

**CONTROL AND IMPLEMENTATION OF THREE  
PHASE SOLAR-PICO-HYDRO-BATTERY BASED  
MICROGRID WITH GRID SYNCHRONIZATION**

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**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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MICROGRID WITH GRID SYNCHRONIZATION**

*by*

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**Submitted**

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# CERTIFICATE

It is certified that the thesis entitled “**Control and Implementation of Three Phase Solar-Pico-Hydro-Battery Based Microgrid with Grid Synchronization,**” being submitted by **Mr. Kanwar Pal** for award of the degree of **Doctor of Philosophy** in the Department of Energy Science and Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

**Dated: Jan. 17, 2022**

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Kanwar Pal

## ABSTRACT

This research work deals with the multi-objective solar PV array based generating systems with grid synchronization, solar PV array-battery based microgrids (MGs), and solar-pico-hydro-battery based microgrids with grid synchronization. These electricity generating systems and microgrids address the solutions of power demand at remote areas, environment problems at industrial sites and at thickly populated commercial locations, and the locations out of the reach of the grid. It facilitates the availability of energy and supports the conservation of the stocks of fossil fuels. A solar-pico-hydro-battery based microgrid maintains load power continuously at outage of the grid or under deficit of power generation in a standalone system. Moreover, fossil fuel-based generation systems are finding difficult to maintain load power at outage of the grid. However, exhibited microgrids have power support to loads for 24x7hours. A converter is used in the grid synchronized mode and in an islanded mode, which enhances the operation of the developed system. These multi-functional aspects of MGs result in substantial saving of capital spending, and maintenance cost of the system. However, in an islanded mode, the battery and RESs supply power to loads at PCC and the loads connected at the DC-port uninterruptedly. The objectives of RESs based microgrids are contributed to local loads and relaxing the load burden on utility network, by this means reduce the energy losses through curtailing in power transmission and power distribution. Therefore, it improves the efficiency and decreases the cost of overall system. It has state transfer ability from the grid synchronized mode to an islanded mode and vice-versa, without interruption in the loads power. A current control approach is utilized to control the switching of the PCC interfaced voltage source converter (VSC) in the grid synchronized mode. However, the switching of the VSC is controlled through a voltage control approach in an islanded mode. The PCC interfaced VSC performs multi-functions, such as, it feeds the harmonics mitigated currents to the grid, compensates the reactive power drawn by the loads and improves power factor of the grid to

unity. In an islanded mode, the VSC controls the magnitude and frequency of the load voltages. However, the voltage at the DC-link is supported by the battery. The battery through absorption of excess power at an excess power generation and discharging deficit power under short of power generation in an islanded mode assures power supply to the loads without interruption. The prime aims of this research work are control and implementation of several three-phase solar PV array based generating systems, solar PV array-battery and solar-pico-hydro-battery based microgrids. These generating systems and microgrids are categorized further based on connection of solar PV array at the DC-port of the VSC (single-stage and double-stage) and connection of the battery at the DC-port (with and without a bidirectional DC-DC converter). In double-stage solar PV array based generating system, the peak power of solar PV array at MPP is tracked through controlled switching of the boost converter. However, in a single-stage solar PV array based generating system, the bidirectional DC-DC converter is used to harness the peak power of the PV array with control of charging and discharging of the battery. The feedforward terms of the solar PV array and pico-hydro generator are used in current control loop, which injects the active power to the grid and improves the dynamic performance of the microgrids. Simulated performance of exhibited microgrids is studied. Their Simulink models are developed to implement various control techniques. Experimental prototypes are developed to validate simulated results of models of microgrids. No availability and outage of the grid are a common issue at remote location and rural areas. Therefore, the simple and multi-functional intelligent control approaches in the exhibited microgrids, are developed to control them in the grid synchronized mode and in an islanded mode, and transition of modes without interruption in the loads.

## सार

यह शोध कार्य ग्रिड सिंक्रोनाइजेशन के साथ मल्टी-ऑब्जेक्टिव सोलर पीवी एरे आधारित जनरेटिंग सिस्टम, ग्रिड सिंक्रोनाइजेशन के साथ सोलर पीवी एरे-बैटरी आधारित माइक्रोग्रिड (एमजी) सिस्टम और ग्रिड सिंक्रोनाइजेशन के साथ सोलर-पिको-हाइड्रो-बैटरी आधारित माइक्रोग्रिड सिस्टम पर आधारित है। ये बिजली उत्पादन प्रणालियां और माइक्रोग्रिड दूरदराज के क्षेत्रों में बिजली की मांग के समाधान, औद्योगिक स्थलों पर और घनी आबादी वाले व्यावसायिक स्थानों पर पर्यावरण की समस्याओं और ग्रिड की पहुंच से बाहर के स्थानों को संबोधित करते हैं। यह ऊर्जा की उपलब्धता को सुगम बनाता है और जीवाश्म ईंधन के भंडार के संरक्षण में सहयोग करता है। सोलर-पिको-हाइड्रो-बैटरी आधारित माइक्रोग्रिड ग्रिड के बाधित होने की अवस्था में या स्टैंडअलोन सिस्टम में बिजली उत्पादन की कमी के तहत लोड को निरबाधित रूप से पावर देता रहता है। इसके अलावा, जीवाश्म ईंधन आधारित उत्पादन प्रणालियां ग्रिड के बंद होने पर लोड पावर को बनाए रखने में विफल रही हैं। हालांकि, प्रदर्शित माइक्रोग्रिड 24x7 घंटे लोड को निर्बाधित पावर सप्लाई करता है। एक ही कनवर्टर का उपयोग ग्रिड सिंक्रोनाइज्ड मोड और स्टैंडअलोन मोड में किया जाता है, जो विकसित सिस्टम के कार्यक्षमता को बढ़ता है। एमजी के इस बहु-कार्यात्मक पहलू के परिणामस्वरूप पूंजीगत व्यय और सिस्टम के रखरखाव की लागत में पर्याप्त बचत होती है। हालांकि, स्टैंडअलोन मोड में, बैटरी और आरईएस पीसीसी पर उपलब्ध लोड के लिए आवश्यक बिजली की आपूर्ति करते हैं और साथ ही साथ डीसी-पोर्ट पर जुड़े लोड को भी निर्बाध रूप से बिजली की आपूर्ति करते हैं।

आरईएस आधारित माइक्रोग्रिड का उद्देश्य स्थानीय लोड को बिजली की आपूर्ति करना है और ग्रिड नेटवर्क पर लोड के बोझ को कम करता है, इस तरह से बिजली पारेषण और बिजली वितरण में कटौती के माध्यम से ऊर्जा के नुकसान को कम करता है। अतः, यह दक्षता में सुधार करता है और समग्र प्रणाली की लागत को कम करता है। इसमें ग्रिड सिंक्रोनाइज्ड मोड से आईलैंडेड मोड में व इसके विपरीत लोड पावर में बिना किसी रुकावट के स्टेट ट्रांसफर की क्षमता होती है। ग्रिड सिंक्रोनाइज्ड मोड में पीसीसी इंटरफेसड वोल्टेज सोर्स कन्वर्टर (वीएससी) के स्विचिंग को नियंत्रित करने के लिए एक करंट कंट्रोल स्कीम का उपयोग किया जाता है। हालांकि, वीएससी के स्विचिंग को आईलैंडेड मोड में वोल्टेज कंट्रोल स्कीम के माध्यम से नियंत्रित किया जाता है। पीसीसी इंटरफेरेड वीएससी मल्टीपल-कार्य करता है, जैसे, यह ग्रिड करंट की हार्मोनिक्स का शमन करता है, लोड द्वारा आवश्यक रियक्टिव शक्ति की भरपाई करता है, और ग्रिड के पावर फैक्टर को सुधारता है। आईलैंडेड मोड में, वीएससी लोड वोल्टेज के परिमाण और आवृत्ति को नियंत्रित करता है। हालांकि, डीसी-लिंक पर वोल्टेज बैटरी द्वारा समर्थित है। आईलैंडेड मोड में अतिरिक्त बिजली उत्पादन पर बैटरी अतिरिक्त बिजली का अवशोषण करता है तथा बिजली उत्पादन की कमी के समय पर लोड को बिजली की आपूर्ति निर्बाध रूप से बिना किसी रुकावट के करता है। इस शोध कार्य का मुख्य उद्देश्य कई श्री-फेज सौर पीवी एरे आधारित जनरेटिंग सिस्टम, सौर पीवी एरे - बैटरी, और सौर-पिको-हाइड्रो-बैटरी आधारित माइक्रोग्रिड का नियंत्रण और कार्यान्वयन है। इन जनरेटिंग सिस्टम और माइक्रोग्रिड को वीएससी के डीसी-पोर्ट पर सोलर पीवी एरे (सिंगल-स्टेज और डबल-स्टेज) के कनेक्शन और डीसी-पोर्ट पर बैटरी के कनेक्शन (बाइ-डायरेक्शनल डीसी- डीसी कनवर्टर के साथ और बिना) के आधार पर वर्गीकृत किया गया है। डबल-स्टेज सोलर पीवी एरे

आधारित जनरेटिंग सिस्टम में, एमपीपी पर सोलर पीवी एरे की पीक पावर को बूस्ट कन्वर्टर के नियंत्रित स्विचिंग के माध्यम से ट्रैक किया जाता है। हालांकि, सिंगल-स्टेज सौर पीवी एरे आधारित जनरेटिंग सिस्टम में, बाइ-डायरेक्शनल डीसी- डीसी कनवर्टर का उपयोग बैटरी के चार्जिंग और डिस्चार्जिंग के नियंत्रण के साथ पीवी एरे की उच्चतम शक्ति का दोहन करने के लिए किया जाता है। सौर पीवी एरे और पिको-हाइड्रो जनरेटर की फीडफॉरवर्ड टर्मिन्स का उपयोग करंट कंट्रोल लूप में किया जाता है, जो ग्रिड में एक्टिव पावर को इंजेक्ट करता है और माइक्रोग्रिड के डायनामिक प्रदर्शन में सुधार करता है। प्रदर्शित माइक्रोग्रिड के सिमुलेटेड प्रदर्शन का अध्ययन किया गया है। उनके सिमुलिक मॉडल विभिन्न नियंत्रण तकनीकों को लागू करने के लिए विकसित किए गए हैं। माइक्रोग्रिड के मॉडल के सिमुलेटेड परिणामों को मान्य करने के लिए प्रयोगात्मक प्रोटोटाइप विकसित किए गए हैं। दूरस्थ स्थान और ग्रामीण क्षेत्रों में ग्रिड की उपलब्धता और आउटेज एक आम समस्या है। इसलिए, प्रदर्शित माइक्रोग्रिड में सरल और बहु-कार्यात्मक इंटेलिजेंट कंट्रोल अप्रोच जो माइक्रोग्रिड को ग्रिड सिंक्रनाइज मोड में और आईलैंडेड मोड में नियंत्रित करने के लिए विकसित किए गए हैं।

## TABLE OF CONTENTS

	<i>Page No.</i>
Certificate	i
Acknowledgements	ii
Abstract	iv
Abstract (Hindi)	vi
Table of Contents	viii
List of Figures	xxi
List of Tables	xxxiv
List of Abbreviations	xxxv
List of Symbols	xxxvii
<b>CHAPTER-I      INTRODUCTION</b>	<b>1-14</b>
1.1    General	1
1.2    State of Art on Renewable Energy Sources Based Microgrids	4
1.3    MPPT Techniques for Solar Photovoltaic Array	8
1.4    Objectives and Scope of Work	8
1.5    Outline of Chapters	11
<b>CHAPTER -II      LITERATURE REVIEW</b>	<b>15-29</b>
2.1    General	15
2.2    Literature Survey	16
2.2.1    Solar PV Generation Based Microgrids	17
2.2.2    Pico-Hydro Generation Based Microgrids	19
2.2.3    Solar and Pico-Hydro Generation Based Microgrids	21
2.2.4    Solar and Battery Based Microgrids	23
2.3    Identified Research Areas	26
2.4    Conclusions	29

<b>CHAPTER-III</b>	<b>CONTROL AND IMPLEMENTATION OF SINGLE-STAGE SOLAR PHOTOVOLTAIC ARRAY BASED GENERATING SYSTEM WITH GRID SYNCHRONIZATION</b>	<b>30-75</b>
3.1	General	30
3.2	Configuration and Operating Principle of Single-Stage Solar Photovoltaic Array Based Generating System	31
3.3	Design of Single-Stage Solar Photovoltaic Array Based Generating System	32
3.4	Control of Single-Stage Solar Photovoltaic Array Based Generating System	33
3.4.1	Solar PV Array Peak Power Extraction	34
3.4.2	Control in Grid Synchronization Mode	37
3.4.3	Control in Islanded Mode	41
3.4.4	Control in Mode Transition	43
3.5	MATLAB Modelling of Single-Stage Solar Photovoltaic Array Based Generating System	44
3.6	Hardware Implementation of Single-Stage Solar Photovoltaic Array Based Generating System	45
3.6.1	Configuration of Experimental System	45
3.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensor	47
3.6.3	Interfacing Circuit for Hall Effect Based Current Sensor	48
3.6.4	Interfacing Circuit for Gate Driver	50
3.6.5	Configuration of Experimental d-SPACE 1103 DSP Controller	51
3.7	Results and Discussion	51
3.7.1	Simulated Performance	51
3.7.1.1	Performance of Single-Stage Solar Photovoltaic Array-Based Generating System at Balanced and Unbalanced Loads	51
3.7.1.2	Performance of Single Stage Solar Photovoltaic Array-Based Generating System at Solar Insolation Change	56
3.7.1.3	Performance of Single-Stage Solar Photovoltaic Array-Based Generating System in Grid Synchronization and Islanded Operating Modes	60

	3.7.1.3.1	Performance of the Generating System in the Grid Synchronization Mode	60
	3.7.1.3.2	Performance of the Generating System in an Islanded Mode	62
3.7.2		Experimental Performance	65
	3.7.2.1	Steady State Performance of Generating System	65
	3.7.2.1.1	Steady State Performance in Grid Synchronized Mode	68
	3.7.2.1.2	Steady State Performance in Islanded Mode	69
	3.7.2.2	Dynamic Performance of Generating System	71
	3.7.2.2.1	Dynamic Performance in Grid Synchronized Mode	71
	3.7.2.2.2	Dynamic Performance in Islanded Mode	72
	3.7.2.2.3	Dynamic Performance under Mode Transition	74
3.8		Conclusions	75
<b>CHAPTER-IV CONTROL AND IMPLEMENTATION OF DOUBLE STAGE SOLAR PHOTOVOLTAIC ARRAY BASED GENERATING SYSTEM WITH GRID SYNCHRONIZATION</b>			<b>76-123</b>
4.1		General	76
4.2		Configuration and Operating Principle of Double-Stage Solar Photovoltaic Array Based Generating System with Grid Synchronization	77
4.3		Design of Double-Stage Solar Photovoltaic Array Based Generating System with Grid Synchronization	78
4.4		Control of Double-Stage Solar Photovoltaic Array Based Generating System with Grid Synchronization	79
	4.4.1	Solar PV Array Peak Power Extraction	81
	4.4.2	Control in Grid Synchronization Mode	83
	4.4.3	Control in Islanded Mode	89
	4.4.4	Control in Mode Transition	91

4.5	MATLAB Modelling of Double-Stage Solar Photovoltaic Array Based Generating System with Grid Synchronization	93
4.6	Hardware Implementation of Double-Stage Solar Photovoltaic Array Based Generating System with Grid Synchronization	94
4.6.1	Configuration of Experimental System	95
4.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensor	95
4.6.3	Interfacing Circuit for Hall Effect Based Current Sensor	96
4.6.4	Interfacing Circuit for Gate Driver	96
4.6.5	Configuration of Experimental d-SPACE 1103 DSP Controller	96
4.7	Results and Discussion	97
4.7.1	Simulated Performance	97
4.7.1.1	Performance of Double-Stage Solar Photovoltaic Array-Based Generating System at Balanced and Unbalanced Loads	97
4.7.1.2	Performance of Double Stage Solar Photovoltaic Array-Based Generating System at Solar Insolation Change	102
4.7.1.3	Performance of Double-Stage Solar Photovoltaic Array-Based Generating System in Grid Synchronization and Islanded Operating Modes	109
4.7.1.3.1	Performance of the Generating System in the Grid Synchronization Mode	109
4.7.1.3.2	Performance of the Generating System in an Islanded Mode	112
4.7.2	Experimental Performance	115
4.7.2.1	Steady State Performance of Generating System	115
4.7.2.1.1	Steady State Performance in Grid Synchronized Mode	116
4.7.2.1.2	Steady State Performance in Islanded Mode	118
4.7.2.2	Dynamic Performance of Generating System	119
4.7.2.2.1	Dynamic Performance in Grid Synchronized Mode	119
4.7.2.2.2	Dynamic Performance in Islanded Mode	121

4.7.2.2.3	Dynamic Performance under Mode Transition	121
4.8	Conclusions	122
<b>CHAPTER-V</b>	<b>CONTROL AND IMPLEMENTATION OF THREE PHASE SOLAR PHOTOVOLTAIC ARRAY-BATTERY BASED MICROGRID WITH GRID SYNCHRONIZATION</b>	<b>124-166</b>
5.1	General	124
5.2	Configuration and Operating Principle of Three Phase Solar Photovoltaic Array-Battery Based Microgrid	125
5.3	Design of Three-Phase Solar Photovoltaic Array-Battery Based Microgrid	126
5.4	Control of Three Phase Solar Photovoltaic Array-Battery Based Microgrid	127
5.4.1	Solar PV Array Peak Power Extraction	129
5.4.2	Control in Grid Synchronization Mode	129
5.4.3	Control in Islanded Mode	133
5.4.4	Control in Mode Transition	134
5.5	MATLAB Modelling of Three-Phase Solar Photovoltaic Array-Battery Based Microgrid	135
5.6	Hardware Implementation of Three-Phase Solar Photovoltaic Array-Battery Based Microgrid with Grid Synchronization	136
5.6.1	Configuration of Experimental System	137
5.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensor	137
5.6.3	Interfacing Circuit for Hall Effect Based Current Sensor	137
5.6.4	Interfacing Circuit for Gate Driver	138
5.6.5	Configuration of Experimental d-SPACE 1103 DSP Controller	138
5.7	Results and Discussion	139
5.7.1	Simulated Performance	139
5.7.1.1	Performance of Three-Phase Solar Photovoltaic Array-Battery Based Microgrid at Balanced and Unbalanced Loads	140
5.7.1.2	Performance of Three-Phase Solar Photovoltaic Array-Battery Based Microgrid at Solar Insolation Change	144

5.7.1.3	Performance of Three-Phase Solar Photovoltaic Array-Battery Based Microgrid in the Grid Synchronized and Islanded Operating Modes	151
5.7.1.3.1	Performance of the Microgrid in the Grid Synchronized Mode	151
5.7.1.3.2	Performance of the Microgrid in an Islanded Mode	154
5.7.2	Experimental Performance	157
5.7.2.1	Steady State Performance of Microgrid	157
5.7.2.1.1	Steady State Performance in Grid Synchronized Mode	158
5.7.2.1.2	Steady State Performance in Islanded Mode	158
5.7.2.2	Dynamic Performance of Microgrid	160
5.7.2.2.1	Dynamic Performance in Grid Synchronization Mode	161
5.7.2.2.2	Dynamic Performance in Islanded Mode	163
5.7.2.2.3	Dynamic Performance under Mode Transition	165
5.8	Conclusions	166
<b>CHAPTER-VI</b>	<b>CONTROL AND IMPLEMENTATION OF THREE PHASE FOUR WIRE SOLAR PHOTOVOLTAIC ARRAY-BATTERY BASED MICROGRID WITH GRID SYNCHRONIZATION</b>	<b>167-215</b>
6.1	General	167
6.2	Configuration and Operating Principle of Three Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid	168
6.3	Design of Three-Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid	169
6.4	Control of Three Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid	170
6.4.1	Solar PV Array Peak Power Extraction	172
6.4.2	Control in Grid Synchronization Mode	173
6.4.3	Control in Islanded Mode	178

6.4.4	Control in Mode Transition	179
6.5	MATLAB Modelling of Three-Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid	180
6.6	Hardware Implementation of Three-Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid	181
6.6.1	Configuration of Experimental System	182
6.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensor	182
6.6.3	Interfacing Circuit for Hall Effect Based Current Sensor	183
6.6.4	Interfacing Circuit for Gate Driver	183
6.6.5	Configuration of Experimental d-SPACE with DSP-1103	183
6.7	Results and Discussion	184
6.7.1	Simulated Performance	184
6.7.1.1	Performance of Three-Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid at Balanced and Unbalanced loads	185
6.7.1.2	Performance of Three-Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid at Solar Insolation Change	186
6.7.1.3	Performance of Three-Phase Four Wire Solar Photovoltaic Array-Battery Based Microgrid in Mode Transition	192
6.7.1.3.1	Performance of the Microgrid in Grid Synchronization Mode	197
6.7.1.3.2	Performance of Microgrid in Transition to an Islanded Mode	199
6.7.2	Experimental Performance	202
6.7.2.1	Steady State Performance of Microgrid	205
6.7.2.1.1	Steady State Performance in Grid Synchronized Mode	206
6.7.2.1.2	Steady State Performance in an Islanded Mode	206
6.7.2.2	Dynamic Performance of Microgrid	208
6.7.2.2.1	Dynamic Performance in Grid Synchronization Mode	209
6.7.2.2.2	Dynamic Performance in Islanded Mode	211

	6.7.2.2.3	Dynamic Performance under Mode Transition	213
6.8		Conclusions	214
		<b>CHAPTER–VII CONTROL AND IMPLEMENTATION OF THREE PHASE SOLAR-PICO-HYDRO-BATTERY BASED MICROGRID WITH GRID SYNCHRONIZATION</b>	<b>216-257</b>
7.1		General	216
7.2		Configuration and Operating Principle of Three Phase Solar-Pico-Hydro-Battery Based Microgrid with Grid Synchronization	217
7.3		Design of Three Phase Solar-Pico-Hydro-Battery Based Microgrid with Grid Synchronization	218
7.4		Control of Three Phase Solar-Pico-Hydro-Battery Based Microgrid with Grid Synchronization	219
	7.4.1	Solar PV Array Peak Power Extraction	221
	7.4.2	Control in Grid Synchronization Mode	221
	7.4.3	Control in Islanded Mode	225
	7.4.4	Control in Transition Mode	228
7.5		MATLAB Modelling of Three Phase Solar-Pico-Hydro-Battery Based Microgrid	229
7.6		Hardware Implementation of Three Phase Solar-Pico-Hydro-Battery Based Microgrid	230
	7.6.1	Configuration of Experimental System	230
	7.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensor	231
	7.6.3	Interfacing Circuit for Hall Effect Based Current Sensor	231
	7.6.4	Interfacing Circuit for Gate Driver	232
	7.6.5	Configuration of Experimental d-SPACE with DSP-1103	232
7.7		Results and Discussion	232
	7.7.1	Simulated Performance	233
		7.7.1.1 Performance of Three Phase Solar-Pico-Hydro-Battery Based Microgrid in Grid Synchronized	233
		7.7.1.2 Performance of Three Phase Solar-Pico-Hydro-Battery Based Microgrid in an Islanded Mode	237

7.7.1.3	Performance of Three Phase Solar-Pico-Hydro-Battery Based Microgrid under Mode Transition	241
7.7.2	Experimental Performance	243
7.7.2.1	Steady State Performance of Microgrid	245
7.7.2.1.1	Steady State Performance in Grid Synchronized Mode	245
7.7.2.1.2	Steady State Performance in an Islanded Mode	248
7.7.2.2	Dynamic Performance of the Microgrid	249
7.7.2.2.1	Dynamic Performance in Grid Synchronized Mode	249
7.7.2.2.2	Dynamic Performance in an Islanded Mode	253
7.7.2.2.3	Dynamic Performance under Mode Transition	255
7.8	Conclusions	257
<b>CHAPTER–VIII CONTROL AND IMPLEMENTATION OF THREE PHASE SOLAR-PICO-HYDRO-BATTERY WITH BIDIRECTIONAL CONVERTER BASED MICROGRID WITH GRID SYNCHRONIZATION</b>		<b>258-304</b>
8.1	General	258
8.2	Configuration and Operating Principle of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid with Grid Synchronization	259
8.3	Design of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid with Grid Synchronization	260
8.4	Control of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid with Grid Synchronization	261
8.4.1	Solar PV Array Peak Power Extraction	263
8.4.2	Control in Grid Synchronization Mode	263
8.4.3	Control in Islanded Mode	269
8.4.4	Control in Transition Mode	272
8.5	MATLAB Modelling of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid	274

8.6	Hardware Implementation of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid with Grid Synchronization	275
8.6.1	Configuration of Experimental System	276
8.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensor	276
8.6.3	Interfacing Circuit for Hall Effect Based Current Sensor	277
8.6.4	Interfacing Circuit for Gate Driver	277
8.6.5	Configuration of Experimental d-SPACE with DSP-1103	277
8.7	Results and Discussion	278
8.7.1	Simulated Performance	278
8.7.1.1	Performance of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid in Grid Synchronized Mode	279
8.7.1.2	Performance of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid in an Islanded Mode	282
8.7.1.3	Performance of Three Phase Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid under Mode Transition	288
8.7.2	Experimental Performance	290
8.7.2.1	Steady State Performance of Microgrid	292
8.7.2.1.1	Steady State Performance in Grid Synchronized Mode	293
8.7.2.1.2	Steady State Performance in Islanded Mode	296
8.7.2.2	Dynamic Performance of Microgrid	296
8.7.2.2.1	Dynamic Performance in Grid Synchronized Mode	298
8.7.2.2.2	Dynamic Performance in Islanded Mode	299
8.7.2.2.3	Dynamic Performance under Mode Transition	300
8.8	Conclusions	303

<b>CHAPTER-IX</b>	<b>CONTROL AND IMPLEMENTATION OF THREE PHASE FOUR WIRE SOLAR-PICO-HYDRO-BATTERY BASED MICROGRID WITH GRID SYNCHRONIZATION</b>	<b>305-343</b>
9.1	General	305
9.2	Configuration and Operating Principle of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid	306
9.3	Design of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid	306
9.4	Control of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid with Grid Synchronization	307
9.4.1	Solar PV Array Peak Power Extraction	309
9.4.2	Control in Grid Synchronization Mode	310
9.4.3	Control in Islanded Mode	314
9.4.4	Control in Transition Mode	317
9.5	MATLAB Modelling of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid	319
9.6	Hardware Implementation of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid	320
9.6.1	Configuration of Experimental System	321
9.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensor	321
9.6.3	Interfacing Circuit for Hall Effect Based Current Sensor	322
9.6.4	Interfacing Circuit for Gate Driver	322
9.6.5	Configuration of Experimental d-SPACE with DSP-1103	322
9.7	Results and Discussion	323
9.7.1	Simulated Performance	323
9.7.1.1	Performance of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid in the Grid Synchronized Mode	324
9.7.1.2	Performance of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid in an Islanded Mode	329
9.7.1.3	Performance of Three Phase Four Wire Solar-Pico-Hydro-Battery Based Microgrid under Mode Transition	333
9.7.2	Experimental Performance	335

9.7.2.1	Steady State Performance of Microgrid	336
9.7.2.1.1	Steady State Performance in Islanded Mode	336
9.7.2.2	Dynamic Performance of Microgrid	337
9.7.2.2.1	Dynamic Performance in an Islanded Mode	339
9.8	Conclusions	343
<b>CHAPTER-X</b>	<b>CONTROL AND IMPLEMENTATION OF THREE-PHASE FOUR-WIRE SOLAR-PICO-HYDRO-BATTERY WITH BIDIRECTIONAL CONVERTER BASED MICROGRID WITH GRID SYNCHRONIZATION</b>	<b>344-386</b>
10.1	General	344
10.2	Configuration and Operating Principle of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid	344
10.3	Design of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid	346
10.4	Control of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid	346
10.4.1	Solar PV Array Peak Power Extraction	349
10.4.2	Control in Grid Synchronization Mode	349
10.4.3	Control in Islanded Mode	354
10.4.4	Control in Transition Mode	358
10.5	MATLAB Modelling of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid	359
10.6	Hardware Implementation of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid	360
10.6.1	Configuration of Experimental System	361
10.6.2	Interfacing Circuit for Hall Effect Based Voltage Sensors	361
10.6.3	Interfacing Circuit for Hall Effect Based Current Sensors	362
10.6.4	Interfacing Circuit for Gate Driver	362
10.6.5	Configuration of Experimental d-SPACE with DSP-1103	362
10.7	Results and Discussion	363

10.7.1	Simulated Performance	363
10.7.1.1	Performance of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid in the Grid Synchronized Mode	364
10.7.1.2	Performance of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid in Islanded Mode	368
10.7.1.3	Performance of Three Phase Four Wire Solar-Pico-Hydro-Battery with Bidirectional Converter Based Microgrid under Mode Transition	376
10.7.2	Experimental Performance	378
10.7.2.1	Steady State Performance of Microgrid	379
10.7.2.1.1	Steady State Performance in Islanded Mode	379
10.7.2.2	Dynamic Performance of Microgrid	382
10.7.2.2.1	Dynamic Performance in Islanded Mode	382
10.8	Conclusions	385
<b>CHAPTER – XI MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK</b>		<b>387-397</b>
11.1	General	387
11.2	Main Conclusions	388
11.3	Suggestions for Further Work	396
	REFERENCES	398
	LIST OF PUBLICATIONS	410
	BIO-DATA	411

## LIST OF FIGURES

- Fig. 3.1 Layout of three-phase single stage solar PV array based generating system with grid synchronization
- Fig. 3.2 P/V characteristic for MPPT by INC method
- Fig. 3.3 Flowchart of INC based MPP tracking method
- Fig. 3.4 Bode plots of the TOSSI controller
- Fig. 3.5 (a) TOSSI based control algorithm (b) block diagram of TOSSI controller
- Fig. 3.6 Multi-loop feedforward control of VSC in Islanded mode
- Fig. 3.7 Simplified control of VSC in an islanded mode
- Figs.3.8 Control in mode transition (a) amplitude and phase matching controller (b) structure of LTI-EPLL
- Fig. 3.9 MATLAB model of single stage solar PV array based generating system
- Fig. 3.10 Configuration of generating system (a) outline of hardware setup with d-SPACE 1103 and its peripherals (b) experimental prototype
- Fig. 3.11 (a) circuit diagram (b) circuit board of voltage sensors
- Fig. 3.12 (a) circuit diagram (b) circuit board of current sensor
- Fig. 3.13 (a) Gate driver circuit diagram (b) isolation board of Opto-coupler
- Fig. 3.14 Simulated performance (a)  $v_{sabc}$ ,  $v_{Labc}$ ,  $i_{sabc}$ ,  $i_{Labc}$ ,  $I_{vsc}$ ,  $V_{dc}$ ,  $I_{spv}$ , and  $P_{spv}$  signals at balanced and unbalanced loads (b)  $i_{La}$ ,  $i_{c1}$ ,  $i_{c2}$ ,  $i_{c3}$ ,  $i_{c4}$ ,  $i_{Lap}$ , and  $i_{Laq}$  signals of controller
- Fig. 3.15 Intermediate signals of control (a)  $v_{sabc}$ ,  $i_{Labc}$ ,  $i_{La}$ ,  $i_{L\beta}$ ,  $v_{sa}$ , and  $v_{s\beta}$  (b)  $i_{Lap}$ ,  $i_{Laq}$ ,  $i_{L\beta p}$ ,  $i_{L\beta q}$ ,  $v_{sap}$ ,  $v_{saq}$ ,  $v_{s\beta p}$ , and  $v_{s\beta q}$  with  $i_{Lp}$  and  $i_{Lq}$  at balanced and unbalanced loads
- Fig. 3.16 Intermediate signals of control (a)  $I_{PL}$ ,  $I_{Loss}$ ,  $I_{pvf}$ ,  $I_{pnet}$ ,  $I_{QL}$ ,  $I_q$ , and  $I_{qnet}$  (b)  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  with  $v_{sa}^*$ ,  $v_{sb}^*$ , and  $v_{sc}^*$  at balanced and unbalanced loads
- Fig. 3.17 FFT analysis (a) THD of  $i_{sc}$  under nonlinear balanced load (b) THD of  $i_{sc}$  under nonlinear unbalanced load (c) THD of  $i_{Lc}$
- Fig. 3.18 Simulated performance (a) under change of PV power from 1000W/m<sup>2</sup> to 500W/m<sup>2</sup> and 500W/m<sup>2</sup> to 1000W/m<sup>2</sup> (b) FFT analysis of  $i_{vsc}$  at 1000W/m<sup>2</sup> (c) FFT analysis of  $i_{vsc}$  at 500W/m<sup>2</sup>
- Fig. 3.19 FFT analysis (a) THD of  $v_{sa}$  at 1000W/m<sup>2</sup> (b) THD of  $v_{sa}$  at 500W/m<sup>2</sup> (c) THD of  $i_{sa}$  at 1000W/m<sup>2</sup> (d) THD of  $i_{sa}$  at 500W/m<sup>2</sup>

- Fig. 3.20 Intermediate signals of control (a)  $I_{spv}$ ,  $I_{PL}$ ,  $I_{Loss}$ ,  $I_{pvf}$ ,  $I_{pnet}$ ,  $I_{QL}$ ,  $I_q$ , and  $I_{qnet}$  (b)  $I_{spv}$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$ ,  $i_{sa}^*$ ,  $i_{sb}^*$ , and  $i_{sc}^*$  under change of solar insolation
- Fig. 3.21 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b)  $v_{sabc}$ ,  $v_{Labc}$ ,  $V_{dc}$ ,  $I_{spv}$ , and  $P_{spv}$  under transition from an islanded mode to the grid synchronized mode
- Fig. 3.22 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$
- Fig. 3.23 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b)  $v_{sabc}$ ,  $v_{Labc}$ ,  $V_{dc}$ ,  $I_{spv}$ , and  $P_{spv}$  under transition from the grid synchronized mode to an islanded mode
- Fig. 3.24 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$
- Fig.3.25 Response of solar simulator in (a) MPPT mode (b) off-MPPT mode
- Fig. 3.26 Steady state test results (a-b-c) grid voltages with grid, VSC, and load currents (d-e-f) active and reactive power of grid, VSC, and loads (g) THD of  $v_{sab}$  and  $i_{sc}$  (h) THD of  $v_{vsab}$  and  $i_{vscc}$  (i) THD of  $v_{Lab}$  and  $i_{Lc}$  (j-k-l) THD of grid voltages and currents and phasor spectrum of the grid (m-n-o) THD of load voltages and currents and the phasor spectrum of the load in grid synchronized mode
- Fig. 3.27 Steady state test results (a)  $v_{La}$ ,  $v_{Lb}$ , and  $v_{Lc}$  with  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$  (b) THD of  $v_{Lab}$  and  $i_{Lc}$  (c) active and reactive components of load power with its power factors (d) THD of load voltages (e) THD of load currents (f) phasor spectrum of load voltages and currents in islanded mode
- Fig. 3.28 Load perturbation response (a)  $V_{pv}$ ,  $V_{dc}$ ,  $i_{sc}$ , and  $i_{Lc}$  (b)  $i_{Lc}$ ,  $i_{vsca}$ ,  $i_{vs cb}$ , and  $i_{vscc}$ , (c)  $i_{Lc}$ ,  $i_{vscc}$ ,  $i_{sc}$ , and  $I_{pv}$  in grid synchronized mode
- Fig.3.29 Dynamic response (a)  $i_{Lc}$ ,  $i_{sc}$ ,  $i_{scc}$ , and  $I_{pv}$  (b)  $i_{Lc}$ ,  $i_{vscc}$ ,  $I_{pv}$ , and  $i_{Lc}$  (c)  $i_{sc}$ ,  $i_{vscc}$ ,  $I_{pv}$ ,  $i_{Lc}$  under solar photovoltaic change in grid synchronization
- Fig.3.30 Dynamic performance (a)  $I_{pv}$ ,  $i_{Lc}$ ,  $V_{dc}$ , and  $v_{Lab}$  under load perturbation (b)  $I_{pv}$ ,  $i_{Lc}$ ,  $V_{dc}$ , and  $v_{Lab}$  under change of solar insolation in islanded mode
- Fig. 3.31 Dynamic performance (a)  $\theta_s$ ,  $\theta_L$ , and  $i_{sc}$  (b)  $i_{Lc}$ , STS,  $v_{sab}$ ,  $v_{Lab}$ , and  $i_{sc}$  (c)  $v_{sab}$ ,  $v_{Lab}$ ,  $i_{Lc}$ , and  $i_{sc}$  under mode transition
- Fig. 4.1 Configuration of a three phase two stage solar PV array based generating system
- Fig. 4.2 INC based control algorithm for MPPT control (a) P/V characteristic of PV array for MPPT, (b) flow-chart for INC based MPPT
- Fig. 4.3 Switching pulse generator for DC-DC converter
- Fig. 4.4 control algorithm generating switching sequence

- Fig. 4.5 Nyquist plot
- Fig. 4.6 Generation of load reference voltages and matching of phase angle in islanding mode
- Figs.4.7 ROGI-FLL for estimation of load voltages and grid voltages control parameters
- Figs.4.8 On-off signal generation for STS for mode transition
- Figs. 4.9 (a)-(b) synchronization constraints in islanded and grid synchronized operating modes
- Fig. 4.10 MATLAB model of double stage solar PV array-based generating system with grid synchronization
- Fig. 4.11 Simulated results as  $v_{sabc}$ ,  $v_{Labc}$ ,  $i_{sabc}$ ,  $i_{Labc}$ ,  $I_{vsc}$ ,  $V_{dc}$ ,  $I_{pv}$ , and  $V_{pv}$  signals of system at balanced and unbalanced loads
- Fig. 4.12 FFT analysis (a) THD of  $i_{sa}$  under nonlinear balanced load (b) THD of  $i_{sa}$  under nonlinear unbalanced load
- Fig. 4.13 FFT analysis (a) THD of  $v_{sa}$  under balanced loads (b) THD of  $v_{La}$  under nonlinear balanced loads (c) THD of  $i_{La}$  under nonlinear balanced loads and (d) THD of  $i_{vsca}$  under nonlinear unbalanced loads
- Fig. 4.14 Intermediate signals of control (a)  $i_{Labc}$ ,  $e_{abc}$ ,  $c_{abc}$ ,  $y_{labc}$ ,  $y_{0abc}$ , and  $i_{Lfabc}$  (b)  $i_{Lfa}$ ,  $i_{Lfb}$ ,  $i_{Lfc}$ ,  $i_{L\beta q}$ ,  $w_{pa}$ ,  $w_{pb}$ ,  $w_{pc}$ , and  $I_{Lp}$  at balanced and unbalanced loads
- Fig. 4.15 Intermediate signals of control (a)  $I_{Lp}$ ,  $I_{Loss}$ ,  $I_{pvf}$ , and  $I_{pnet}$  (b)  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  with  $v_{sa}^*$ ,  $v_{sb}^*$ , and  $v_{sc}^*$  at balanced and unbalanced loads
- Fig. 4.16 Model performance (a)  $v_{sabc}$ ,  $v_{Labc}$ ,  $i_{sabc}$ ,  $i_{Labc}$ ,  $I_{vsc}$ ,  $V_{dc}$ ,  $I_{pv}$ , and  $V_{pv}$  signals of system under change of solar insolation (b) THD of  $i_{sa}$  at 500W/m<sup>2</sup> (c) THD of  $i_{sa}$  at 1000W/m<sup>2</sup>
- Fig. 4.17 FFT analysis (a) THD of  $v_{sa}$  at 500W/m<sup>2</sup> (b) THD of  $v_{La}$  at 1000W/m<sup>2</sup> (c) THD of  $v_{La}$  at 1000W/m<sup>2</sup> and (d) THD of  $i_{La}$  at 500W/m<sup>2</sup> solar insolation
- Fig. 4.18 Intermediate signals of control (a)  $i_{Labc}$ ,  $e_{abc}$ ,  $c_{abc}$ ,  $y_{labc}$ ,  $y_{0abc}$ , and  $i_{Lfabc}$  (b)  $i_{Lfa}$ ,  $i_{Lfb}$ ,  $i_{Lfc}$ ,  $i_{L\beta q}$ ,  $w_{pa}$ ,  $w_{pb}$ ,  $w_{pc}$ , and  $I_{Lp}$  at different solar insolation
- Fig. 4.19 Intermediate signals of control (a)  $I_{Lp}$ ,  $I_{Loss}$ ,  $I_{pvf}$ , and  $I_{pnet}$  (b)  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  with  $v_{sa}^*$ ,  $v_{sb}^*$ , and  $v_{sc}^*$  at change of solar insolation
- Fig. 4.20 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b)  $v_{sabc}$ ,  $v_{Labc}$ ,  $V_{dc}$ ,  $I_{spv}$ , and  $P_{spv}$  under mode transition
- Fig. 4.21 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$

- Fig. 4.22 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b)  $v_{sabc}$ ,  $v_{Labc}$ ,  $V_{dc}$ ,  $I_{spv}$ , and  $P_{spv}$  under mode transition
- Fig. 4.23 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$
- Fig.4.24 Characteristics of solar simulator under (a) the grid synchronized mode (b) off grid mode.
- Fig. 4.25 Steady state response (a)-(b)-(c) grid voltages with grid currents, VSC currents, and load currents (d)-(e)-(f) active and reactive powers of grid, VSC, and load (g) THD of  $v_{sab}$  and  $i_{sc}$  (h) THD of  $v_{vsca}$  and  $i_{vsca}$  (i) THD of  $v_{Lab}$  and  $i_{Lc}$  (j)-(k) THD of grid voltages and currents (l) phasor spectrum of the grid (m)-(n) THD of load voltages and currents (o) phasor spectrum of the loads in grid synchronized mode
- Fig. 4.26 Steady state response (a) load voltages and currents (b) THD of  $v_{Lab}$  and  $i_{Lc}$  (c) active and reactive power of three phase loads with power factor (d) THD of load voltages (e) THD of load currents (f) phasor spectrum of load voltages and currents in islanded mode
- Fig. 4.27 Load perturbation response (a)  $i_{Lc}$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b)  $i_{Lc}$ ,  $i_{sc}$ ,  $i_{vsca}$ , and  $V_{pv}$ , (c)  $I_{pv}$ ,  $i_{vsca}$ ,  $i_{Lc}$ , and  $i_{sc}$  in grid synchronization mode
- Fig.4.28 Dynamic response of generating system in the grid synchronized mode (a)  $i_{sc}$ ,  $i_{vsca}$ ,  $I_{pv}$ , and  $i_{Lc}$  (b)  $I_{pv}$ ,  $i_{vsca}$ ,  $i_{Lc}$ , and  $i_{sc}$  (c)  $I_{pv}$ ,  $i_{vsca}$ ,  $i_{Lc}$ , and  $i_{sc}$
- Fig. 4.29 Dynamic performance of generating system in an islanded mode (a)  $v_{Lab}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $V_{dc}$  under load perturbation (b)  $v_{Lab}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $V_{dc}$  under change of solar insolation
- Fig. 4.30 Dynamic performance of generating system (a)  $i_{Lc}$ ,  $V_{dc}$ ,  $v_{sab}$ , and  $v_{Lab}$  (b)  $i_{Lc}$ , STS,  $v_{sab}$ ,  $v_{Lab}$ , and  $i_{sc}$  (c)  $\theta_s$ ,  $\theta_L$ , and  $i_{Lc}$  under mode transition
- Fig. 5.1 Configuration of three phase solar photovoltaic array-battery based microgrid with grid synchronization
- Fig. 5.2 IFOGI-IFLL based current controller
- Fig. 5.3 (a) Control algorithm for generating switching sequence (b) bidirectional converter
- Fig. 5.4 Developed MATLAB model of a three-phase three-wire solar PV array-battery based microgrid
- Fig. 5.5 Simulated results as  $v_{abc}$ ,  $v_{Labc}$ ,  $i_{abc}$ ,  $i_{Labc}$ ,  $I_{vsc}$ ,  $V_{dc}$ ,  $I_{pv}$ ,  $V_{pv}$ , and  $I_{batt}$  and  $V_{batt}$  signals of microgrid at balanced and unbalanced loads

- Fig. 5.6 FFT analysis (a) harmonics spectrum of  $i_{sc}$  under nonlinear balanced load (b) harmonics spectrum of  $i_{sc}$  under nonlinear unbalanced load (c) harmonics spectrum of  $v_{sc}$  under balanced loads (d) harmonics spectrum of  $v_{sc}$  under nonlinear unbalanced loads
- Fig. 5.7 FFT analysis (a) harmonics spectrum of  $i_{Lc}$  and (b) harmonics spectrum of  $i_{vsc}$  under nonlinear balanced loads
- Fig. 5.8 Intermediate signals of control (a)  $i_{Labc}$ ,  $i_{e0}$ ,  $i_{e1}$ ,  $i_{e2}$ ,  $i_{Lfp}$ , and  $i_{Lfq}$  (b)  $i_{Lfpa}$ ,  $i_{Lfpb}$ ,  $i_{Lfpc}$ ,  $u_{pa}$ ,  $u_{pb}$ ,  $u_{pc}$ , and  $I_{Lp}$  at balanced and unbalanced loads
- Fig. 5.9 Internal performance of control (a)  $I_{Lp}$ ,  $I_{Loss}$ ,  $I_{pvf}$ , and  $I_{pnet}$  (b)  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  with  $v_{sa}^*$ ,  $v_{sb}^*$ , and  $v_{sc}^*$  at balanced and unbalanced loads
- Fig. 5.10 Simulated performance (a)  $v_{abc}$ ,  $v_{Labc}$ ,  $i_{abc}$ ,  $i_{Labc}$ ,  $I_{vsc}$ ,  $V_{dc}$ ,  $I_{pv}$ ,  $V_{pv}$ ,  $I_{batt}$ , and  $V_{batt}$  under change of solar insolation (b) harmonics spectrum of  $i_{sc}$  at  $500\text{W}/\text{m}^2$  (c) harmonics spectrum of  $i_{sc}$  at  $1000\text{W}/\text{m}^2$
- Fig. 5.11 Harmonics spectrum of (a)  $v_{sa}$  at  $500\text{W}/\text{m}^2$  (b)  $v_{La}$  at  $1000\text{W}/\text{m}^2$  (c)  $v_{La}$  at  $1000\text{W}/\text{m}^2$  and (d)  $i_{La}$  at  $500\text{W}/\text{m}^2$  solar insolation
- Fig. 5.12 Intermediate signals of control (a)  $i_{Labc}$ ,  $i_{e0}$ ,  $i_{e1}$ ,  $i_{e2}$ ,  $i_{Lfp}$ , and  $i_{Lfq}$  (b)  $i_{Lfpa}$ ,  $i_{Lfpb}$ ,  $i_{Lfpc}$ ,  $u_{pa}$ ,  $u_{pb}$ ,  $u_{pc}$ , and  $I_{Lp}$  under change of solar insolation
- Fig. 5.13 Internal performance of control (a)  $I_{Lp}$ ,  $I_{Loss}$ ,  $I_{pvf}$ , and  $I_{pnet}$  (b)  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  with  $v_{sa}^*$ ,  $v_{sb}^*$ , and  $v_{sc}^*$  under change of solar insolation
- Fig. 5.14 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b)  $v_{abc}$ ,  $v_{Labc}$ ,  $V_{dc}$ ,  $I_{pv}$ , and  $I_{batt}$  under mode transition
- Fig. 5.15 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$
- Fig. 5.16 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b) microgrid  $v_{sabc}$ ,  $v_{Labc}$ ,  $V_{dc}$ ,  $I_{pv}$ , and  $I_{batt}$
- Fig. 5.17 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$
- Fig. 5.18 Characteristics of experimental solar simulator at a solar insolation of  $1000\text{W}/\text{m}^2$
- Fig. 5.19 Steady state response (a)-(c) grid voltages with grid currents, VSC currents, and load currents (d)-(f) active and reactive powers of grid, VSC, and load (g) harmonics spectra of  $v_{sab}$  and  $i_{sc}$  (h) harmonics spectra of  $v_{vscab}$  and  $i_{vsc}$  (i) harmonics spectra of  $v_{Lab}$  and  $i_{Lc}$  (j)-(k) harmonics spectra of grid voltages and currents (l) phasor spectrum of the grid (m)-(n) harmonics spectra of load voltages and currents (o) phasor spectrum of the loads

- Fig. 5.20 Steady state response (a) load voltages and currents (b) *THD* of  $v_{Lab}$  and  $i_{Lc}$  (c) active and reactive power of three phase loads (d) *THD* of three phase load voltages (e) *THD* of three phase load currents (f) phasor spectrum of load voltages and currents in islanded mode
- Fig. 5.21 Load perturbation response (a)  $i_{Lc}$ ,  $I_b$ ,  $i_{sc}$ , and  $I_{pv}$  (b)  $I_{pv}$ ,  $i_{sc}$ ,  $I_b$ , and  $i_{Lc}$ , (c)-(d)  $i_{Lc}$ ,  $i_{sc}$ ,  $i_{vscc}$ , and  $I_{pv}$  in grid synchronization mode
- Fig.5.22 Dynamic performance (a)  $I_{pv}$ ,  $i_{sc}$ ,  $V_{dc}$ , and  $i_{Lc}$  (b)  $I_{pv}$ ,  $i_{sc}$ ,  $I_b$ , and  $i_{Lc}$  (c)  $I_b$ ,  $i_{sc}$ ,  $I_{pv}$ , and  $i_{Lc}$  (d)  $i_{Lc}$ ,  $i_{sc}$ ,  $i_{vscc}$ , and  $I_{pv}$  under solar photovoltaic change in islanding mode
- Fig. 5.23 Dynamic performance (a)  $v_{Lab}$ ,  $I_b$ ,  $I_{pv}$ , and  $i_{Lc}$  (b)  $i_{Lc}$ ,  $I_b$ ,  $V_{dc}$ , and  $I_{pv}$  under change of solar insolation in islanded mode
- Fig. 5.24 Dynamic response (a)-(b)  $i_{Lc}$ ,  $I_b$ ,  $V_{dc}$ , and  $I_{pv}$  (c)-(d)  $v_{Lab}$ ,  $I_b$ ,  $I_{pv}$ , and  $i_{Lc}$ , under load perturbation in islanded mode
- Fig. 5.25 Dynamic performance (a)  $v_{sab}$ ,  $v_{Lab}$ ,  $i_{Lc}$ , and  $i_{sc}$  from grid synchronized mode to an islanded mode (b)  $v_{sab}$ ,  $v_{Lab}$ ,  $i_{Lc}$ , and  $i_{sc}$  from an islanded mode to the grid synchronized mode (c)  $i_{Lc}$ ,  $V_{dc}$ ,  $STS$ ,  $v_{sab}$ , and  $v_{Lab}$  under mode transition
- Fig. 6.1 Configuration of three phase four wire solar photovoltaic array-battery based microgrid with grid synchronization
- Fig. 6.2 P & O based MPPT algorithm
- Fig. 6.3 Comb-MOGI-IFLL based controller
- Fig. 6.4 Control algorithm for generating switching sequences
- Figs.6.5 (a) ROGI-FLL for parameters estimation (b) mode transition controller
- Fig. 6.6 Developed MATLAB model of three phase four wire solar PV array-battery based microgrid
- Fig. 6.7 Simulated results (a)  $v_{abc}$ ,  $v_{Labc}$ ,  $i_{abc}$ ,  $i_{Labc}$ ,  $I_{vscc}$ , and  $i_{sn}$  (b)  $V_{dc}$ ,  $V_{pv}$ ,  $V_{batt}$ ,  $I_{pv}$ ,  $I_{batt}$ , and G signals of microgrid at balanced and unbalanced loads
- Fig. 6.8 FFT analysis (a) Harmonics spectrum of  $i_{sc}$  at balanced loads (b) Harmonics spectrum of  $i_{sc}$  at unbalanced loads
- Fig. 6.9 FFT analysis (a)  $v_{sc}$  under balanced loads (b)  $v_{sc}$  under unbalanced loads (c)  $i_{Lc}$  at unbalanced loads and (d)  $v_{Lc}$  at unbalanced loads
- Fig. 6.10 Intermediate signals of controller as  $i_{Labc}$ ,  $i_{e0}$ ,  $i_{e1}$ ,  $i_{e2}$ ,  $i_{e1}$ ,  $i_{e2}$ , and  $i_{Lfp}$  at balanced and unbalanced loads
- Fig. 6.11 Intermediate signals of control approach as  $i_{Lfpa}$ ,  $i_{Lfpb}$ ,  $i_{Lfpc}$ ,  $u_{pa}$ ,  $u_{pb}$ ,  $u_{pc}$ , and  $I_{Lp}$  at balanced and unbalanced loads

- Fig. 6.12 Internal signals of control (a)  $I_{Lp}$ ,  $I_{Loss}$ ,  $I_{pvf}$ , and  $I_{pnet}$  (b)  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  with  $v_{sa}^*$ ,  $v_{sb}^*$ , and  $v_{sc}^*$  at balanced and unbalanced loads
- Fig. 6.13 Simulated performance (a)  $v_{sabc}$ ,  $v_{Labc}$ ,  $i_{sabc}$ ,  $i_{Labc}$ ,  $I_{vsc}$ , and  $i_{sn}$  (b)  $V_{dc}$ ,  $V_{pv}$ ,  $V_{batt}$ ,  $I_{pv}$ ,  $I_{batt}$ , and  $G$  under change in solar insolation
- Fig. 6.14 FFT analysis (a) harmonic spectrum of  $i_{sc}$  at  $500\text{W/m}^2$  (b) harmonic spectrum of  $i_{sc}$  at  $1000\text{W/m}^2$
- Fig. 6.15 FFT analysis (a) THD of  $v_{sc}$  at  $1000\text{W/m}^2$  (b) THD of  $v_{sc}$  at  $500\text{W/m}^2$  (c) THD of  $i_{Lc}$  at  $1000\text{W/m}^2$  (d) THD of  $v_{Lc}$  at  $1000\text{W/m}^2$
- Fig. 6.16 Intermediate signals of control (a)  $i_{Labc}$ ,  $i_{e0}$ ,  $i_{e1}$ ,  $i_{e2}$ ,  $i_{e3}$ ,  $i_{e4}$ , and  $i_{Lfp}$  (b)  $i_{Lfpa}$ ,  $i_{Lfpb}$ ,  $i_{Lfpc}$ ,  $u_{pa}$ ,  $u_{pb}$ ,  $u_{pc}$ , and  $I_{Lp}$  under change of solar insolation
- Fig. 6.17 Internal performance of control (a)  $I_{Lp}$ ,  $I_{Loss}$ ,  $I_{pvf}$ ,  $I_{battf}$ , and  $I_{pnet}$  (b)  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  with  $v_{sa}^*$ ,  $v_{sb}^*$ , and  $v_{sc}^*$  under change of solar insolation
- Fig. 6.18 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b)  $v_{abc}$ ,  $v_{Labc}$ ,  $i_{abc}$ ,  $V_{dc}$ ,  $I_{pv}$ , and  $I_{batt}$  under mode transition
- Fig. 6.19 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$
- Fig. 6.20 Mode transition performance (a) STS signal with  $\theta_s$  and  $\theta_L$ ,  $v_{sa}$  and  $v_{La}$ ,  $v_{sb}$  and  $v_{Lb}$ , and  $v_{sc}$  and  $v_{Lc}$  (b) STS,  $v_{sabc}$ ,  $v_{Labc}$ ,  $V_{dc}$ ,  $I_{pv}$ , and  $I_{batt}$
- Fig. 6.21 Mode transition performance (a) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{sa}$ ,  $i_{sb}$ , and  $i_{sc}$  (b) STS with  $\theta_s$  and  $\theta_L$ ,  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$
- Fig. 6.22 Characteristics of solar simulator at a solar insolation of  $666\text{W/m}^2$
- Fig. 6.23 Steady state response (a)-(b)-(c) grid voltages with grid currents, VSC currents, and load currents (d)-(e)-(f) active and reactive powers of grid, VSC, and load (g) THD of  $v_{sab}$  and  $i_{sc}$  (h) THD of  $v_{vscc}$  and  $i_{vscc}$  (i) THD of  $v_{Lc}$  and  $i_{Lc}$  (j)-(k) THD of grid voltages and currents (l) phasor spectrum of the grid (m)-(n) THD of load voltages and currents (o) phasor spectrum of the loads in the grid synchronized mode
- Fig. 6.24 Steady state response (a) load voltages and currents (b) THD of  $v_{Lab}$  and  $i_{Lc}$  (c) active and reactive power of three phase loads (d) THD of three phase load voltages (e) THD of three phase load currents (f) phasor spectrum of load voltages and currents in an islanded mode
- Fig. 6.25 Dynamic response (a)  $I_{pv}$ ,  $i_{sc}$ ,  $V_{dc}$ , and  $i_{Lc}$  (b)  $I_{pv}$ ,  $i_{sc}$ ,  $I_b$ , and  $i_{Lc}$  (c)  $I_b$ ,  $I_{pv}$ ,  $i_{sc}$ , and  $i_{Lc}$  (d)  $i_{Lc}$ ,  $i_{sc}$ ,  $i_{vscc}$ , and  $I_{pv}$  under change in solar insolation in grid synchronization mode
- Fig. 6.26 Dynamic response (a)  $i_{Lc}$ ,  $I_b$ ,  $i_{sc}$ , and  $I_{pv}$  (b)  $I_{pv}$ ,  $i_{sc}$ ,  $I_b$ , and  $i_{Lc}$  (c) and (d)  $i_{Lc}$ ,  $i_{sc}$ ,  $i_{vscc}$ , and  $I_{pv}$  in grid synchronization mode

- Fig. 6.27 Dynamic performance (a)  $v_{Lab}$ ,  $I_b$ ,  $I_{pv}$ , and  $i_{Lc}$  (b)  $i_{Lc}$ ,  $I_b$ ,  $V_{dc}$ , and  $I_{pv}$  under change of solar insolation in an islanded mode
- Fig. 6.28 Dynamic performance (a) and (b)  $v_{Lab}$ ,  $I_b$ ,  $I_{pv}$ , and  $i_{Lc}$  (c) and (d)  $i_{Lc}$ ,  $I_b$ ,  $V_{dc}$ , and  $I_{pv}$  under load perturbation in islanded mode
- Fig. 6.29 Dynamic performance (a) and (b)  $v_{sab}$ ,  $v_{Lab}$ ,  $i_{Lc}$ , and  $i_{sc}$  (c)  $i_{Lc}$ ,  $V_{dc}$ ,  $STS$ ,  $v_{sab}$ , and  $v_{Lab}$  under mode transition
- Fig. 7.1 Configuration of three phase solar-pico-hydro-battery based microgrid with grid synchronization
- Fig. 7.2 CLO-TOGI-IFLL controller
- Fig. 7.3 Control algorithm for generating switching sequences in the grid synchronization mode
- Fig. 7.4 Control algorithm for generating switching sequences in islanded mode
- Fig. 7.5 MATLAB model of three phase solar-pico-hydro-battery based microgrid
- Fig. 7.6 Simulated performance (a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and  $STS$  (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads in the grid synchronization mode
- Fig. 7.7 FFT analysis (a) harmonics spectrum of the grid current of phase ‘c’ at balanced load (b) harmonics spectrum of the grid current of phase ‘c’ at unbalanced load
- Figs. 7.8 Simulated performance (a)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  (b)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and  $STS$  under change in solar insolation
- Figs. 7.9 Simulated performance (a)  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and  $STS$  (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads in an islanded mode
- Fig. 7.10 FFT analysis (a) harmonics spectrum of pico-hydro-based generator voltage,  $v_{hyc}$  (b) harmonics spectrum of pico-hydro based generator current,  $i_{hyc}$  at unbalanced load
- Figs. 7.11 Simulated performance (a)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  (b)  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and  $STS$  under change in solar insolation
- Figs. 7.12 Simulated performance (a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and  $STS$  (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under mode transition
- Fig. 7.13 Characteristics of solar simulator at a solar insolation of 692W/m<sup>2</sup>
- Fig. 7.14 Steady state response (a)-(b)-(c) voltages at PCC with grid currents, VSC currents, and load currents (d)-(e)-(f) active and reactive powers of the grid, VSC, and load (g) THD of  $v_{sc}$  and  $i_{sc}$  (h) THD of  $v_{vsc}$  and  $i_{vsc}$  (i) THD of  $v_{Lc}$  and  $i_{Lc}$  (j)-(k) THD of the grid voltages and currents (l) phasor spectrum of the

grid (m)-(n) THD of the load voltages and currents (o) phasor spectrum of the loads in the grid synchronized mode

- Fig. 7.15 Steady state test results (a) pico-hydro-generator voltages with currents (b) THD of pico-hydro-generator phase 'c' voltage and current (c) phasor spectrum of pico-hydro-generator voltages and currents (d) THD of pico-hydro-generator voltages (e) THD of pico-hydro-generator currents (f) active and reactive power of pico-hydro-generator with their power factors
- Fig. 7.16 Steady state test results of microgrid in islanding mode (a)-(b)-(c)  $v_{ha}$ ,  $v_{hb}$ , and  $v_{hc}$  with  $i_{ha}$ ,  $i_{hb}$ , and  $i_{hc}$ ,  $i_{vsca}$ ,  $i_{vscb}$ , and  $i_{vscc}$ , and  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$  (d)-(e)-(f) active and reactive powers of pico-hydro-generator, VSC, and load (g) THDs of  $v_{hc}$  and  $i_{hc}$  (h) THDs of  $v_{vscc}$  and  $i_{vscc}$  (i) THDs of  $v_{Lc}$  and  $i_{Lc}$  (j)-(k)-(l) THDs of pico-hydro-generator voltages, currents, and their phasor spectrum (m)-(n)-(o) THDs of load voltages, currents, and their phasor spectrum
- Fig. 7.17 Performance of microgrid (a)  $i_{sa}$ ,  $i_{sb}$ ,  $i_{sc}$ , and  $i_{Lc}$  (b)  $i_{Lc}$ ,  $i_{sc}$ ,  $I_b$ , and  $i_{vscc}$  (c)  $i_{Lc}$ ,  $i_{sc}$ ,  $I_b$ , and  $i_{vscc}$  (d)  $i_{sc}$ ,  $I_{pv}$ ,  $I_b$ , and  $i_{Lc}$  under load perturbation in the grid synchronized mode
- Fig. 7.18 Dynamic performance (a)  $I_{pv}$ ,  $i_{hc}$ ,  $I_b$ , and  $i_{Lc}$  (b)  $I_{pv}$ ,  $i_{sc}$ ,  $I_{ev}$ , and  $I_b$  (c)  $I_{pv}$ ,  $I_b$ ,  $i_{Lc}$ , and  $i_{sc}$  (d)  $i_{vscc}$ ,  $I_b$ ,  $i_{Lc}$ , and  $i_{sc}$  in the grid synchronized mode
- Fig. 7.19 Dynamic performance (a)  $i_{ha}$ ,  $i_{hb}$ ,  $i_{hc}$ , and  $i_{Lc}$  (b)  $i_{hc}$ ,  $I_{pv}$ ,  $I_b$ , and  $i_{Lc}$  (c)  $I_{ev}$ ,  $i_{hc}$ ,  $I_b$ , and  $i_{Lc}$  (d)  $i_{Lc}$ ,  $i_{hc}$ ,  $I_{ev}$ , and  $I_b$  in an islanded mode
- Fig. 7.20 Dynamic performance in an islanded mode (a)  $I_{pv}$ ,  $i_{hc}$ ,  $I_{ev}$ , and  $I_b$  (b)  $I_{pv}$ ,  $I_b$ ,  $V_{batt}$ , and  $V_{dc}$  (c)  $I_{pv}$ ,  $i_{hc}$ ,  $I_b$ , and  $i_{Lc}$  under change of solar insolation
- Fig. 7.21 Mode transition performance (a)  $v_{sc}$ ,  $v_{hc}$ ,  $i_{sc}$ , and  $i_{Lc}$  from an islanded mode to the grid synchronized mode (b)  $v_{sc}$ ,  $v_{hc}$ ,  $i_{sc}$ , and  $i_{Lc}$  from the grid synchronized mode to an islanded mode (c)  $I_b$ ,  $i_{sc}$ ,  $i_{Lc}$ , and  $i_{hc}$  from an islanded mode to the grid synchronized mode (d)  $I_b$ ,  $i_{sc}$ ,  $i_{Lc}$ , and  $i_{hc}$  from the grid connected mode to an islanded mode (e)  $v_{sc}$ ,  $\theta_s$ ,  $\theta_h$ , and  $i_{sc}$  under transition from an islanded mode to the grid synchronized mode (f)  $v_{sc}$ ,  $\theta_s$ ,  $\theta_h$ , and  $i_{sc}$  under transition from the grid synchronized mode to an islanded mode
- Fig. 8.1 Configuration of three phase solar-pico-hydro-battery with bidirectional converter based microgrid
- Fig. 8.2 (a) Comb-TOGI-IFLL controller (b) Control algorithm for generating switching sequences in the grid synchronization mode (c) bidirectional converter (d) Control algorithm for generating switching sequences in an islanded mode
- Fig. 8.3 (a) flow chart of mode transition controller (b) Block diagram presentation of SOGI-FLL

- Fig. 8.4 Developed MATLAB model of three phase solar-pico-hydro-battery with bidirectional converter based microgrid with grid synchronization
- Fig. 8.5 Simulated performance (a)  $v_g, i_g, v_{hy}, i_{hy}, i_L, i_{vsc}, V_{dc}$ , and STS (b)  $I_{ev}, I_b, V_{pv}, I_{pv}, f, V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads in the grid synchronization mode
- Fig. 8.6 FFT analysis (a) harmonics spectrum of the grid current of phase ‘c’ at balanced nonlinear load (b) harmonics spectrum of the grid current of phase ‘c’ at unbalanced nonlinear load
- Figs. 8.7 Simulated performance under change in solar insolation (a)  $v_g, i_g, v_{hy}, i_{hy}, i_L, i_{vsc}, V_{dc}$ , and STS (b)  $I_{ev}, I_b, V_{pv}, I_{pv}, f, V_{tm}$ , and  $\theta_g$
- Figs. 8.8 Simulated performance in an islanded mode (a)  $v_{hy}, i_{hy}, i_L, i_{vsc}, V_{dc}$ , and STS (b)  $I_{ev}, I_b, V_{pv}, I_{pv}, f, V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads
- Fig. 8.9 FFT analysis (a) harmonics spectrum of pico-hydro generator voltage,  $v_{hyc}$  (b) harmonics spectrum of pico-hydro generator current,  $i_{hyc}$  at unbalanced load
- Figs. 8.10 Simulated performance (a)  $v_{hy}, i_{hy}, i_L, i_{vsc}, V_{dc}$ , and STS (b)  $I_{ev}, I_b, V_{pv}, I_{pv}, f, V_{tm}$ , and  $\theta_g$  under change in solar insolation
- Figs. 8.11 Simulated performance (a)  $v_{hy}, i_{hy}, i_L, i_{vsc}, V_{dc}$ , and STS (b)  $I_{ev}, I_b, V_{pv}, I_{pv}, f, V_{tm}$ , and  $\theta_g$  under change in charging port power
- Figs. 8.12 Simulated performance (a)  $v_g, i_g, v_{hy}, i_{hy}, i_L, i_{vsc}, V_{dc}$ , and STS (b)  $I_{ev}, I_b, V_{pv}, I_{pv}, f, V_{tm}$ , and  $\theta_g$  under mode transition
- Fig. 8.13 Characteristics of solar simulator at a solar insolation of  $692\text{W}/\text{m}^2$
- Fig. 8.14 Steady state performance in the grid synchronized mode (a)-(b)-(c) voltages at PCC with grid currents, VSC currents, and load currents (d)-(e)-(f) active and reactive powers of the grid, VSC, and the load (g) THD of  $v_{sa}$  and  $i_{sa}$  (h) THD of  $v_{vsca}$  and  $i_{vsca}$  (i) THD of  $v_{La}$  and  $i_{La}$  (j)-(k) THD of the grid voltages and currents (l) phasor spectrum of the grid (m)-(n) THD of the load voltages and currents (o) phasor spectrum of the load
- Fig. 8.15 Steady state performance of pico-hydro generator (a) voltages with currents (b) THD of  $i_{ha}$  and  $v_{ha}$  (c) phasor spectrum of hydro-generator (d) THD of hydro-generator voltages (e) THD hydro-generator currents (f) active and reactive power with its power factor
- Fig. 8.16 Steady state performance in an islanded mode (a)  $v_{ha}, v_{hb}$ , and  $v_{hc}$  with  $i_{ha}, i_{hb}$ , and  $i_{hc}$  (b)  $v_{vsca}, v_{vsch}$ , and  $v_{vscc}$  with  $i_{vsca}, i_{vsch}$ , and  $i_{vscc}$  (c)  $v_{La}, v_{Lb}$ , and  $v_{Lc}$  with  $i_{La}, i_{Lb}$ , and  $i_{Lc}$  (d-e-f) active and reactive components of three phase hydro, VSC, and load power with power factor (g-h-i) THD of  $i_{ha}, i_{vsca}$ , and  $i_{La}$  (j-k) THD of  $v_{ha}, v_{hb}, v_{hc}$  and  $i_{ha}, i_{hb}, i_{hc}$  (l) phase spectrum of hydro generator (m-n) THD of  $v_{La}, v_{Lb}, v_{Lc}$  and  $i_{La}, i_{Lb}, i_{Lc}$  (o) phase spectrum of the load

- Fig. 8.17 Dynamic response (a)  $I_b$ ,  $i_{hc}$ ,  $I_{pv}$ , and  $V_{dc}$  (b)  $i_{Lc}$ ,  $I_b$ ,  $i_{hc}$ , and  $V_{dc}$  (c)  $I_b$ ,  $i_{Lc}$ ,  $i_{gc}$ , and  $I_{pv}$  (d)  $I_{pv}$ ,  $i_{Lc}$ ,  $I_b$ , and  $i_{gc}$  in the grid synchronized mode.
- Fig. 8.18 Dynamic performance in the grid synchronization mode (a)  $i_{Lc}$ ,  $I_{pv}$ ,  $i_{gc}$ , and  $I_b$  (b)  $i_{Lc}$ ,  $i_{hc}$ ,  $i_{gc}$ , and  $I_b$  (c)  $v_{hc}$ ,  $v_{gc}$ ,  $i_{gc}$ , and  $i_{Lc}$  (d)  $v_{hc}$ ,  $v_{gc}$ ,  $i_{gc}$ , and  $i_{Lc}$
- Fig. 8.19 Dynamic performance in islanded mode (a)  $I_b$ ,  $i_{hc}$ ,  $I_{pv}$ , and  $V_{dc}$  (b)  $i_{Lc}$ ,  $I_{pv}$ ,  $I_b$ , and  $i_{hc}$  (c)  $i_{Lc}$ ,  $I_b$ ,  $i_{hc}$ , and  $V_{dc}$  (d)  $i_{Lc}$ ,  $i_{hc}$ ,  $i_{vsc}$ , and  $I_b$
- Fig. 8.20 Mode transition performance (a)  $v_{gab}$ ,  $v_{hab}$ ,  $i_{gc}$ , and  $i_{Lc}$  from an islanded mode to the grid synchronized mode (b)  $v_{gab}$ ,  $v_{hab}$ ,  $i_{gc}$ , and  $i_{Lc}$  from the grid synchronized mode to an islanded mode (c)  $I_b$ ,  $i_{gc}$ ,  $i_{Lc}$ , and  $i_{hc}$  from an islanded mode to the grid synchronized mode (d)  $I_b$ ,  $i_{gc}$ ,  $i_{Lc}$ , and  $i_{hc}$  from the grid connected mode to an islanded mode (e)  $i_{Lc}$ ,  $v_{gab}$ ,  $v_{hab}$ , and  $i_{gc}$  under transition from the grid synchronized mode to an islanded mode (f)  $i_{Lc}$ ,  $v_{gab}$ ,  $v_{hab}$ , and  $i_{gc}$  under transition from an islanded mode to the grid synchronized mode
- Fig. 9.1 Configuration of three phase four wire solar-pico-hydro-battery based microgrid with grid synchronization
- Fig. 9.2 Comb-CLO-TOGI-FLL controller
- Fig. 9.3 Control algorithm for generating switching sequences in the grid synchronization mode
- Fig. 9.4 Control algorithm for generating switching sequences in islanded mode
- Figs.9.5 Block diag. presentation of (a) LTI-EPLL (b) mode transition controller
- Fig. 9.6 Developed Simulink model in the MATLAB of a three phase four wire solar-pico-hydro-battery based microgrid
- Fig. 9.7 Simulated performance (a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads in the grid synchronization mode
- Fig. 9.8 FFT analysis (a)-(b) harmonics spectrum of phase 'a' of the grid voltage and current at balanced load (c)-(d) harmonics spectrum of phase 'a' of the grid voltage and current at unbalanced load
- Figs. 9.9 Simulated performance (a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{pv}$ ,  $I_b$ ,  $I_{ev}$ ,  $V_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under change in solar insolation and change in charging port current
- Figs. 9.10 Simulated performance (a)  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads in an islanded mode

- Fig. 9.11 FFT analysis (a) harmonics spectrum of pico-hydro-based generator voltage,  $v_{hya}$  (b) harmonics spectrum of pico-hydro-based generator current,  $i_{hya}$  at unbalanced load
- Figs. 9.12 Simulated performance (a)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  (b)  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS under change in solar insolation
- Figs. 9.13 Simulated performance under Mode transition (a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{pv}$ ,  $I_b$ ,  $I_{ev}$ ,  $V_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$
- Fig. 9.14 Characteristics of a solar simulator
- Fig.9.15 Test results (a)-(b)-(c) PCC voltages with  $i_{ga}$ ,  $i_{gb}$ , and  $i_{gc}$ ,  $i_{vsca}$ ,  $i_{vs cb}$ , and  $i_{vscc}$ , and  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$  (d)-(e)-(f) active and reactive components of power of hydro-generator, VSC, and load with power factor (g)-(h)-(i) THD of hydro-generator voltages and currents, and its phasor spectrum (j)-(k)-(l) THD of load voltages and currents and its phasor spectrum (m)-(n)-(o) THD of VSC voltages and currents and its phasor spectrum in an islanded mode
- Fig. 9.16 Dynamic performance of three-phase four wire solar-pico-hydro-battery based microgrid with grid synchronization in an islanded mode (a)  $I_b$ ,  $I_{ev}$ ,  $V_{batt}$ , and  $i_{Lc}$  (b)  $i_{Lc}$ ,  $i_{hc}$ ,  $f$ , and  $I_{pv}$  (c)-(d)  $i_{hc}$ ,  $V_{batt}$ ,  $i_{Lc}$ , and  $I_{ev}$  (e)-(f)  $I_b$ ,  $V_{dc}$ ,  $i_{Lc}$ , and  $v_{hab}$  (g)-(h)  $I_b$ ,  $i_{vscc}$ ,  $i_{Lc}$ , and  $i_{hc}$  under disconnection and connection of phase 'c' load
- Fig. 9.17 Dynamic test results (a)-(b)  $i_{hc}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $I_b$  (c)  $I_{pv}$ ,  $I_b$ ,  $V_{batt}$ , and  $i_{Lc}$  (d)  $i_{hc}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $I_b$  under change in solar insolation in an islanded mode
- Fig. 10.1 Configuration of three phase four wire solar-pico-hydro-battery with bidirectional converter based microgrid
- Fig. 10.2 Block diagram presentation (a) CLO-FOGI-IFLL controller (b) CLO-FOGI-IFLL based current Control algorithm for generating gating pulses in the grid synchronization mode (c) bidirectional converter for battery charging and discharging
- Fig. 10.3 Control algorithm for generating switching sequences in islanded mode
- Fig. 10.4 Developed MATLAB model of three phase four wire solar-pico-hydro-battery with bidirectional converter based microgrid with grid synchronization
- Fig. 10.5 Simulated results (a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads in the grid synchronization mode
- Fig. 10.6 FFT analysis (a) harmonics spectrum of the grid voltage of phase 'c' at balanced load (b) harmonics spectrum of the grid current of phase 'c' at balanced load (c) harmonics spectrum of the grid voltage of phase 'c' at unbalanced load (d) harmonics spectrum of the grid current of phase 'c' at unbalanced load
- Figs. 10.7 Simulated results (a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under change in solar insolation

- Figs. 10.8 Simulated results in an islanded mode (a)  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under balanced and unbalanced loads
- Fig. 10.9 FFT analysis (a) harmonics spectrum of pico-hydro driven generator voltage,  $v_{hya}$  of phase 'a' at unbalanced load (b) harmonics spectrum of pico-hydro driven generator current,  $i_{hya}$  of phase 'a' at unbalanced load
- Figs.10.10 Simulated results (a)  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under change in solar insolation
- Figs.10.11 Simulated results (a)  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under change in charging port power
- Figs.10.12 Simulated results(a)  $v_g$ ,  $i_g$ ,  $v_{hy}$ ,  $i_{hy}$ ,  $i_L$ ,  $i_{vsc}$ ,  $V_{dc}$ , and STS (b)  $I_{ev}$ ,  $I_b$ ,  $V_{pv}$ ,  $I_{pv}$ ,  $f$ ,  $V_{tm}$ , and  $\theta_g$  under mode transition
- Fig.10.13 Characteristics of solar simulator
- Fig.10.14 Steady state test results (a)  $v_{ha}$ ,  $v_{hb}$ , and  $v_{hc}$  with  $i_{ha}$ ,  $i_{hb}$ , and  $i_{hc}$  (b)  $v_{vsca}$ ,  $v_{vs cb}$ , and  $v_{vscc}$  with  $i_{vsca}$ ,  $i_{vs cb}$ ,  $i_{vscc}$  (c)  $v_{La}$ ,  $v_{Lb}$ , and  $v_{Lc}$  with  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$  (d-e-f) active and reactive powers of hydro generator, VSC, and load with power factor (g-h-i) THD of  $v_{ha}$  with  $i_{ha}$ ,  $v_{vsca}$  with  $i_{vscc}$ , and  $v_{La}$  with  $i_{La}$  (j-k-l) THD of  $v_{ha}$ ,  $v_{hb}$ , and  $v_{hc}$  and  $i_{ha}$ ,  $i_{hb}$ , and  $i_{hc}$  with their phasor spectrum (m-n-o) THD of  $v_{La}$ ,  $v_{Lb}$ , and  $v_{Lc}$  and  $i_{La}$ ,  $i_{Lb}$ , and  $i_{Lc}$  with their phasor spectrum in islanded mode
- Fig.10.15 Dynamic test results (a)  $i_{hc}$ ,  $I_b$ ,  $i_{Lc}$ , and  $i_{vscc}$  at disconnection of phase 'c' load (b)  $i_{hc}$ ,  $I_b$ ,  $i_{Lc}$ , and  $i_{vscc}$  at connection of phase 'c' load (c)  $i_{hc}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $I_{ev}$  at disconnection of phase 'c' load (d)  $i_{hc}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $I_{b2}$  at connection of phase 'c' load (e)  $i_{hc}$ ,  $I_b$ ,  $i_{Lc}$ , and  $i_{vscc}$  at disconnection of phase 'c' load and without PV array power (f)  $i_{hc}$ ,  $I_b$ ,  $i_{Lc}$ , and  $i_{vscc}$  at connection of phase 'c' load and without PV array power
- Fig.10.16 Dynamic test results (a)  $i_{hc}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $I_b$  at decrease of solar insolation (b)  $i_{hc}$ ,  $I_{pv}$ ,  $i_{Lc}$ , and  $I_b$  at increase of solar insolation (c)  $I_{pv}$ ,  $i_{hc}$ ,  $I_b$ , and  $V_{dc}$  at increase of solar insolation (d)  $I_{pv}$ ,  $I_b$ ,  $i_{Lc}$ , and  $V_{batt}$  under decrease of solar insolation in an islanded mode

## LIST OF TABLES

Table-3.1	Designed parameters of experimental prototype of a three-phase single stage solar PV array based generating system
Table-4.1	Designed parameters of an experimental prototype of three- phase double-stage solar photovoltaic array based generating system
Table-5.1	Designed parameters of experimental prototype of three-phase solar PV array-battery based microgrid developed in the laboratory
Table-6.1	Designed parameters of experimental prototype of three-phase four-wire solar photovoltaic array-battery based microgrid
Table-7.1	Designed parameters of an experimental prototype of a three-phase solar-pico-hydro-battery based microgrid
Table-8.1	Designed parameters of developed prototype of a three-phase solar-pico-hydro-battery with a buck-boost converter based microgrid
Table-9.1	Designed parameters of three-phase four-wire solar-pico-hydro-battery based microgrid
Table-10.1	Designed parameters of three-phase four wire solar-pico-hydro-battery with bidirectional converter based microgrid
Table 11.1	Important characteristics of existing and proposed controllers

## LIST OF ABBREVIATIONS

RES	Renewable Energy Source
MG	Microgrid
PV	Photovoltaic
SPVA	Solar photovoltaic Array
MPPT	Maximum power point tracking
SEIG	Self Excited Induction Generator
PMSG	Permanent Magnet Synchronous Generator
INC	Incremental conductance
P & O	Perturb & Observe
VSC	Voltage Source Converter
PCC	Point of Common Coupling
BDC	Bidirectional Converter
BES	Battery Energy Storage
DSP	Digital Signal Processor
SES	Solar Energy Source
STS	State Transition Switch
SOC	State of Charge
PIR	Proportional-Integral Regulator
EPLL	Enhanced Phase Locked Loop
PLL	Phase Locked Loop
TOSSI	Third Order Sinusoidal Signal Integrator
LTI-EPLL	Linear Time Invariant-Enhanced Phase Locked Loop
THD	Total Harmonic Distortion
ZCD	Zero Crossing Detector
S & H	Sample and Hold logic
LPF	Low Pass Filter
ROGI-FLL	Reduced Order Generalized Integrator-Frequency Locked Loop
IFOGI-IFLL	Improved Forth Order Generalized Integrator with Improved Frequency Lock-Loop
FC	Fundamental Component of Load Current

ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
SPVEGS	Solar Photovoltaic Energy Generation System
MOGI-FLL	Multi-Order Generalized Integrator-Frequency Locked Loop
CLO-TOGI-IFLL	Limit Cycle Oscillator Based Third Order Generalized Integrator
FFT	Fast Fourier Transform
PQ	Power quality
CLO-FOGI-IFLL	Limit Cycle Oscillator Based Fifth Order Generalized Integrator

## LIST OF SYMBOLS

$v_{sa}, v_{sb}, v_{sc} / v_{ga}, v_{gb}, v_{gc}$	Grid phase voltages
$v_{sab}, v_{sbc} / v_{gab}, v_{gbc}$	Grid line voltages
$i_{sa}, i_{sb}, i_{sc} / i_{ga}, i_{gb}, i_{gc}$	Grid currents
$i_{La}, i_{Lb}, i_{Lc}$	Load currents
$i_{vsca}, i_{vs cb}, i_{vscc}$	VSC currents
$v_a, v_b, v_c$	PCC voltages
$V_{dc}$	DC-link voltage
$C_{dc}$	DC-link capacitor
$I_{PV}$	PV array current
$R_p, C_p$	Ripple filters resistor and capacitor
$\theta_s$	Grid voltages phasor
$\theta_L$	Load voltages phasor
$f_s$	Frequency of the Grid voltage
$f_l$	Frequency of the load voltage
$L_{fp}$	Grid interfacing inductor
$I_{sw}$	Current rating of VSC switches
$V_{sw}$	Voltage rating of VSC switches
$P_{PV}$	PV array power
$V_{PV}$	PV array voltage
$V_{dc}^*$	Reference for DC-link voltage
$V_{edc}$	DC-link voltage error
$u_{pa}, u_{pb}, u_{pc}$	In-phase unit templates
$V_l / V_{lm}$	PCC phase voltages amplitude
$i_{c1}, i_{c2}, i_{c3}, i_{c4}$	Internal signals of controller
$k_{f1}, k_{f2}$	Parameters of controller
$\omega_0$	Fundamental frequency of the system
$I_{Loss}$	Loss component of current
$I_{pvf}$	Feed forward power component
$I_{pnet}$	Active fundamental component of control

$I_{qnet}$	Reactive fundamental component of control
$P^*$	Active power of load
$Q^*$	Reactive power of load
$i_{sa}^*, i_{sb}^*, i_{sc}^* / i_{ga}^*, i_{gb}^*, i_{gc}^*$	Reference current for the grid
$i_{esa}, i_{esb}, i_{esc} / i_{ega}, i_{egb}, i_{egc}$	Errors between reference currents and sensed currents of grid
$v_{La}, v_{Lb}, v_{Lc}$	Load phase voltages
$v_{lab}, v_{lbc}$	Load line voltages
$v_{La}^*, v_{Lb}^*, v_{Lc}^*$	Generated reference voltages of the load
$V_{mc}^*$	Peak amplitude of load reference voltages
$\omega_0$	Frequency of load reference voltages
$L_b$	Boost converter inductor
$K_{New}, K_{Old}, \delta K$	Duty cycles and change in duty cycle of Boost converter
$u_{qa}, u_{qb}, u_{qc}$	Quadrature phase unit templates
$i_{Labc}$	Three phase load currents
$i_{Lpa}, i_{Lpb}, i_{Lpc}$	Active components of load current
$i_{Lqa}, i_{Lqb}, i_{Lqc}$	Reactive components of load current
$e_{abc}$	Error component of three phase load current
$i_{Lafp}, i_{Lbfp}, i_{Lcfp}$	Fundamental active components of load currents
$i_{Lafq}, i_{Lbfq}, i_{Lcfq}$	Fundamental reactive components of load currents
$C_{abc}$	Feedback component
$y_{1abc}$	Positive sequence components
$y_{2abc}$	Negative sequence components
$\omega_1, \phi_1, A_1$	Frequency, phase, and magnitude of positive sequence components
$\omega_2, \phi_2, A_2$	Frequency, phase, and magnitude of negative sequence components
$\omega_0, \phi_0, A_0$	Frequency, phase, and magnitude of zero sequence components
$e_{abc}, r_{abc}, C_{abc}$	Internal signals
$y_{0abc}$	Zero sequence components
$i_{evsca}, i_{evscb}, i_{evsc}$	Errors between reference and sensed VSC currents
$i_{eLa}, i_{eLb}, i_{eLc}$	Errors between reference currents and sensed currents of load

$k_{pv}, k_{iv}$	Proportional and integral gains of voltage controller
$v_{eLa}, v_{eLb}, v_{eLc}$	Errors between reference and sensed voltages of load
$\omega_{err}$	Error between reference and estimated frequency
$V_{tl}^*/V_{tm}^*$	Reference amplitude of voltage at PCC
$V_{err}$	Error between reference and estimated amplitude of voltage at PCC
$\theta_{err}$	Error between phasor of grid voltage and load voltage
$I_{batt}/I_b$	Battery current
$V_{batt}$	Battery voltage
$I_b^*$	Reference current of battery
$I_{battf}$	Feed forward power component of battery
$I_{eb}$	Error in battery current
$i_{sn}/i_{gn}$	Neutral current of grid
$i_{Ln}$	Neutral current of load
$i_{esn}/i_{egn}$	Error in neutral current of grid
$i_{eLn}$	Error in neutral current of load
$C_{hg}$	Excitation capacitor
$I_{Lfav}$	Active component of load current
$P_{hyg}$	Pico-hydro driven generator power
$v_{ha}, v_{hb}, \text{ and } v_{hc}$	Hydro generator phase voltages
$v_{hab}, v_{hbc}$	Hydro generator line voltages
$i_{ha}, i_{hb}, \text{ and } i_{hc}$	Hydro generator currents
$i_{ha}^*, i_{hb}^*, \text{ and } i_{hc}^*$	Hydro generator reference currents
$i_{eha}, i_{ehb}, \text{ and } i_{ehc}$	Error in hydro generator currents
$I_{hyf}$	Feedforward component of pico-hydro generator power
$\theta_g$	Phasor of PCC voltages
$I_{ey}$	Additional charging port current
$k_{pf}, k_{if}$	Proportional integral gains of frequency regulator
$k_{pb}, k_{ib}$	Proportional integral gains of battery current regulator
$k_{pc}, k_{ic}$	Proportional integral gains of DC-link voltage regulator