and current waveform; (c-d) harmonic spectrum of grid voltage and current.
- Fig. 4.38 Load indices (a-b) load voltage and current waveform; (c-d) harmonic spectrum of load voltage and current.
- Fig. 4.39 (a-c) Microgrid performance during transition from grid connected to islanded operating mode and vice-versa.
- Fig. 4.40 Microgrid performance during islanded operating mode (a-d) under wind speed change (e-h) under load disconnection and retention.

- Fig. 4.41 Battery parameters (a-b) at rated generation of wind, (c-d) generation from wind at 7.2m/s, (e-f) wind generation is off, (g-h) load is off, (i-j) load is reduced
- Fig. 4.42 Grid synchronization and islanded operating modes
- Fig. 4.43 Microgrid behavior under mode transition, load change and wind speed change.
- Fig. 4.44 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 4.45 Microgrid performance during grid connected operating mode (a-b) generator current and load current w.r.t wind speed (c) load variations (d-f) wind speed change.
- Fig. 4.46 (a-c) load current, power and harmonic analysis, (d-g) grid voltage, current, power, harmonic analysis of grid current and grid voltage.
- Fig. 4.47 Microgrid response during mode transition
- Fig. 4.48 Islanded microgrid performance (a-c) under load change, (d) wind speed change.
- Fig. 4.49 Battery response (V_{bat} , I_{bat} , P_b) (a-b) when generation from SG meets load demand and feeds the battery; (c-d) generation from wind is nil and load is satisfied by the battery (e-f) V_{bat} , I_{bat} , P_b at load removal and generation from SG charges the battery.
- Fig. 4.50 Grid synchronization and islanded operating modes.
- Fig. 4.51 Behaviour of microgrid under mode transition, load variation and wind speed change.
- Fig. 4.52 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 4.53 Microgrid response during grid connected operating mode (a-d) wind speed change (e-f) load variations.
- Fig. 4.54 (a-d) load current, power and harmonic analysis, (e-h) grid voltage, current, power, harmonic analysis of grid current and grid voltage.
- Fig. 4.55 Seamless transition behavior of the microgrid.
- Fig. 4.56 Dynamic performance of WEGU at wind speed change (a) response of SG current, load current and battery current; (b) power variation of SG, battery and load under varying wind speeds; (c) power variation of SG, battery and load when the wind speed is varied from below cut-in to cut-out speed; (d) response of the battery power, battery current and DC link voltage.
- Fig. 4.57 Dynamic performance of the WEGU under load disconnection and insertion.
- Fig. 4.58 Performance of the battery (a) battery voltage and current when SG is feeding load and battery; (b) battery power when SG is feeding load and battery; (c) battery voltage and current when SG is off and battery feeds the load; (d) battery power when SG is off and battery feeds the load; (e) battery voltage and current when load is disconnected and SG feeds the battery; (f) battery power when load is disconnected and SG feeds the battery.
- Fig. 4.59 Grid synchronization and islanded operating modes.

- Fig. 4.60 Microgrid performance under load variation, wind speed change, microgrid isolation and reconnection to the grid.
- Fig. 4.61 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 4.62 Grid connected operating mode of microgrid and its response under (a-b) load variations (c) wind speed variation.
- Fig. 4.63 (a-d) grid current, power and harmonic analysis of grid current and voltage, (e-h) load voltage, current, power, harmonic analysis of load current and load voltage
- Fig. 4.64 Seamless mode transition behavior of the microgrid.
- Fig. 4.65 Isolated microgrid response under (a-b) wind speed variations i.e. rise and fall.
- Fig. 4.66 Battery performance (a-b) Only battery feeds load, (c-d) wind generation feeds load and battery, (e-f) under load disconnection, wind generation feeds battery for storage.
- Fig. 4.67 Grid synchronization and islanded operating modes.
- Fig. 4.68 Microgrid response under load perturbation and wind speeds variations during mode transition.
- Fig. 4.69 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 4.70 (a-c) Grid connected microgrid and its response during load change.
- Fig. 4.71 (a-d) grid current, power and harmonic analysis of grid current and voltage, (e-h) load voltage, current, power, harmonic analysis of load current and load voltage.
- Fig. 4.72 (a-b) Behavior of microgrid under mode transition i.e. grid connected to islanded mode of operation.
- Fig. 4.73 Islanded operating mode and its behavior under (a-c) wind speed change.
- Fig. 4.74 Battery performance (a-b) Only battery feeds load, (c-d) wind generation feeds load and battery, (e-f) under load disconnection, wind generation {at 8.4m/s} feeds battery for storage.
- Fig. 5.1 Structure of single stage solar PV array and wind energy generation based single phase grid interactive microgrid.
- Fig. 5.2 Structure of double stage solar PV array and wind energy generation based single phase grid interactive microgrid.
- Fig. 5.3 Structure of single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid.
- Fig. 5.4 Structure of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid.
- Fig. 5.5 Structure of single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid.
- Fig. 5.6 Structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid.

- Fig. 5.7 Control architecture of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid for islanding and resynchronization.
- Fig. 5.8 Flow diagram of INC-MPPT algorithm.
- Fig. 5.9 Control structure of machine side converter.
- Fig. 5.10 Control architecture of double stage solar PV array and wind energy generation based single phase grid interactive microgrid for islanding and resynchronization.
- Fig. 5.11 Solar P&O MPPT technique.
- Fig. 5.12 Control architecture of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid for islanding and resynchronization.
- Fig. 5.13 Control structure of machine side converter
- Fig. 5.14 Control architecture of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid for islanding and resynchronization.
- Fig. 5.15 Flow diagram of INC-MPPT algorithm
- Fig. 5.16 Control architecture of the single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid for islanding and resynchronization.
- Fig. 5.17 Control Logic of MSC.
- Fig. 5.18 Control architecture of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid for islanding and resynchronization.
- Fig. 5.19 Matlab model of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid with islanding and resynchronization capabilities.
- Fig. 5.20 Matlab model of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with islanding and resynchronization capabilities.
- Fig. 5.21 Matlab model of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with islanding and resynchronization capabilities.
- Fig. 5.22 Matlab model of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with islanding and resynchronization capabilities.
- Fig. 5.23 Matlab model of the single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with islanding and resynchronization capabilities.
- Fig. 5.24 Matlab model of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with islanding and resynchronization capabilities.

- Fig. 5.25 Hardware developed prototype of the battery supported microgrid
- Fig. 5.26 Grid synchronization and islanded operating modes.
- Fig. 5.27 Microgrid performance under load disconnection.
- Fig. 5.28 Microgrid performance under solar insolation change.
- Fig. 5.29 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 5.30 Microgrid response during (a) solar insolation change; (c) wind speed change; (d-e) load disconnection.
- Fig. 5.31 Load profile indices (a-b) load voltage/current waveform and load power; (c-d) harmonic spectrum of load voltage and current.
- Fig. 5.32 Grid indices when wind and solar PV array are generating at rated values (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current.
- Fig. 5.33 Grid indices when wind and solar PV array are generating at half power (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current.
- Fig. 5.34 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 5.35 Microgrid response during seamless mode transition.
- Fig. 5.36 Islanded microgrid performance.
- Fig. 5.37 Grid synchronization and islanded operating modes.
- Fig. 5.38 Microgrid performance under (a) solar insolation change; (b) load disconnection.
- Fig. 5.39 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 5.40 Microgrid response during (a) solar insolation change; (c) wind speed change; (d-e) load disconnection.
- Fig. 5.41 Load profile indices (a-b) load voltage/current waveform and load power; (c-d) harmonic spectrum of load voltage and current
- Fig. 5.42 Grid profile indices when wind and solar PV array are at rated generation (a-b) voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current.
- Fig. 5.43 Grid profile indices when wind and solar PV array are at half generation (a-b) voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current.
- Fig. 5.44 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 5.45 Microgrid response during mode transition
- Fig. 5.46 Microgrid response during islanded mode of operation.
- Fig. 5.47 Grid synchronization and islanded operating modes.
- Fig. 5.48 Microgrid performance during wind speed change and solar insolation change.
- Fig. 5.49 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .

- Fig. 5.50 Microgrid response during grid connected operating mode (a-c) load disconnection; (d) wind speed variation; (e) solar insolation change.
- Fig. 5.51 Performance of microgrid when feeding load with wind and solar at their rated conditions: (a) grid voltage and current; (b) grid power (P_{grid}), (c) load voltage and current, (d) load power (P_{Load}), (e) LSC voltage and current, (f) LSC power.
- Fig. 5.52 Behaviour microgrid, when wind driven SG is generating its power at 7.2 m/s wind speed and the system feeds load with solar generating maximum power: (a) v_{ga} and i_{ga} , (b) P_{grid} , (c) v_{La} and i_{La} , (d) P_{Load} , (e) LSC voltage and current, (f) LSC power.
- Fig. 5.53 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 5.54 Microgrid response during transition of operating modes.
- Fig. 5.55 Microgrid response during islanded operating mode.
- Fig. 5.56 Grid synchronization and islanded operating modes.
- Fig. 5.57 Microgrid performance during solar insolation change and wind speed variation.
- Fig. 5.58 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 5.59 Microgrid response during grid connected mode (a-b) wind speed change; (c-d) solar insolation change; (e-f) load change.
- Fig. 5.60 Load indices (a-b) load voltage/current waveform and Load power; (c-d) harmonic spectrum of load voltage and current.
- Fig. 5.61 Grid parameters when (a-d) rated generation from solar and wind; (e-h) when wind and solar units generate half power.
- Fig. 5.62 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 5.63 Microgrid response during mode transition.
- Fig. 5.64 Microgrid response during islanded operating mode.
- Fig. 5.65 Grid synchronization and islanded operating modes.
- Fig. 5.66 Microgrid performance under (a) load variation due to off-MPPT tracking, (b) wind speed change.
- Fig. 5.67 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 5.68 Microgrid parameters during grid connected mode (a) wind and solar PV array feeding grid (b-e) load change and its effect on microgrid parameters.
- Fig. 5.69 Load profile indices (a-b) load voltage/current waveform and load power; (c-d) harmonic spectrum of load voltage and current.
- Fig. 5.70 Grid parameters when (a-d) rated generation from solar and wind; (e-h) when wind and solar units generate half power.
- Fig. 5.71 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 5.72 Microgrid response during transition of operating mode.
- Fig. 5.73 Microgrid power variations during islanded operating mode.
- Fig. 5.74 Grid synchronization and islanded operating modes.

- Fig. 5.75 Microgrid response under (a) grid isolation (b) wind speed change
- Fig. 5.76 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 5.77 Microgrid response during grid connected mode for (a) wind and solar PV array feeding grid and load (b-e) load change.
- Fig. 5.78 Load profile indices (a-b) load voltage/current waveform and load power; (c-d) harmonic spectrum of load voltage and current.
- Fig. 5.79 Grid parameters when (a-d) rated generation from solar and wind; (e-h) when wind and solar units generate half power.
- Fig. 5.80 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 5.81 Microgrid response during seamless mode transition.
- Fig. 5.82 Islanded microgrid performance and power variations.
- Fig. 6.1 Structure of single stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 6.2 Structure of double stage solar PV array and wind energy generation based single phase grid interactive microgrid with battery for islanding and resynchronization.
- Fig. 6.3 Structure of double stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery for islanding and resynchronization
- Fig. 6.4 Structure of single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 6.5 Structure of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with battery for islanding and resynchronization.
- Fig. 6.6 Structure of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 6.7 Structure of single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 6.8 Structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with battery for islanding and resynchronization.
- Fig. 6.9 Structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization.

- Fig. 6.10 Control architecture of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery for islanding and resynchronization
- Fig. 6.11 Flow diagram of INC-MPPT algorithm.
- Fig. 6.12 MSC control.
- Fig. 6.13 Control architecture of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with battery for islanding and resynchronization.
- Fig. 6.14 Solar P&O MPPT technique.
- Fig. 6.15 Control architecture of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 6.16 Control architecture of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization.
- Fig. 6.17 Control structure of machine side converter.
- Fig. 6.18 Control architecture of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with battery for islanding and resynchronization
- Fig. 6.19 Control architecture of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization
- Fig. 6.20 Control architecture of single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization
- Fig. 6.21 MSC control Structure.
- Fig. 6.22 Control structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with battery for islanding and resynchronization.
- Fig. 6.23 Flow diagram of INC-MPPT algorithm.
- Fig. 6.24 Control structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery for islanding and resynchronization
- Fig. 6.25 Matlab model of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery.
- Fig. 6.26 Matlab model of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with battery.
- Fig. 6.27 Matlab model of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery.

- Fig. 6.28 Matlab model of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery.
- Fig. 6.29 Matlab model of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with battery.
- Fig. 6.30 Matlab model of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery.
- Fig. 6.31 Matlab model of the single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery.
- Fig. 6.32 Matlab model of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with battery.
- Fig. 6.33 Matlab model of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery.
- Fig. 6.34 Hardware developed prototype of the battery supported microgrid.
- Fig. 6.35 Grid synchronization and islanded operating modes.
- Fig. 6.36 Microgrid performance under (a) wind speed change (b) solar insolation change.
- Fig. 6.37 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 6.38 Grid connected microgrid response.
- Fig. 6.39 Grid indices when grid is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices
- Fig. 6.40 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2
- Fig. 6.41 Microgrid response during seamless mode transition.
- Fig. 6.42 Islanded microgrid performance.
- Fig. 6.43 BES indices (a-b) when renewable generation is off; (c-d) PV generation is off; (e-f) wind generation is off; (g-h) load is off and rated generation from renewables is attained; (i-j) when renewable generation feeds battery and load.
- Fig. 6.44 Grid synchronization and islanded operating modes.
- Fig. 6.45 Microgrid performance under (a) wind speed change; (b) solar insolation change.
- Fig. 6.46 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 6.47 Microgrid response during grid connected operating mode.
- Fig. 6.48 Grid indices when grid is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 6.49 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .

- Fig. 6.50 Microgrid response during operating mode transition.
- Fig. 6.51 Microgrid operation during islanded operating mode.
- Fig. 6.52 Battery profile parameters (a-b) at rated generation, (c-d) load disconnected, (e-f) wind generation is off, (g-h) solar generation is off, (i-j) only battery feeds the load as generation of solar and wind is zero.
- Fig. 6.53 Grid synchronization and islanded operating modes.
- Fig. 6.54 Microgrid performance under (a) wind speed change; (b) solar insolation change.
- Fig. 6.55 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of v_L .
- Fig. 6.56 Grid connected microgrid and its response during wind speed change, solar insolation change and load perturbation.
- Fig. 6.57 Grid indices when grid is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 6.58 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 6.59 Microgrid operation during mode transition.
- Fig. 6.60 Islanded microgrid operation and response.
- Fig. 6.61 Battery profile parameters (a-b) at rated generation of wind, (c-d) generation from wind at 7.2 m/s , (e-f) wind generation is off, (g-h) load is off, (i-j) load is reduced.
- Fig. 6.62 Grid synchronization and islanded operating modes.
- Fig. 6.63 Microgrid performance during wind speed change and solar insolation change.
- Fig. 6.64 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 6.65 Grid connected microgrid response under wind speed change, solar insolation change and load perturbation.
- Fig. 6.66 Grid indices when the excess generation from wind and solar PV array is fed into the grid (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 6.67 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 6.68 Microgrid response during mode transition.
- Fig. 6.69 Microgrid response during islanded operating mode.
- Fig. 6.70 (a-b) battery parameters when wind and solar power are at rated values; (c-d) when wind power is zero and solar PV array is at rated value.
- Fig. 6.71 (a-c) Grid synchronization and islanded operating modes.
- Fig. 6.72 Microgrid performance during (a) wind speed change (b) solar insolation change.
- Fig. 6.73 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 6.74 Grid connected response of the microgrid.

- Fig. 6.75 Grid indices when the excess generation from wind and solar PV array is fed into the grid (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices
- Fig. 6.76 MPPT response of the solar PV array: (a) at 1000 W/m² (b) at 500 W/m².
- Fig. 6.77 Microgrid response during mode transition.
- Fig. 6.78 Microgrid response during islanded operating mode.
- Fig. 6.79 V_{bat} , I_{bat} , P_{bat} (a-b) renewable generation is fed to the battery as load is off, (c-d) renewable generation feeds load and rest is fed to the battery, (e-f) Solar generation is off and wind generation feeds load and battery, (g-h) generation of wind is off, PV array feeds load and battery, (i-j) renewable generation is off, battery fulfills the load demand
- Fig. 6.80 Grid synchronization and islanded operating modes.
- Fig. 6.81 Microgrid performance during (a) wind speed variation (b) solar insolation change.
- Fig. 6.82 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 6.83 Grid connected operating mode response of the microgrid.
- Fig. 6.84 Grid indices when the excess generation from wind and solar PV array is fed into the grid (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 6.85 MPPT response of the solar PV array: (a) at 1000 W/m² (b) at 500 W/m².
- Fig. 6.86 Microgrid response during mode transition.
- Fig. 6.87 Microgrid response during islanded operating mode.
- Fig. 6.88 Battery parameters during islanded operation of the microgrid.
- Fig. 6.89 Grid synchronization and islanded operating modes.
- Fig. 6.90 Microgrid performance during (a) wind speed variation (b) solar insolation change.
- Fig. 6.91 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 6.92 Microgrid response during grid connected operating mode.
- Fig. 6.93 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 6.94 MPPT response of the solar PV array: (a) at 1000 W/m² (b) at 500 W/m².
- Fig. 6.95 Seamless transition of the operating modes.
- Fig. 6.96 Islanded operating mode response of the microgrid.
- Fig. 6.97 (a-b) Battery feeding load; (c-d) Solar and wind feeding load and battery at half power.
- Fig. 6.98 Grid synchronization and islanded operating modes.

- Fig. 6.99 Microgrid performance during (a) wind speed variation (b) solar insolation change.
- Fig. 6.100 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 6.101 Microgrid response during grid connected operating mode.
- Fig. 6.102 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 6.103 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 6.104 Seamless transfer of the operating mode.
- Fig. 6.105 Microgrid islanded operating mode response.
- Fig. 6.106 Battery performance during grid isolated mode (a-b) Only battery feeds load (c-d) WEGU feeds load and battery (e-f) Wind and solar generation feed load and battery (g-h) only solar generation feed load and battery (i-j) load disconnected, wind and solar generation is fed to the battery.
- Fig. 6.107 Grid synchronization and islanded operating modes.
- Fig. 6.108 Microgrid performance during (a) wind speed variation (b) solar insolation change.
- Fig. 6.109 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 6.110 Grid connected response of the microgrid.
- Fig. 6.111 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 6.112 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 6.113 Microgrid response during seamless transition of operating modes.
- Fig. 6.114 Islanded operating mode response of the microgrid.
- Fig. 6.115 Battery response during islanded operating mode (a-b) when only battery feeds the load; (c-d) Load is disconnected (wind and solar at half power feeding battery).
- Fig. 7.1 Structure of wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.2 Structure of battery supported wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization
- Fig. 7.3 Structure of BDC controlled battery supported wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization
- Fig. 7.4 Structure of wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.

- Fig. 7.5 Structure of battery supported wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.6 Structure of BDC controlled battery supported wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.7 Structure of wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.8 Structure of battery supported wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.9 Structure of BDC controlled battery supported wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.10 (a) Control architecture of the wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization; (b) DO-PLL control for synchronization phase angle detection
- Fig. 7.11 (a) Control architecture of the battery supported wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization; (b) MSC control.
- Fig. 7.12 Control architecture of the BDC controlled battery supported wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.13 (a) Control architecture of the wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization; (b) MBAF-PLL structure.
- Fig. 7.14 Control architecture of battery supported wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.15 Control architecture of BDC controlled battery supported wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.16 (a) Control architecture of wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization, (b) DMGI-PLL control for synchronization; (c) MSC control.
- Fig. 7.17 Control structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with battery for islanding and resynchronization.

- Fig. 7.18 Control structure of BDC controlled battery supported wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 7.19 MATLAB model of the wind energy generation based single phase grid interactive microgrid with diesel generator.
- Fig. 7.20 MATLAB model of the battery supported wind energy generation based single phase grid interactive microgrid with diesel generator.
- Fig. 7.21 MATLAB model of the BDC controlled battery supported wind energy generation based single phase grid interactive microgrid with diesel generator.
- Fig. 7.22 Matlab model of the wind energy generation based three phase three wire grid interactive microgrid with diesel generator.
- Fig. 7.23 Matlab model of the battery supported wind energy generation based three phase three wire grid interactive microgrid with diesel generator.
- Fig. 7.24 Matlab model of the BDC controlled battery supported wind energy generation based three phase three wire grid interactive microgrid with diesel generator.
- Fig. 7.25 Matlab model of the wind energy generation based three phase four wire grid interactive microgrid with diesel generator.
- Fig. 7.26 Matlab model of the battery supported wind energy generation based three phase four wire grid interactive microgrid with diesel generator.
- Fig. 7.27 Matlab model of the BDC controlled battery supported wind energy generation based three phase four wire grid interactive microgrid with diesel generator.
- Fig. 7.28 Hardware developed prototype of the wind energy generation based grid interactive microgrids with diesel generator.
- Fig. 7.29 Grid/DG synchronization and islanded operating modes.
- Fig. 7.30 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 7.31 DG connected microgrid response.
- Fig. 7.32 Grid indices when grid/DG is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 7.33 Microgrid response during seamless mode transition.
- Fig. 7.34 Islanded microgrid performance.
- Fig. 7.35 Grid/DG synchronization and islanded operating modes.
- Fig. 7.36 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 7.37 Microgrid response during DG connected operating mode.
- Fig. 7.38 Grid indices when grid/DG is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 7.39 Microgrid response during operating mode transition.

- Fig. 7.40 Microgrid operation during islanded operating mode.
- Fig. 7.41 Battery profile parameters (a-b) When battery feeds load, (c-d) when wind generation feeds load and battery.
- Fig. 7.42 Grid/DG synchronization and islanded operating modes.
- Fig. 7.43 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 7.44 DG connected microgrid response.
- Fig. 7.45 Grid indices when grid/DG is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 7.46 Microgrid response during mode transition
- Fig. 7.47 Microgrid response during islanded operating mode.
- Fig. 7.48 Battery profile parameters (a-b) When battery feeds load, (c-d) when wind generation is half of rated generation and feeds load and battery, (e-f) when wind generation is at rated generation and feeds load and battery.
- Fig. 7.49 Grid/DG synchronization and islanded operating modes.
- Fig. 7.50 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of load voltage (v_{La}).
- Fig. 7.51 DG connected response of the microgrid.
- Fig. 7.52 Grid indices when grid/DG is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 7.53 Microgrid response during mode transition.
- Fig. 7.54 Microgrid response during islanded operating mode.
- Fig. 7.55 Grid/DG synchronization and islanded operating modes.
- Fig. 7.56 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of load voltage (v_{La}).
- Fig. 7.57 Grid/DG connected operating mode response of the microgrid.
- Fig. 7.58 Grid indices (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 7.59 Microgrid response during mode transition.
- Fig. 7.60 Microgrid response during islanded operating mode.
- Fig. 7.61 Battery profile parameters (a-b) When battery feeds load, (c-d) when wind generation is half of rated generation and feeds load and battery, (e-f) when wind generation is at rated generation and feeds load and battery.
- Fig. 7.62 (a-b) Grid synchronization and islanded operating modes, (c-d) DG synchronization and islanded operating modes.
- Fig. 7.63 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 7.64 Microgrid response during DG connected operating mode

- Fig. 7.65 Grid indices (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 7.66 Microgrid response during mode transition.
- Fig. 7.67 Islanded operating mode response of the microgrid
- Fig. 7.68 Battery profile parameters (a-b) When battery feeds load, (c-d) when wind generation is half of rated generation and feeds load and battery, (e-f) when wind generation is at rated generation and feeds load and battery.
- Fig. 7.69 Grid/DG synchronization and islanded operating modes.
- Fig. 7.70 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 7.71 Microgrid response during grid/DG connected operating mode.
- Fig. 7.72 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind is fed into the grid; (i-l) load profile indices, (m) grid neutral current.
- Fig. 7.73 Seamless transition of the operating modes.
- Fig. 7.74 Islanded operating mode response of the microgrid.
- Fig. 7.75 Grid/DG synchronization and islanded operating modes.
- Fig. 7.76 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 7.77 Microgrid response during DG connected operating mode.
- Fig. 7.78 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind is fed into the grid; (i-l) load profile indices, (m) grid neutral current.
- Fig. 7.79 Seamless transfer of the operating mode.
- Fig. 7.80 Microgrid islanded operating mode response.
- Fig. 7.81 Battery profile parameters (a-b) When battery feeds load, (c-d) when wind generation is half of rated generation and feeds load and battery, (e-f) when wind generation is at rated generation and feeds load and battery.
- Fig. 7.82 Grid/DG synchronization and islanded operating modes.
- Fig. 7.83 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 7.84 Grid/DG connected response of the microgrid.
- Fig. 7.85 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind is fed into the grid; (i-l) load profile indices, (m) grid neutral current.
- Fig. 7.86 Microgrid response during seamless transition of operating modes.
- Fig. 7.87 Islanded operating mode response of the microgrid.

- Fig. 7.88 Battery profile parameters (a-b) when battery feeds load, (c-d) when wind generation is half of rated generation and feeds load and battery, (e-f) when wind generation is at rated generation and feeds load and battery.
- Fig. 8.1 Structure of single stage solar PV array and wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.2 Structure of double stage solar PV array and wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.3 Structure of single stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig.8.4 Structure of double stage solar PV array and wind energy generation based single phase grid interactive microgrid with battery and diesel generator for islanding and resynchronization.
- Fig. 8.5 Structure of double stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.6 Structure of single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.7 Structure of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.8 Structure of single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.9 Structure of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with battery and diesel generator for islanding and resynchronization.
- Fig. 8.10 Structure of double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.11 Structure of single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.12 Structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.

- Fig. 8.13 Structure of single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.14 Structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with battery and diesel generator for islanding and resynchronization.
- Fig. 8.15 Structure of double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.16 Control architecture of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization for islanding and resynchronization.
- Fig. 8.17 (a) Control architecture of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization;(b) solar P&O MPPT technique.
- Fig. 8.18 Control architecture of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.19 (a) Control architecture of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with battery and diesel generator for islanding and resynchronization; (b) Control structure of machine side converter.
- Fig. 8.20 Control architecture of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.21 Control architecture of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.22 Control architecture of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.23 Control architecture of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.24 Control architecture of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with battery and diesel generator for islanding and resynchronization.
- Fig. 8.25 Control architecture of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.

- Fig. 8.26 Control architecture of the single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.27 Control architecture of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.28 Control architecture of the single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.29 Control architecture of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with battery and diesel generator for islanding and resynchronization.
- Fig. 8.30 Control architecture of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.31 MATLAB model of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.32 MATLAB model of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.33 MATLAB model of the single stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.34 MATLAB model of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with battery and diesel generator for islanding and resynchronization.
- Fig. 8.35 MATLAB model of the double stage solar PV array and wind energy generation based single phase grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.36 MATLAB model of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.37 MATLAB model of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with diesel generator for islanding and resynchronization.
- Fig. 8.38 MATLAB model of the single stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.

- Fig. 8.39 MATLAB model of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with battery and diesel generator for islanding and resynchronization.
- Fig. 8.40 MATLAB model of the double stage solar PV array and wind energy generation based three phase three wire grid interactive microgrid with BDC controlled battery and diesel generator.
- Fig. 8.41 MATLAB model of the single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with diesel generator.
- Fig. 8.42 MATLAB model of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with diesel generator.
- Fig. 8.43 MATLAB model of the single stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery and diesel generator.
- Fig. 8.44 MATLAB model of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with battery and diesel generator.
- Fig. 8.45 MATLAB model of the double stage solar PV array and wind energy generation based three phase four wire grid interactive microgrid with BDC controlled battery and diesel generator for islanding and resynchronization.
- Fig. 8.46 Hardware developed prototype of the hybrid solar PV and wind energy generation based grid interactive microgrids with diesel generator.
- Fig. 8.47 Grid/DG synchronization and islanded operating modes.
- Fig. 8.48 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 8.49 DG connected microgrid response.
- Fig. 8.50 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.51 Grid indices when grid/DG is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when renewable generation feeds the load and extra is given to the grid; (i-l) load profile indices.
- Fig. 8.52 Microgrid response during seamless mode transition.
- Fig. 8.53 Islanded microgrid performance.
- Fig. 8.54 Grid/DG synchronization and islanded operating modes.
- Fig. 8.55 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 8.56 Microgrid response during DG connected operating mode.
- Fig. 8.57 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.58 Grid indices when grid is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices

when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.

- Fig. 8.59 Microgrid response during operating mode transition.
- Fig. 8.60 Microgrid operation during islanded operating mode.
- Fig. 8.61 Grid/DG synchronization and islanded operating modes.
- Fig. 8.62 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 8.63 DG connected microgrid response.
- Fig. 8.64 MPPT response of the solar PV array: (a) at 1000 W/m² (b) at 500 W/m²
- Fig. 8.65 Grid indices when grid is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 8.66 Microgrid response during mode transition
- Fig. 8.67 Microgrid response during islanded operating mode.
- Fig. 8.68 BES indices (a-b) when renewable generation is off and BES; (c-d) when renewable generation feeds battery and load.
- Fig. 8.69 Grid/DG synchronization and islanded operating modes.
- Fig. 8.70 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 8.71 DG connected microgrid response.
- Fig. 8.72 MPPT response of the solar PV array: (a) at 1000 W/m² (b) at 500 W/m².
- Fig. 8.73 Grid indices when grid is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 8.74 Microgrid response during mode transition.
- Fig. 8.75 Islanded microgrid performance.
- Fig. 8.76 BES indices (a-b) when renewable generation is off; (c-d) when renewable generation feeds battery and load.
- Fig. 8.77 Grid/DG synchronization and islanded operating modes.
- Fig. 8.78 (a-b) Harmonic spectrum of utility current (i_g) (c-d) Harmonic spectrum of Load current (i_L) (e-f) Harmonic spectrum of load voltage (v_L).
- Fig. 8.79 DG connected microgrid response.
- Fig. 8.80 MPPT response of the solar PV array: (a) at 1000 W/m² (b) at 500 W/m².
- Fig. 8.81 Grid indices when grid is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind and solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 8.82 Microgrid response during mode transition.

- Fig. 8.83 Islanded microgrid performance.
- Fig. 8.84 BES indices (a-b) when renewable generation is off; (c-d) when renewable generation feeds battery and load
- Fig. 8.85 Grid/DG synchronization and islanded operating modes.
- Fig. 8.86 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of load voltage (v_{La}).
- Fig. 8.87 DG connected response of the microgrid.
- Fig. 8.88 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.89 Grid indices when grid/DG is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 8.90 Microgrid response during mode transition.
- Fig. 8.91 Microgrid response during islanded operating mode.
- Fig. 8.92 Grid/DG synchronization and islanded operating modes.
- Fig. 8.93 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of load voltage (v_{La}).
- Fig. 8.94 DG connected response of the microgrid.
- Fig. 8.95 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.96 Grid indices when grid/DG is feeding load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 8.97 Microgrid response during mode transition.
- Fig. 8.98 Microgrid response during islanded operating mode.
- Fig. 8.99 Grid/DG synchronization and islanded operating modes.
- Fig. 8.100 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of load voltage (v_{La}).
- Fig. 8.101 Grid/DG connected operating mode response of the microgrid.
- Fig. 8.102 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.103 Grid indices (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 8.104 Microgrid response during mode transition.
- Fig. 8.105 Microgrid response during islanded operating mode.
- Fig. 8.106 BES indices (a-b) when renewable generation is off and BES; (c-d) when renewable generation feeds battery and load.
- Fig. 8.107 (a) Grid synchronization and islanded operating modes, (b) DG synchronization and islanded operating modes.
- Fig. 8.108 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 8.109 Microgrid response during DG connected operating mode
- Fig. 8.110 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .

- Fig. 8.111 Grid indices (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 8.112 Microgrid response during mode transition.
- Fig. 8.113 Islanded operating mode response of the microgrid.
- Fig. 8.114 (a-b) battery parameters when wind and solar power are not present; (c-d) when wind power and solar PV array is at rated value and feeds load and battery.
- Fig. 8.115 (a) Grid synchronization and islanded operating modes, (b) DG synchronization and islanded operating modes.
- Fig. 8.116 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 8.117 Microgrid response during DG connected operating mode.
- Fig. 8.118 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.119 Grid indices (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) load profile indices.
- Fig. 8.120 Microgrid response during mode transition.
- Fig. 8.121 Islanded operating mode response of the microgrid.
- Fig. 8.122 Battery profile parameters (a-b) When battery feeds load, (c-d) when renewable generation is half of rated generation and feeds load and battery.
- Fig. 8.123 Grid/DG synchronization and islanded operating modes.
- Fig. 8.124 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 8.125 Microgrid response during DG connected operating mode.
- Fig. 8.126 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.127 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind/Solar PV array is fed into the grid; (i-l) load profile indices.
- Fig. 8.128 Seamless transition of the operating modes.
- Fig. 8.129 Islanded operating mode response of the microgrid.
- Fig. 8.130 Grid/DG synchronization and islanded operating modes
- Fig. 8.131 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 8.132 Microgrid response during DG connected operating mode.
- Fig. 8.133 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.134 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind is fed into the grid; (i-l) load profile indices
- Fig. 8.135 Seamless transfer of the operating mode.
- Fig. 8.136 Microgrid islanded operating mode response.
- Fig. 8.137 Grid/DG synchronization and islanded operating modes

- Fig. 8.138 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 8.139 Grid/DG connected response of the microgrid.
- Fig. 8.140 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.141 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind is fed into the grid; (i-l) load profile indices
- Fig. 8.142 Microgrid response during seamless transition of operating modes.
- Fig. 8.143 Islanded operating mode response of the microgrid
- Fig. 8.144 Battery profile parameters (a-b) when battery feeds load, (c-d) when wind and solar generation is half of rated generation and feeds load and battery.
- Fig. 8.145 Grid/DG synchronization and islanded operating modes.
- Fig. 8.146 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 8.147 Grid/DG connected response of the microgrid.
- Fig. 8.148 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.149 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind is fed into the grid; (i-l) load profile indices.
- Fig. 8.150 Microgrid response during seamless transition of operating modes.
- Fig. 8.151 Islanded operating mode response of the microgrid.
- Fig. 8.152 Battery profile parameters (a-b) when battery feeds load, (c-d) when wind and solar generation are half of rated generation and feeds load and battery
- Fig. 8.153 Grid/DG synchronization and islanded operating modes.
- Fig. 8.154 (a-b) Harmonic spectrum of utility current (i_{ga}) (c-d) Harmonic spectrum of Load current (i_{La}) (e-f) Harmonic spectrum of v_{La} .
- Fig. 8.155 DG connected response of the microgrid.
- Fig. 8.156 MPPT response of the solar PV array: (a) at 1000 W/m^2 (b) at 500 W/m^2 .
- Fig. 8.157 Grid indices when grid feeds the load (a-b) grid voltage/current waveform and grid power; (c-d) harmonic spectrum of grid voltage and current; (e-h) grid indices when the excess generation from wind is fed into the grid; (i-l) load profile indices.
- Fig. 8.158 Microgrid response during seamless transition of operating modes.
- Fig. 8.159 Islanded operating mode response of the microgrid.
- Fig. 8.160 Battery profile parameters (a-b) when battery feeds load, (c-d) when wind and solar generation are half of rated generation and feeds load and battery.

LIST OF TABLES

Table 2.1	Certification Standards for Solar PV Panels
Table 2.2	Certification Standards for Solar PV Inverters
Table 2.3	Certification Standards for Small Wind Turbines
Table 3.1	Design of Wind Energy Generation Based Single Phase Grid Interactive Microgrid
Table 3.2	Design of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid
Table 3.3	Design of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid
Table 3.4	Parameters Selection for Simulation of Wind Energy Generation Based Single Phase Grid Interactive Microgrid
Table 3.5	Parameter Selection for Simulation of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid
Table 3.6	Parameter Selection for Simulation of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid
Table 4.1	Design of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Experimental Validation
Table 4.2	Design of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 4.3	Design of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Experimental Validation
Table 4.4	Design of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 4.5	Design of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Experimental Validation
Table 4.6	Design of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 4.7	Parameter Selection of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Simulation Verification
Table 4.8	Parameter Selection of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 4.9	Parameter Selection of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Simulation Verification

Table 4.10	Parameter Selection of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 4.11	Parameter Selection of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Simulation Verification
Table 4.12	Parameter Selection of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 5.1	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Experimental Validation
Table 5.2	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Experimental Validation
Table 5.3	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Experimental Validation
Table 5.4	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Experimental Validation
Table 5.5	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Experimental Validation
Table 5.6	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Experimental Validation
Table 5.7	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Simulation Verification
Table 5.8	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid for Simulation Verification
Table 5.9	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Simulation Verification
Table 5.10	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid for Simulation Verification
Table 5.11	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Simulation Verification
Table 5.12	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid for Simulation Verification

Table 6.1	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 6.2	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Experimental Validation
Table 6.3	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 6.4	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 6.5	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Experimental Validation
Table 6.6	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 6.7	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 6.8	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Experimental Validation
Table 6.9	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Experimental Validation
Table 6.10	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 6.11	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery for Simulation Verification
Table 6.12	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 6.13	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification

Table 6.14	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery for Simulation Verification
Table 6.15	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 6.16	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 6.17	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery for Simulation Verification
Table 6.18	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery for Simulation Verification
Table 7.1	Design of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.2	Design of Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.3	Design of BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.4	Design of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.5	Design of Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.6	Design of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.7	Design of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.8	Design of Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.9	Design of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 7.10	Parameter Selection of Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Simulation Verification

Table 7.11	Parameter Selection of Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 7.12	Parameter Selection of BDC Controlled Battery Supported Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 7.13	Parameter Selection of Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 7.14	Parameter Selection of Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 7.15	Parameter Selection of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 7.16	Parameter Selection of Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 7.17	Parameter Selection of Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 7.18	Parameter Selection of BDC Controlled Battery Supported Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 8.1	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 8.2	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 8.3	Design of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Experimental Validation
Table 8.4	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Experimental Validation
Table 8.5	Design of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Experimental Validation

Table 8.6	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 8.7	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 8.8	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Experimental Validation
Table 8.9	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Experimental Validation
Table 8.10	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Experimental Validation
Table 8.11	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 8.12	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Experimental Validation
Table 8.13	Design of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Experimental Validation
Table 8.14	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery and Diesel Generator for Experimental Validation
Table 8.15	Design of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Experimental Validation
Table 8.16	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 8.17	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 8.18	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Simulation Verification

Table 8.19	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with Battery and Diesel Generator for Simulation Verification
Table 8.20	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Single Phase Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Simulation Verification
Table 8.21	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 8.22	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 8.23	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Simulation Verification
Table 8.24	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with Battery and Diesel Generator for Simulation Verification
Table 8.25	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Three Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Simulation Verification
Table 8.26	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 8.27	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Diesel Generator for Simulation Verification
Table 8.28	Parameter Selection of Single Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Simulation Verification
Table 8.29	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with Battery and Diesel Generator for Simulation Verification
Table 8.30	Parameter Selection of Double Stage Solar PV Array and Wind Energy Generation Based Three Phase Four Wire Grid Interactive Microgrid with BDC Controlled Battery and Diesel Generator for Simulation Verification

LIST OF ABBREVIATIONS

RESs	Renewable Energy Resources
PV	Photovoltaic
REC	Rural Electrification Corporation
BES	Battery Energy Storage
DERs	Distributed Energy Resources
DG	Diesel Generator
PCC	Point Of Common Coupling
NDZ	Non-Detection Zone
VSCs	Voltage Source Converters
PLLs	Phase Locked Loops
SG	Synchronous Generator
MPPT	Maximum Power Point Tracking
WECS	Wind Energy Conversion System
PMSG	Permanent Magnet Synchronous Generator
DFIG	Doubly Fed Induction Generator
SCIG	Squirrel-Cage Induction Generator
WEGS	Wind Energy Generation System
PEC	Power Electronic Converters
P & O	Perturb And Observe
INC	Incremental Conductance
FLC	Fuzzy Logic Control
FOC	Field Oriented Control
PQ	Power Quality
LMS	Least Mean Square
LMF	Least Mean Fourth
SOGI	Second Order Generalized Integrators
ANF	Adaptive Notch Filters
FLLs	Frequency Locked Loops
WEGU	Wind Energy Generation Unit
VSWEGU	Variable Speed Wind Energy Generation
SPG	Single Phase Grid
TPTWG	Three Phase Three Wire Grid
TPFWG	Three Phase Four Wire Grid
MSC	Machine Side Converter
LSC	Load Side Converter
UPF	Unity Power Factor
BEMF	Back Electromotive Force

TLMS	Total Least Mean Square
CGI-PLL	Combined Generalized Integrator Based Phase Locked Loop
HCC	Hysteresis Current Controller
SCSS	Self-Correcting Sign-Sign
BGI-PLL	Binary Generalized Integrator Based Phase Locked Loop
LMLS	Least Mean Logarithmic Square
SOAP-FLL	Synchronous Observer Aided Preprocessing Based Frequency Locked Loop Filter
PR	Proportional Resonant Regulator
MTPA	Maximum Torque Per Ampere Control
DSP	Digital Signal Processing
DACs	Digital-To-Analog Converters
IGBT	Insulated Gate Bipolar Transistor
BDC	Bidirectional DC–DC Converter
SOC	State Of Charge
INSR-LMS	Improved Normalized Sign Regressor Least Mean Square
FLL-AVF	Frequency Locked Loop Unified Adaptive Vectorial Filter
MLEF	Maximum-Likelihood Estimator Framework
FADO-FLL	Frequency Adaptive Disturbance Observer Based Frequency Locked Loop
PWM	Pulse Width Modulated
LLAD	Least Logarithmic Absolute Difference
SA	Sign Algorithm
EMSE	Excess Mean Square Error
APF-FLL	All Pass Filter Based Frequency Locked Loop
THD	Total Harmonic Distortion
S	Synchronization Switches
SE-LMS	Sign-Error Least Mean Square
FAHO-FLL	Frequency Adaptive Harmonic Oscillator Based Frequency Locked Loop Filter
NAAP	Normalized Adaptive All Pass Filter
eSOGI-FLL	Extended Second Order Generalized Integrator Based Frequency Locked Loop
M-AAPL	M-Approximated Affine Projection Like Adaptive Filter
AP	Affine Projection
LPF	Low Pass Filters
PI	Proportional Integrator
MNF-SOGI-FLL	Modified Notch Filter Based Second Order Generalized Integrator-Frequency Locked Loop
BTB	Back To Back

AVR	Automatic Voltage Regulator
SEIG	Self-Excited Induction Generator
LMMN	Least Mean Mixed Norm
MSE	Mean Square Error
DO-PLL	Disturbance Observer Based Phase Locked Loop
MLMS	Momentum Based Least Mean Square
MBAF-PLL	Modified Binate Adaptive Filter Integrated To A Phase Locked Loop
MANF	Modified Adaptive Notch Filter
RNMN	Robust Normalized Mixed Norm Adaptive Algorithm
SRLMS	Stochastic Gradient Sign Error Least Mean Square Algorithm
DMGI-PLL	Dual Modified Generalized Integrator Based Phase Locked Loop

LIST OF SYMBOLS

β, r	Wind turbine pitch angle, blade radius
V_{wind}, ω_{rm}	Wind speed, speed of wind turbine
$P_t, \lambda, C_p(\lambda, \beta)$	Mechanical power, Tip speed ratio, coefficient of turbine power
$V_{dc}, V_{dc ref} C_{dc}$	Sensed DC link voltage, Reference DC link voltage, DC link capacitor
R_f, C_f	Ripple filter
L_f	Interfacing inductor
u_p, V_{gm}	Unit template, amplitude of voltage (single phase)
$w_{Lp}, \vartheta,$	Weight component, step size
w_{cp}	VSC DC loss component
w_{wff}, P_{wind}	Wind feed-forward term, Wind power
w_{sp}	Peak value of net active load weight component
$i_g, i_{g ref}^*$	Grid current, reference grid current for single phase microgrid
v_L, i_L	Load voltage, load current
S, S_2	Grid synchronization switch, DG synchronization switch
$\theta_g, \theta_L, \theta_e$	Grid voltage phase angle, Load voltage phase angle, phase angle error
θ_s	operating voltage angle for standalone control
$I_{q ref}, I_{d ref}$	Reference quadrature axis current of SG, reference direct axis current of SG
$\omega_{gen est}, \omega_{gen ref}$	Estimated SG speed, reference SG speed
$i_{gena} i_{genb}, i_{genc}$	Sensed SG stator currents
θ_{est}	Estimated rotor position of SG
$i_{genaref}, i_{genref}, i_{genref}$	Reference SG stator currents
V_{ga}, V_{gb}, V_{gc}	Phase voltages of the three phase grid
V_{gab}, V_{gbc}	Sensed line voltages of the grid
V_t	Amplitude of the PCC terminal voltage
u_a, u_b, u_c	In-phase unit templates
$w_a,$	Weight component of the load current of phase ‘a’
w_{loss}	DC loss component
i_{ga}, i_{gb}, i_{gc}	Sensed three phase grid currents
$i_{ga ref}, i_{gb ref}, i_{gc ref}$	Reference three phase grid currents
v_{La}, v_{Lb}, v_{Lc}	Sensed load voltages
i_{La}, i_{Lb}, i_L	Sensed load currents
$i_{Laref}, i_{Lbref}, i_{Lcref}$	Reference load currents
I_{gn}, i_{Ln}, i_{LSCn}	Neutral currents of grid, load and LSC converter
P_{grid}, P_{Load}	Grid power, Load power

V_{pv}, I_{pv}, P_{pv}	Solar PV array voltage, current and power
V_b, I_b, P_b	Battery voltage, current and power
D/δ	Duty ratio of bidirectional converter
L_{bdc}	bidirectional converter inductor
w_{Lp}	active weight component of the load current
w_{Load}	average weight component of the load current
w_{net}	net weight component of load current
$V_{sa}^*, V_{sb}^*, V_{sc}^*$	Three phase reference phase voltages of load
$P_{mpp}, V_{mpp}, i_{mpp}$	Peak power, MPP voltage, MPP current of solar PV array
L_{BC}	Boost converter inductor
N_s, N_p	No. of solar cells in series and parallel
f_{sw}	Switching frequency
$i_{La\text{fil}}, i_{Lb\text{fil}}, i_{Lc\text{fil}}$	Filtered load currents
V_{dg}, i_{dg}	SEIG DG set voltage and current
$V_{dga}, V_{dgb}, V_{dgc}, i_{dga}, i_{dgb}, i_{dgc}$	SG based DG set voltages and currents
P_{dg}	Power of DG set
$i_{dga\text{ ref}}, i_{dgb\text{ ref}}, i_{dgc\text{ ref}}$	Reference DG currents