

**CONTROL OF RELIABLE CHARGING INFRASTRUCTURE FOR EVS
WITH RENEWABLE ENERGY GRID INTERFACE**

ANJEET KUMAR VERMA



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

MAY 2021

© Indian Institute of Technology Delhi (IITD), New Delhi, 2021

**CONTROL OF RELIABLE CHARGING INFRASTRUCTURE FOR EVS
WITH RENEWABLE ENERGY GRID INTERFACE**

by

ANJEET KUMAR VERMA

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2021

CERTIFICATE

This is to certify that the thesis entitled, “**Control of Reliable Charging Infrastructure for EVs with Renewable Energy Grid Interface**” being submitted by **Mr. Anjeet Kumar Verma** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Anjeet Kumar Verma has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

Date: 10-05-2021

Place: New Delhi

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

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and indebtedness to **Prof. Bhim Singh** for providing me guidance and constant supervision to carry out the Ph.D. work. Working under him has been a wonderful experience, which has provided a deep insight to the world of research. Determination, dedication, innovativeness, resourcefulness and discipline of **Prof. Bhim Singh** have been the inspiration for me to complete this work. His consistent encouragement, continuous monitoring and commitments to excellence have always motivated me to improve my work and use the best of my capabilities. Due to his blessing I have earned various experiences, other than research, which will help me throughout my life. My sincere thanks and deep gratitude are to Prof. Sukumar Mishra, Dr. Anandrup Das, Dr. Ashu Verma, all SRC members for their valuable guidance and consistent support during my research work. I wish to convey my sincere thanks to **Prof. Bhim Singh**, Prof. G. Bhuvanewari, Prof. B. K. Panigrahi, Prof. Mummadi Veerachary, Prof. (late) KR Rajagopal, Dr. Anandarup Das and Dr. Ramkrishan Maheshwari for their valuable inputs during my course work, which has made the foundation for my research work. I am grateful to IIT Delhi for providing me the research facilities. I would wish to express my sincere gratitude to **Prof. Bhim Singh**, Prof. G. Bhuvanewari and the Prof. A.K. Jain, as Prof. in-charge of PG Machine Lab, for providing me immense facilities to carry out experimental work. Thanks are due to Sh. Srichand, Sh. Puran Singh, Sh. Jagbir Singh, Sh. Amit Kumar, Sh. Jitendra, Sh. Anurag Singh, Sh. Rahul Divakar of PG Machines Lab, UG Machines Lab and Power Electronics Lab., IIT Delhi for providing me the facilities and assistance during this work. I would like to thank all my seniors, Dr. Chinmay Jain, Dr. Rajan Sonkar, Dr. Ikhlq Hussain, Dr. Aniket Anand, Dr. Nishant Kumar, Mr. Anshul Varshney, Dr. Saurabh Shukla, Dr. Radha Kushwaha, Dr. Nidhi Mishra, Dr.

Geeta Pathak, Dr. Shailendra Kumar Dwivedi, Dr. Shadab Murshid, Dr. Piyush Kant, Dr. Sachin Devassy, Mr. Vineet P. Chandran, Dr. Tripurari Nath Gupta, Ms. Shatakshi, Ms. Vandana Jain and Dr. Anjaneer Kumar Mishra to motivate me in the starting of my research work. I would like to use this opportunity to thank Dr. Seema, Mr. Sreejith R., Mr. Debashish Mishra, Mr. Gurmeet Singh, Mr. Yalavarthi Amarnath, Mr. Suri Praneeth, and Mr. Priyvratt Vats who have constantly helped me on all technical issues. I would like to thank Dr. Deepu Vijay Menon, Ms. Subarni Pradhan, Dr. Tabish Nazir Mir, Mr. Praveen Kumar Singh, Dr. Amresh Singh, and all other colleagues for their valuable aid and cooperation. My heartfelt thanks to Mr. Sunil Kumar Pandey, Mr. Utkarsh Sharma, Mr. P. Sambasivaiah, Mr. Munesh Kumar Singh, Ms. Rohini Sharma, Ms. Pavitra Shukl, Ms. Farheen Chishti, Mrs. Shubhra, Mr. Aryadip Sen, Mr. Mohd. Kashi, Ms. Hina Parveen, Ms. Rashmi Rai, Mr. Niranjana Rao Deevela, Ms. Yashi Singh, Mr. Souvik Das, Mr. Sudip Bhattacharya, Ms. Shalvi Tyagi, Mr. Sandeep Kumar Sahoo, Mr. Gaurav Modi, Mr. Syed Bilal Qaiser Naqvi, Mr. Jitendra Gupta, Mr. Utsav Sharma, Mr. Sayandeer Ghosh, Mr. Saran Chaurasiya, Mr. Vivek Narayanan, Mr. Rahul Kumar, Mr. Sharankumar Shastri, Mr. Deepak Saw, Mr. Shivam Kumar Yadav, Ms. Kousalya V, Ms. Sanjenbam Chandrakala Devi, Mr. Saurabh Mishra, Mr. Muhammad Zarkab Farqooi, Ms. Kripa Tiwari, Mr. Rohit Kumar, Mr. Vipin Kumar Singh, Mr. Arjun Kumar, Mr. Biswajit Saha, Ms. Farha Siddique, Mr. Sumit Kumar, Mr. Gaurav Kumar, Mr. Madan Gopal Sharma, and all other PG Machine Lab mates for their help and informal support in pursuing this research work.

I would like to thank my friends, Mr. Pragyey Kumar Kaushik, Mr. Ajay Singh, Mr. Adarsh Singh, Mr. Pankaj Yadav, Mr. Parmeshwar Saini, Dr. Deepak Gupta, Mr. Ravish Kumar, Dr. Avneet Kumar Chauhan, Dr. Naresh K Pilli, Dr. Motiur Reza, Dr. M. Raghuram, Dr. V. Venkat Ratnam, Mr. Anand, Mr. Ankit Kumar, Mr. Deepak Patil, Mr. Mohinish Singh, Dr. Sarvesh Mishra, Mr.

Athar Kamal, Mr. Nitin Gupta, Mr. Jaswant, Mr. Satyaranjan, Mr. Ajay Kumar Agrawal for their unconditional support and motivation.

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

Moreover, I would like to thank Department of Science and Technology (DST), Govt. of India for funding this research work under the fund for improvement of S&T infrastructure in higher educational institutions (FIST), UKICERI (RP03391), UI-ASSIST (RP03443), SERI-II and J C Bose Fellowship (RP03128).

My deepest love, appreciation and indebtedness go to my father, Mr. Chandrabali Verma for his dreams, sacrifices and wholeheartedly endorses. His trust in my capabilities have always motivated me to reach higher academic degrees. I would like to convey my unbounded love to my mother Mrs. Chandrawati Verma as I spent a major part of my childhood in her lap. A great deal of effort, endurance, encouragement and blessings of my parents. Moreover, I would like to thank my brothers Mr. Sanjeet Kumar Verma and Mr. Ankit Kumar Verma, my sister Mrs. Renu Singh Verma, and other family members for giving me the inner strength and wholeheartedly support. Their trust in my capabilities had been a key factor to all my achievements. At last, I am beholden to almighty for their blessings to help me to raise my academic level to this stage. I pray for their benediction in my future endeavors. Their blessings may be showered on me for strength, wisdom and determination to achieve in future.

Date: 10-05-2021

Anjeet Kumar Verma

ABSTRACT

In view of the proliferation of EVs, the development of the multi-functional EV charging infrastructure is of paramount importance. In addition, integrating renewable energy into the core of the EV charging system is crucially significant. Therefore, this thesis deals with the design, control and implementation of various configurations of PV array, wind energy conversion system (WECS), storage battery, grid/DG set based EV charging station, beneficial for EVs, domestic loads, and utility. For EVs and the household loads, the charging stations are designed to operate in multimodes such in an islanded mode, the grid connected mode and the DG set connected mode with automatic and seamless mode transition among them, to provide the uninterruptible power. Moreover, it takes care of the harmonics distortion created by the EVs and the household loads by mitigating them locally, thus avoiding the penalty from the utility. For utility, the charging station provides the facility to exchange active and reactive powers with the grid in vehicle-to grid (V2G), grid-to-vehicle (G2V), storage-to-grid (S2G), grid-to-storage (G2S) etc., without compromising the power quality at grid side. Besides, the charging station supports other multi-functional operations such as vehicle-to-home (V2H), storage-to-home (S2H), storage-to-vehicle (S2V), vehicle-to-storage (V2S) and vehicle-to-vehicle (V2V), which improves the operational efficiency of the charging station. In the designed charging station configurations, a single voltage source converter is used to performs various tasks, such as energy management among different energy sources, extraction of maximum power from the PV array, the regulation of voltage and frequency of the DG set etc. The charging station also ensures the maximum power point operation of the renewable energy sources for maximum utilization of them. All the designed charging station configurations are modelled and simulated in the MATLAB/Sumulink environment using the Simpower technol-

ogy blocks and the same has been verified through the laboratory prototype. The performance of the charging stations are discussed in various steady state conditions and the dynamic conditions.

ABSTRACT

ईवी के प्रसार को देखते हुए, मल्टी फंक्शनल ईवी चार्जिंग इंफ्रास्ट्रक्चर का विकास सबसे महत्वपूर्ण है। इसके अलावा, ईवी चार्ज प्रणाली के मूल में अक्षय ऊर्जा का एकीकरण करना महत्वपूर्ण है। इसलिए, इस शोध-प्रबन्ध में पीवी सरणी, पवन ऊर्जा रूपांतरण प्रणाली, स्टोरेज बैटरी, ग्रिड / डीजी सेट आधारित ईवी चार्जिंग स्टेशन के डिजाइन और उस के नियंत्रण पर कार्य किया है। ईवी और घरेलू भार को अबाधित पॉवर प्रदान करने लिए चार्जिंग स्टेशनों को बहु-मोड, जैसे कि स्टैंडअलोन मोड, ग्रिड कनेक्टेड मोड, डीजी सेट कनेक्टेड मोड तथा उनके बीच स्वचालित और सीमलेस मोड परिवर्तन के साथ संचालित किया गया है। इसके अलावा, यह इवीस् और घरेलू भार द्वारा निर्मित हार्मोनिक्स विकृति का ख्याल रखता है तथा उन्हें स्थानीय स्तर पर कम करता है। ग्रिड के लिए, चार्जिंग स्टेशन एक्टिव तथा रिएक्टिव पॉवर एक्सचेंज करने की सुविधा, ग्रिड की पॉवर क्वालिटी से समझौता किए बिना, व्हीकल - टू -ग्रिड, ग्रिड-टू-व्हीकल, स्टोरेज-टू-ग्रिड, ग्रिड-टू-स्टोरेज मोड्स में प्रदान करता है। इसके अलावा, चार्जिंग स्टेशन अन्य बहुआयामी कार्यों जैसे व्हीकल -टू-होम (V2H), स्टोरेज-टू-होम (S2H), स्टोरेज-टू-व्हीकल (S2V), व्हीकल-टू-स्टोरेज (V2S) का समर्थन करता है, जो कि चार्जिंग स्टेशन की परिचालन दक्षता को बढ़ाता है। डिजाइन किए गए चार्जिंग स्टेशन कॉन्फिगरेशन में केवल एक वोल्टेज स्रोत कनवर्टर का उपयोग विभिन्न कार्यों, जैसे विभिन्न ऊर्जा स्रोतों के बीच ऊर्जा प्रबंधन, पीवी सरणी से अधिकतम शक्ति का निष्कर्षण, वोल्टेज का विनियमन और डीजी सेट की आवृत्ति आदि, को करने के लिए किया जाता है। चार्जिंग स्टेशन नवीकरणीय ऊर्जा स्रोतों के अधिकतम शक्ति बिंदु संचालन को भी उनके अधिकतम उपयोग के लिए सुनिश्चित करता है। डिजाइन किए गए सभी चार्जिंग स्टेशन कॉन्फिगरेशनस का MATLAB/Simulink वातावरण में सिमपावर प्रौद्योगिकी ब्लॉकों का उपयोग करके मॉडल और सिमुलेट किया गया है और उसी को प्रयोगशाला प्रोटोटाइप के माध्यम से सत्यापित किया गया है। चार्जिंग स्टेशनों के प्रदर्शन की चर्चा विभिन्न स्थिर स्थितियों और गतिशील स्थितियों में किया गया है।

TABLE OF CONTENTS

| | Page |
|--|-------------|
| Certificate | i |
| Acknowledgments | iii |
| Abstract | vii |
| List of Figures | xli |
| List of Tables | lxxvii |
| List of Abbreviations | lxxxix |
| List of Symbols | lxxxv |
| CHAPTER - I INTRODUCTION | 1 |
| 1.1 General | 1 |
| 1.2 State of Art of Electric Vehicle Charging Stations | 4 |
| 1.3 Scope of Work | 6 |
| 1.3.1 Design, Control and Implementation of Grid/DG Set Connected and Battery Supported Multifunctional EV Charging Station | 9 |
| 1.3.2 Design, Control and Implementation of Solar PV Array Powered, Battery and Grid Supported Multifunctional EV Charging Station | 9 |
| 1.3.3 Design, Control and Implementation of Solar PV Array Powered, Battery and Grid/DG Set Supported Multifunctional EV Charging Station | 10 |
| 1.3.4 Design, Control and Implementation of Solar PV Array and Wind Energy Powered, Battery and Grid Supported Multifunctional EV Charging Station | 11 |
| 1.3.5 Design, Control and Implementation of Solar PV Array And Wind Powered, Battery, and Grid /DG Set Supported Multifunctional EV Charging Station | 11 |
| 1.4 Outlines of Chapters | 12 |
| CHAPTER - II LITERATURE REVIEW | 17 |
| 2.1 General | 17 |
| 2.2 Literature Survey | 17 |
| 2.2.1 Research on Electric Vehicle Charging Infrastructure | 18 |
| 2.2.2 Research on Battery Swap Based Charging Infrastructure | 18 |
| 2.2.3 Research on Renewable Energy Based Charging Infrastructure | 20 |
| 2.2.4 Research on Energy Storage and Second Life of EV Battery | 23 |
| 2.2.5 Research on Home Charging and Residential Microgrid | 23 |
| 2.2.6 Research on Power Quality Aspects of EVs | 24 |
| 2.2.7 Research on Ancillary Services Provided by Charging Infrastructure | 25 |

| | | |
|--|---|----|
| 2.2.8 | Research on Integration of DG Set with Renewable Energy | 26 |
| 2.3 | Identified Research Areas | 28 |
| 2.4 | Conclusions | 29 |
| CHAPTER - III CLASSIFICATION AND CONFIGURATIONS OF EV CHARGING STATIONS | | 31 |
| 3.1 | General | 31 |
| 3.2 | Classification of EV Charging Stations | 31 |
| 3.2.1 | Renewable Energy Sources Based EV Charging Stations | 32 |
| 3.2.2 | Hybrid EV Charging Stations | 32 |
| 3.2.3 | Multiport and Multifunctional EV Charging Stations | 33 |
| 3.2.4 | Multimode Operating EV Charging Stations | 33 |
| 3.3 | Configurations of Multifunctional EV Charging Stations | 34 |
| 3.3.1 | Grid/DG Set Connected and Battery Supported Multifunctional EVCS | 35 |
| 3.3.2 | Solar PV Array Powered, Battery and Grid Supported Multifunctional EV Charging Station | 38 |
| 3.3.3 | Solar PV Array Powered, Battery and Grid/DG Set Supported Multifunctional EV Charging Station | 43 |
| 3.3.4 | Solar PV Array and Wind Powered, Battery and Grid Supported Multifunctional EV Charging Station | 47 |
| 3.3.5 | Solar PV Array and Wind Powered, Battery, and Grid /DG Set Supported Multifunctional EV Charging Station | 52 |
| 3.4 | Conclusions | 57 |
| CHAPTER - IV DESIGN, CONTROL AND IMPLEMENTATION OF GRID/DG SET CONNECTED AND BATTERY SUPPORTED MULTIFUNCTIONAL EV CHARGING STATIONS | | 59 |
| 4.1 | General | 59 |
| 4.2 | Configurations of Grid/DG set Connected and Battery Supported EV Charging Station | 59 |
| 4.2.1 | Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 59 |
| 4.2.2 | Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 60 |
| 4.2.3 | Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bi-directional DC-DC Converter | 61 |
| 4.2.4 | Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bi-directional DC-DC Converter | 61 |

| | | |
|---------|---|----|
| 4.3 | Design of Grid/DG Set Connected and Battery Supported EV Charging Station | 62 |
| 4.3.1 | Design of Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 63 |
| 4.3.1.1 | Design of DC Link Voltage | 63 |
| 4.3.1.2 | Design of DC-Link Capacitor | 64 |
| 4.3.1.3 | Design of Interfacing Inductor | 65 |
| 4.3.1.4 | Design of Ripple Filter | 65 |
| 4.3.1.5 | Design and Selection of Devices of VSC | 66 |
| 4.3.2 | Design of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 67 |
| 4.3.3 | Design of Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bi-directional DC-DC Converter | 68 |
| 4.3.4 | Design of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bi-directional DC-DC Converter | 69 |
| 4.4 | Control of Grid/DG Set and Battery Based EV Charging Station | 70 |
| 4.4.1 | Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 71 |
| 4.4.1.1 | Islanded Mode Control of Single Phase Grid/DG Set Connected EVCS with Battery Directly on DC Link | 71 |
| 4.4.1.2 | Grid/DG Set Connected Mode Control of Single Phase Grid/DG Set based EVCS with Battery Directly on DC Link | 72 |
| 4.4.1.3 | Voltage and Frequency Control in DG Set Connected Mode | 75 |
| 4.4.1.4 | Control for Synchronization and Seamless Mode Switching | 75 |
| 4.4.1.5 | Control of EV1/EV2 for CC/CV Charging and V2G Power Transfer | 77 |
| 4.4.2 | Control of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 79 |
| 4.4.2.1 | Islanded Mode Control of Three Phase Grid/DG Set Connected EVCS with Battery Directly on DC Link | 79 |
| 4.4.2.2 | Grid/DG Set Connected Mode Control of Three Phase Grid/DG Set Based EVCS with Battery Directly on DC Link | 81 |
| 4.4.2.3 | Control for Synchronization and Seamless Mode Switching | 83 |
| 4.4.2.4 | Control of EV1/EV2 for CC/CV Charging and V2G Power Transfer | 84 |
| 4.4.3 | Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bidirectional Converter | 86 |
| 4.4.3.1 | Islanded Mode Control of Single Phase Grid/DG Set Connected EVCS with Battery Through a Bidirectional DC-DC Converter | 86 |

| | | |
|---------|--|-----|
| 4.4.3.2 | Grid/DG Set Connected Mode Control of Single Phase Grid/DG Set based EVCS with Battery Through a Bidirectional DC-DC Converter | 87 |
| 4.4.3.3 | Voltage and Frequency Control in DG Set Connected Mode | 90 |
| 4.4.3.4 | Control for Synchronization and Seamless Mode Switching | 91 |
| 4.4.3.5 | Control of Bi-directional Converter of Storage Battery | 92 |
| 4.4.3.6 | Control of EV1/EV2 for CC/CV Charging and V2G Power Transfer | 94 |
| 4.4.4 | Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bidirectional Converter | 95 |
| 4.4.4.1 | Islanded Mode Control of Three Phase Grid/DG Set Connected EVCS with Battery Through a Bidirectional DC-DC Converter | 95 |
| 4.4.4.2 | Grid/DG Set Connected Mode Control of Three Phase Grid/DG Set based EVCS with Battery Through a Bidirectional DC-DC Converter | 96 |
| 4.4.4.3 | Control of Bi-directional Converter of Storage Battery | 100 |
| 4.4.4.4 | Control for Synchronization and Seamless Mode Switching | 101 |
| 4.5 | MATLAB Based Modelling and Simulation of Grid/DG Set Connected and Battery Supported EV Charging Station | 102 |
| 4.5.1 | MATLAB Modelling of Single Phase Grid/DG Set Connected EV Charging Station with Battery Directly on DC Link | 103 |
| 4.5.2 | MATLAB Modelling of Three Phase Grid/DG Set Connected EV Charging Station with Battery Directly on DC Link | 104 |
| 4.5.3 | MATLAB Modelling of Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bidirectional Converter | 105 |
| 4.5.4 | MATLAB Modelling of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bidirectional Converter | 105 |
| 4.6 | Hardware Implementation of Grid/DG Set Connected and Battery Supported EV Charging Station | 106 |
| 4.6.1 | Hardware Configuration of Digital Controller dSPACE-1006 | 107 |
| 4.6.2 | Interfacing Circuit for Hall Effect Voltage Sensors | 109 |
| 4.6.3 | Interfacing Circuit for Hall Effect Current Sensors | 109 |
| 4.6.4 | Interfacing circuits of Gating Signal Optical Isolation and Signal Conditioning | 109 |
| 4.7 | Results and Discussion | 111 |
| 4.7.1 | Performance of Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 112 |
| 4.7.1.1 | Simulated Performance of Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 112 |

| | | |
|---|--|-----|
| 4.7.1.2 | Experimental Performance of Single Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 115 |
| 4.7.2 | Performance of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 122 |
| 4.7.2.1 | Simulated Performance of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 123 |
| 4.7.2.2 | Experimental Performance of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Directly on DC Link | 127 |
| 4.7.3 | Performance of Single Phase Grid/DG Set Connected EV Charging Station with Battery a Through Bidirectional DC-DC Converter | 136 |
| 4.7.3.1 | Simulated Performance of Single Phase Grid/DG Set Connected EV Charging Station with Battery a Through Bidirectional DC-DC Converter | 136 |
| 4.7.3.2 | Experimental Performance of Single Phase Grid/DG Set Connected EV Charging Station with Battery Through a Bidirectional DC-DC Converter | 138 |
| 4.7.4 | Performance of Three Phase Grid/DG Set Connected EV Charging Station with Battery Through a Bidirectional DC-DC Converter | 145 |
| 4.7.4.1 | Simulated Performance of Three Phase Grid/DG Set Connected EV Charging Station with Support of Battery Through a Bidirectional DC-DC Converter | 145 |
| 4.7.4.2 | Experimental Performance of Three Phase Grid/DG Set Connected EV Charging Station with Battery Through a Bidirectional DC-DC Converter | 148 |
| 4.8 | Conclusions | 157 |
| CHAPTER - V DESIGN, CONTROL AND IMPLEMENTATION OF SOLAR PV ARRAY POWERED, BATTERY AND GRID SUPPORTED MULTIFUNCTIONAL EV CHARGING STATION | | 159 |
| 5.1 | General | 159 |
| 5.2 | Configurations of Solar PV Array Powered, Battery and Grid Supported Multifunctional EV Charging Station | 159 |
| 5.2.1 | Single Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 160 |
| 5.2.2 | Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 161 |

| | | |
|---------|--|-----|
| 5.2.3 | Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 162 |
| 5.2.4 | Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 163 |
| 5.2.5 | Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 164 |
| 5.2.6 | Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 165 |
| 5.3 | Design of Solar PV Array Powered, Battery and Grid Supported Multifunctional EV Charging Station | 166 |
| 5.3.1 | Design of Single Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 166 |
| 5.3.1.1 | Design and Selection of PV Array | 166 |
| 5.3.2 | Design of Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 167 |
| 5.3.3 | Design of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 168 |
| 5.3.4 | Design of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 169 |
| 5.3.5 | Design of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 170 |
| 5.3.6 | Design of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 171 |
| 5.4 | Control of Solar PV Array Powered, Battery and Grid Supported Multifunctional EV Charging Station | 172 |
| 5.4.1 | Control of Single Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 172 |
| 5.4.1.1 | Islanded Mode Control of Single Phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 173 |

| | | |
|---------|--|-----|
| 5.4.1.2 | Grid Connected Mode Control of Single Phase EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 174 |
| 5.4.1.3 | Control for Synchronization and Seamless Mode Switching | 180 |
| 5.4.1.4 | Bi-directional DC-DC Converter Control of Storage Battery | 181 |
| 5.4.1.5 | Control of EV1/EV2 for CC/CV Charging and V2G Power Transfer | 182 |
| 5.4.2 | Control of Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 184 |
| 5.4.2.1 | Islanded Mode Control of Three Phase EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 184 |
| 5.4.2.2 | Grid Connected Mode Control of Three Phase EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 185 |
| 5.4.2.3 | Control for Synchronization and Seamless Mode Switching | 190 |
| 5.4.2.4 | Bi-directional DC-DC Converter Control of Storage Battery | 191 |
| 5.4.2.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 193 |
| 5.4.3 | Control of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 194 |
| 5.4.3.1 | Islanded Mode Control of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 195 |
| 5.4.3.2 | GCM Control of Single Phase Grid Connected EVCS with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 196 |
| 5.4.3.3 | Control for Synchronization and Seamless Mode Switching | 198 |
| 5.4.3.4 | MPPT and Boost Converter Control of Solar PV Array | 199 |
| 5.4.3.5 | Bi-directional DC-DC Converter Control of Storage Battery | 200 |
| 5.4.3.6 | Control of EV1/EV2 for CC/CV Charging and V2G Power Transfer | 200 |
| 5.4.4 | Control of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 201 |

| | | |
|---------|--|-----|
| 5.4.4.1 | Islanded Mode Control of Three Phase Grid Connected EVCS with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 202 |
| 5.4.4.2 | Grid Connected Mode Control of Three Phase EVCS with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 203 |
| 5.4.4.3 | Control for Synchronization and Seamless Mode Switching | 206 |
| 5.4.4.4 | MPPT and Boost Converter Control of Solar PV Array | 207 |
| 5.4.4.5 | Bi-directional DC-DC Converter Control of Storage Battery | 208 |
| 5.4.4.6 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 210 |
| 5.4.5 | Control of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 211 |
| 5.4.5.1 | Islanded Mode Control of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 211 |
| 5.4.5.2 | Grid Connected Mode Control of Single Phase Grid Connected EVCS with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 212 |
| 5.4.5.3 | Control for Synchronization and Seamless Mode Switching | 214 |
| 5.4.5.4 | MPPT and Boost Converter Control of Solar PV Array | 215 |
| 5.4.5.5 | Control of EV1/EV2 for CC/CV Charging and V2G Power Transfer | 215 |
| 5.4.6 | Control of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 215 |
| 5.4.6.1 | Islanded Mode Control of Three Phase EVCS with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 216 |
| 5.4.6.2 | Grid Connected Mode Control of Three Phase EVCS with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 217 |
| 5.4.6.3 | Control for Synchronization and Seamless Mode Switching | 220 |
| 5.4.6.4 | MPPT and Boost Converter Control of Solar PV Array | 220 |
| 5.4.6.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 221 |
| 5.5 | MATLAB Based Modelling and Simulation of Solar PV Array Powered, Battery and Grid Supported Multifunctional EV Charging Station | 221 |
| 5.5.1 | MATLAB Modelling of Single Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 221 |

| | | |
|---------|--|-----|
| 5.5.2 | MATLAB Modelling of Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 222 |
| 5.5.3 | MATLAB Modelling of Single Phase EVCS with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 223 |
| 5.5.4 | MATLAB Modelling of Three Phase EVCS with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 224 |
| 5.5.5 | MATLAB Modelling of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 224 |
| 5.5.6 | MATLAB Modelling of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 225 |
| 5.6 | Hardware Implementation of Solar PV Array Powered, Battery and Grid Supported Multifunctional EV Charging Station | 226 |
| 5.7 | Results and Discussion | 227 |
| 5.7.1 | Performance of Single Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 228 |
| 5.7.1.1 | Simulated performance of single phase grid connected EV charging station with solar PV array directly on DC Link and battery through a Bi-directional DC-DC converter | 228 |
| 5.7.1.2 | Experimental performance of single phase grid connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 230 |
| 5.7.2 | Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bidirectional DC-DC Converter | 241 |
| 5.7.2.1 | Simulated Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bidirectional DC-DC Converter | 241 |
| 5.7.2.2 | Experimental Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bidirectional DC-DC Converter | 247 |

| | | |
|---------|--|-----|
| 5.7.3 | Performance of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 255 |
| 5.7.3.1 | Simulated Performance of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 256 |
| 5.7.3.2 | Experimental Performance of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 259 |
| 5.7.4 | Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 266 |
| 5.7.4.1 | Simulated Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 266 |
| 5.7.4.2 | Experimental Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bidirectional DC-DC Converter | 270 |
| 5.7.5 | Performance of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 278 |
| 5.7.5.1 | Simulated performance of single phase grid connected EV charging station with solar PV array through a boost converter and battery directly on DC link | 279 |
| 5.7.5.2 | Experimental performance of single phase grid connected EV charging station with solar PV array through a boost converter and battery directly on DC link | 282 |
| 5.7.6 | Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 289 |
| 5.7.6.1 | Simulated Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 289 |
| 5.7.6.2 | Experimental Performance of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 292 |
| 5.8 | Conclusions | 301 |

| | |
|---|------------|
| CHAPTER - VI DESIGN, CONTROL AND IMPLEMENTATION OF SOLAR PV ARRAY POWERED, BATTERY AND GRID/DG SET SUPPORTED MULTIFUNCTIONAL EV CHARGING STATION | 303 |
| 6.1 General | 303 |
| 6.2 Configurations of Solar PV Array Powered, Battery and Grid/DG Set Supported Multifunctional EVCS | 303 |
| 6.2.1 Configuration of Single Phase Grid/DG Set Based EVCS with PV Array Directly on DC-Link and Storage Battery Through a Bidirectional DC-DC Converter | 304 |
| 6.2.2 Configuration of Three Phase Grid/DG Set Based EVCS with PV Array Directly on DC-Link and Storage Battery Through a Bidirectional DC-DC Converter | 304 |
| 6.2.3 Configuration of Single Phase Grid/DG Set Based EV Charging Station with PV Array Through a Boost Converter and Storage Battery Through a Bidirectional DC-DC Converter | 305 |
| 6.2.4 Configuration of Three Phase Grid/DG Set Based EV Charging Station with PV Array Through a Boost Converter and Storage Battery Through a Bidirectional DC-DC Converter | 306 |
| 6.2.5 Configuration of Single Phase Grid/DG Set Based EV Charging Station with PV Array Through a Boost Converter and Storage Battery Directly on DC Link | 307 |
| 6.2.6 Configuration of Three Phase Grid/DG Set Based EV Charging Station with PV Array Through a Boost Converter and Storage Battery Directly on DC Link | 308 |
| 6.3 Design of Solar PV Array Powered, Battery and Grid/DG Set Supported Multifunctional EV Charging Station | 309 |
| 6.3.1 Design of Single Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 309 |
| 6.3.2 Design of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 310 |
| 6.3.3 Design of Single Phase Grid/DG Set Connected EV Charging Station with PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 311 |
| 6.3.4 Design of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 312 |

| | | |
|---------|--|-----|
| 6.3.5 | Design of Single Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 313 |
| 6.3.6 | Design of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 314 |
| 6.4 | Control of PV Array Powered, Battery and Grid/DG Set Supported Multifunctional EVCS | 315 |
| 6.4.1 | Control of Single Phase Grid/DG Set Connected EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 315 |
| 6.4.1.1 | Islanded Mode Control of Single Phase Grid/DG Set Connected EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 315 |
| 6.4.1.2 | Grid/DG Set Connected Mode Control of Single Phase Grid/DG Set based EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 316 |
| 6.4.1.3 | Control for Synchronization and Seamless Mode Switching | 321 |
| 6.4.1.4 | Control of Bi-directional Converter of Storage Battery | 322 |
| 6.4.1.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 323 |
| 6.4.2 | Control of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 324 |
| 6.4.2.1 | IM Control of Three Phase Grid/DG Set Connected EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 324 |
| 6.4.2.2 | GCM/DGCM Control of Three Phase EVCS with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 325 |
| 6.4.2.3 | Control for Synchronization and Seamless Mode Switching | 329 |
| 6.4.2.4 | Control of Bi-directional Converter of Storage Battery | 330 |
| 6.4.2.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 331 |
| 6.4.3 | Control of Single Phase Grid/DG Set Connected EVCS with Solar PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 332 |
| 6.4.3.1 | IM Control of Single Phase Grid/DG Set Connected EVCS with Solar PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 333 |

| | | |
|---------|---|-----|
| 6.4.3.2 | GCM Control of Single Phase Grid/DG Set Connected EVCS with Solar PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 333 |
| 6.4.3.3 | Control for Synchronization and Seamless Mode Switching | 337 |
| 6.4.3.4 | MPPT and Boost Converter Control of Solar PV Array | 337 |
| 6.4.3.5 | Control of Bi-directional Converter of Storage Battery | 338 |
| 6.4.3.6 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 338 |
| 6.4.4 | Control of Three Phase Grid/DG Set Connected EVCS with Solar PV Array Through a Boost converter and Battery Through a Bidirectional DC-DC Converter | 338 |
| 6.4.4.1 | IM Control of Three Phase EVCS with Solar PV Array Through a Boost Converter and and Battery Through a Bidirectional DC-DC Converter | 339 |
| 6.4.4.2 | GCM/DGCM Control of Three Phase EVCS with Solar PV Array Through a Boost converter and Battery Through a Bidirectional DC-DC Converter | 339 |
| 6.4.4.3 | Control for Synchronization and Seamless Mode Switching | 340 |
| 6.4.4.4 | MPPT and Boost Converter Control of Solar PV Array | 340 |
| 6.4.4.5 | Control of Bi-directional Converter of Storage Battery | 340 |
| 6.4.4.6 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 341 |
| 6.4.5 | Control of Single Phase Grid/DG Set Connected EVCS with Solar PV Array Through a Boost converter and and Battery Directly on DC Link | 341 |
| 6.4.5.1 | Islanded Mode Control of Single Phase Grid/DG Set Connected EVCS with Solar PV Array Through a Boost converter and and Battery Directly on DC Link | 341 |
| 6.4.5.2 | Grid/DG Set Connected Mode Control of Single Phase EVCS with Solar PV Array Through a Boost converter and and Battery Directly on DC link | 343 |
| 6.4.5.3 | Voltage and Frequency control of Single Phase DG Set | 345 |
| 6.4.5.4 | Control for Synchronization and Seamless Mode Switching | 345 |
| 6.4.5.5 | MPPT and Boost Converter Control of Solar PV Array | 346 |
| 6.4.5.6 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 346 |
| 6.4.6 | Control of Three Phase Grid/DG Set Connected EVCS with Solar PV Array Through a Boost converter and Battery Directly on DC Link | 346 |
| 6.4.6.1 | IM Control of Three Phase EVCS with Solar PV Array Through a Boost converter and Battery Directly on DC Link | 347 |

| | | |
|---------|---|-----|
| 6.4.6.2 | GCM Control of Three Phase EVCS with Solar PV Array Through a Boost converter and and Battery Directly on DC Link | 348 |
| 6.4.6.3 | Control for Synchronization and Seamless Mode Switching | 350 |
| 6.4.6.4 | MPPT and Boost Converter Control of Solar PV Array | 350 |
| 6.4.6.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 351 |
| 6.5 | MATLAB Based Modelling and Simulation of Solar PV Array Powered, Battery and Grid/DG set Based Multifunctional EV Charging Station | 351 |
| 6.5.1 | MATLAB Modelling of Single Phase Grid/DG Set Based EVCS with PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 351 |
| 6.5.2 | MATLAB Modelling of Three Phase Grid/DG Set Based EVCS with PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 352 |
| 6.5.3 | MATLAB Modelling of Single Phase Grid/DG Set Based EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 352 |
| 6.5.4 | MATLAB Modelling of Three Phase Grid/DG Set Based EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 353 |
| 6.5.5 | MATLAB Modelling of Single Phase Grid/DG Set Based EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 354 |
| 6.5.6 | MATLAB Modelling of Three Phase Grid/DG Set Based EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 355 |
| 6.6 | Hardware Implementation of Solar PV Array Powered, Battery and Grid/DG Set Supported Multifunctional EV Charging Station | 355 |
| 6.7 | Results and Discussion | 356 |
| 6.7.1 | Performance of Single Phase Grid/DG Set Connected EV Charging Station with PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 357 |
| 6.7.1.1 | Simulated Performance of Single Phase Grid/DG Set Connected EV Charging Station with PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 357 |
| 6.7.1.2 | Experimental Performance of Single Phase Grid/DG Set Connected EV Charging Station with PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 360 |

| | | |
|---------|---|-----|
| 6.7.2 | Performance of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 370 |
| 6.7.2.1 | Simulated Performance of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 370 |
| 6.7.2.2 | Experimental Performance of Three Phase Grid/DG Set Connected EVCS with PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 376 |
| 6.7.3 | Performance of Single Phase Grid/DG Set Based EV Charging Station with PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 387 |
| 6.7.3.1 | Simulated Performance of Single Phase Grid/DG Set Connected EV Charging Station with PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 387 |
| 6.7.3.2 | Experimental Performance of Single Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 391 |
| 6.7.4 | Performance of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 399 |
| 6.7.4.1 | Simulated Performance of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 399 |
| 6.7.4.2 | Experimental Performance of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through Boost Converter and Battery Through a Bi-directional DC-DC Converter | 403 |
| 6.7.5 | Performance of Single Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through a Boost converter and and Battery Directly on DC Link | 412 |
| 6.7.5.1 | Simulated Performance of Single Phase Grid/DG Set Connected EV Charging Station with PV Array Through a Boost converter and Battery Directly on DC Link | 412 |
| 6.7.5.2 | Experimental Performance of Single Phase Grid/DG Set Connected EV Charging Station with PV Array Through a Boost converter and and Battery Directly on DC Link | 416 |

| | | |
|---|---|-----|
| 6.7.6 | Performance of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through Boost Converter and Battery Directly on DC Link | 427 |
| 6.7.6.1 | Simulated Performance of Three Phase Grid/DG Set Connected EV Charging Station with PV Array Through Boost Converter and Battery Directly on DC Link | 427 |
| 6.7.6.2 | Experimental Performance of Three Phase Grid/DG Set Connected EV Charging Station with PV Array Through Boost Converter and Battery Directly on DC Link | 431 |
| 6.8 | Conclusions | 442 |
| CHAPTER - VII DESIGN, CONTROL AND IMPLEMENTATION OF SOLAR PV ARRAY-WIND POWERED, BATTERY AND GRID SUPPORTED MULTIFUNCTIONAL EV CHARGING STATIONS | | 443 |
| 7.1 | General | 443 |
| 7.2 | Configurations of Solar PV Array and Wind Powered, Battery and Grid Supported Multifunctional EVCS | 443 |
| 7.2.1 | Configuration of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 443 |
| 7.2.2 | Configuration of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 444 |
| 7.2.3 | Configuration of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 445 |
| 7.2.4 | Configuration of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 446 |
| 7.2.5 | Configuration of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 447 |
| 7.2.6 | Configuration of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 448 |

| | | |
|---------|---|-----|
| 7.3 | Design of Solar PV Array-Wind Powered, Battery and Grid Supported Multifunctional EVCS | 449 |
| 7.3.1 | Design of Single Phase Grid Connected EV Charging Station with WECS Through Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 449 |
| 7.3.2 | Design of Three Phase Grid Connected EV Charging Station with WECS Through Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 450 |
| 7.3.3 | Design of Single Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 451 |
| 7.3.4 | Design of Three Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 452 |
| 7.3.5 | Design of Single Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 453 |
| 7.3.6 | Design of Three Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 454 |
| 7.4 | Control of Solar PV Array-Wind Powered, Battery and Grid Supported Multifunctional EVCS | 455 |
| 7.4.1 | Control of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 456 |
| 7.4.1.1 | Islanded Mode Control of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 456 |
| 7.4.1.2 | Grid Connected Mode Control of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 457 |
| 7.4.1.3 | Control for Synchronization and Seamless Mode Switching | 461 |
| 7.4.1.4 | Control of Bi-directional Converter of Storage Battery | 462 |
| 7.4.1.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 463 |

| | | |
|---------|---|-----|
| 7.4.1.6 | Boost Converter and MPPT Control of WECS | 464 |
| 7.4.2 | Control of Three Phase EVCS Powered By WECS Through a Boost Converter, PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 465 |
| 7.4.2.1 | Islanded Mode Control of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 466 |
| 7.4.2.2 | Grid Connected Mode Control of Three Phase EV Charging Station Powered By WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 466 |
| 7.4.2.3 | Control for Synchronization and Seamless Mode Switching | 470 |
| 7.4.2.4 | Control of Bi-directional Converter of Storage Battery | 471 |
| 7.4.2.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 472 |
| 7.4.2.6 | MPPT Control of WECS | 473 |
| 7.4.3 | Control of Single Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 473 |
| 7.4.3.1 | Islanded Mode Control of Single Phase EV Charging Station Powered by Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 474 |
| 7.4.3.2 | Grid Connected Mode Control of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 475 |
| 7.4.3.3 | Control for Synchronization and Seamless Mode Switching | 477 |
| 7.4.3.4 | Control of Bi-directional Converter of Storage Battery | 478 |
| 7.4.3.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 480 |
| 7.4.3.6 | Control of Boost Converter of PV Array | 480 |
| 7.4.3.7 | MPPT Control of WECS | 481 |
| 7.4.4 | Control of Three Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 481 |

| | | |
|---------|---|-----|
| 7.4.4.1 | Islanded Mode Control of Three Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 482 |
| 7.4.4.2 | Grid Connected Mode Control of Three Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 482 |
| 7.4.4.3 | Control for Synchronization and Seamless Mode Switching | 485 |
| 7.4.4.4 | Control of Bi-directional Converter of Storage battery | 485 |
| 7.4.4.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 486 |
| 7.4.4.6 | Control of Boost Converter of PV Array | 487 |
| 7.4.4.7 | MPPT Control of WECS | 488 |
| 7.4.5 | Control of Single Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Directly on DC link | 488 |
| 7.4.5.1 | Islanded Mode Control of Single Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Directly on DC link | 489 |
| 7.4.5.2 | Grid Connected Mode Control of Single Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Directly on DC link | 489 |
| 7.4.5.3 | Control for Synchronization and Seamless Mode Switching | 492 |
| 7.4.5.4 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 493 |
| 7.4.5.5 | Control of Boost Converter of PV Array | 493 |
| 7.4.5.6 | MPPT Control of WECS | 493 |
| 7.4.6 | Control of Three Phase EV Charging Station Powered By WECS Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Directly on DC link | 494 |
| 7.4.6.1 | IM Control of Three Phase EV Charging Station Powered By WECS Through a Boost Converter, PV Array through a Boost Converter and Battery Directly on DC Link | 494 |
| 7.4.6.2 | GCM Control of Three Phase EVCS Powered By WECS Through a Boost Converter, PV Array Through a Boost Converter and Battery Directly on DC link | 495 |
| 7.4.6.3 | Control for Synchronization and Seamless Mode Switching | 498 |

| | | |
|---------|--|-----|
| 7.4.6.4 | MPPT and Boost Converter Control of PV Array | 498 |
| 7.4.6.5 | MPPT and Boost Converter Control of WECS | 498 |
| 7.5 | MATLAB Based Modelling and Simulation of PV array, WECS Based Grid Connected and Battery Supported EV Charging Station | 499 |
| 7.5.1 | MATLAB Modelling of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 499 |
| 7.5.2 | MATLAB Modelling of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 499 |
| 7.5.3 | MATLAB Modelling of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 501 |
| 7.5.4 | MATLAB Modelling of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a boost Converter and Battery Through a Bi-directional DC-DC Converter | 502 |
| 7.5.5 | MATLAB Modelling of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 503 |
| 7.5.6 | MATLAB Modelling of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 503 |
| 7.6 | Results and Discussion | 504 |
| 7.6.1 | Performance of Single Phase EV Charging Station Powered By WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 504 |
| 7.6.1.1 | Simulated Performance of Single Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 505 |
| 7.6.1.2 | Experimental Performance of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 509 |
| 7.6.2 | Performance of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 518 |

| | | |
|---------|--|-----|
| 7.6.2.1 | Simulated Performance of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 518 |
| 7.6.2.2 | Experimental Performance of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 521 |
| 7.6.3 | Performance of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 529 |
| 7.6.3.1 | Simulated Performance of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 529 |
| 7.6.3.2 | Experimental Performance of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 535 |
| 7.6.4 | Performance of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 543 |
| 7.6.4.1 | Simulated Performance of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 543 |
| 7.6.4.2 | Experimental Performance of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 548 |
| 7.6.5 | Performance of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 556 |
| 7.6.5.1 | Simulated Performance of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 556 |

| | | |
|--|---|---------|
| 7.6.5.2 | Experimental Performance of Single Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 559 |
| 7.6.6 | Performance of Three Phase EVCS Powered By WECS Through a Boost Converter, PV Array Through a Boost Converter and Battery Directly on DC link | 567 |
| 7.6.6.1 | Simulated Performance of Three Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 567 |
| 7.6.6.2 | Experimental Performance of Three Phase Grid Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 571 |
| 7.7 | Conclusions | 579 |
| CHAPTER - VIII DESIGN, CONTROL AND IMPLEMENTATION OF SOLAR PV ARRAY AND WIND POWERED, BATTERY AND GRID/DG SET SUPPORTED MULTIFUNCTIONAL EV CHARGING STATION | | 581 |
| 8.1 | General | 581 |
| 8.2 | Configurations of Solar PV Array and Wind Powered, Battery and Grid/DG set Supported Multifunctional EVCS | 581 |
| 8.2.1 | Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 581 |
| 8.2.2 | Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 583 |
| 8.2.3 | Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 584 |
| 8.2.4 | Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 585 |
| 8.2.5 | Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 586 |

| | | |
|---------|---|-----|
| 8.2.6 | Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 587 |
| 8.3 | Design of Solar PV Array and Wind Powered, Battery and Grid/DG Set Supported Multifunctional EVCS | 588 |
| 8.3.1 | Design of Single Phase Grid/DG Set Connected EV Charging Station with WECS Through Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 588 |
| 8.3.2 | Design of Three Phase Grid/DG Set Connected EV Charging Station with WECS Through Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 589 |
| 8.3.3 | Design of Single Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 590 |
| 8.3.4 | Design of Three Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 591 |
| 8.3.5 | Design of Single Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 592 |
| 8.3.6 | Design of Three Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 593 |
| 8.4 | Control of Solar PV Array and Wind Powered, Battery and Grid/DG Set Supported Multifunctional EV Charging Station | 594 |
| 8.4.1 | Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 595 |
| 8.4.1.1 | Islanded Mode Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 595 |
| 8.4.1.2 | Grid/DG Set Connected Mode Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 596 |

| | | |
|---------|---|-----|
| 8.4.1.3 | Control for Synchronization and Seamless Mode Switching | 598 |
| 8.4.1.4 | Control of Bi-directional Converter of Storage Battery | 599 |
| 8.4.1.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 601 |
| 8.4.1.6 | MPPT and Boost Converter Control of WECS | 602 |
| 8.4.2 | Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 602 |
| 8.4.2.1 | IM Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 602 |
| 8.4.2.2 | GCM/DGCM Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 603 |
| 8.4.2.3 | Control for Synchronization and Seamless Mode Switching | 607 |
| 8.4.2.4 | Control of Bi-directional Converter of Storage Battery | 607 |
| 8.4.2.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 607 |
| 8.4.2.6 | MPPT and Boost Converter Control of WECS | 607 |
| 8.4.3 | Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 608 |
| 8.4.3.1 | IM Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 608 |
| 8.4.3.2 | GCM/DGCM Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 609 |
| 8.4.3.3 | Control for Synchronization and Seamless Mode Switching | 609 |
| 8.4.3.4 | Control of Bi-directional Converter of Storage Battery | 609 |
| 8.4.3.5 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 610 |
| 8.4.3.6 | Boost Converter and MPPT control of PV Array | 610 |
| 8.4.3.7 | Boost Converter and MPPT control of WECS | 611 |

| | | |
|---------|--|-----|
| 8.4.4 | Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 611 |
| 8.4.4.1 | IM Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 611 |
| 8.4.4.2 | GCM/DGCM Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 612 |
| 8.4.4.3 | Control for Synchronization and Seamless Mode Switching | 613 |
| 8.4.4.4 | Control of Bi-directional Converter of Storage Battery | 613 |
| 8.4.4.5 | Control of EV1/EV2 for CC/CV Charging and V2G Power Transfer | 614 |
| 8.4.4.6 | Boost Converter and MPPT control of PV Array | 614 |
| 8.4.4.7 | Boost Converter and MPPT control of WECS | 614 |
| 8.4.5 | Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 614 |
| 8.4.5.1 | IM Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 615 |
| 8.4.5.2 | GCM Control of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 616 |
| 8.4.5.3 | Control for Synchronization and Seamless Mode Switching | 617 |
| 8.4.5.4 | MPPT and Boost Converter Control of Solar PV Array | 618 |
| 8.4.5.5 | MPPT and Boost Converter Control of WECS | 618 |
| 8.4.5.6 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 618 |
| 8.4.6 | Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 618 |
| 8.4.6.1 | IM Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 619 |

| | | |
|---------|---|-----|
| 8.4.6.2 | GCM Control of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 620 |
| 8.4.6.3 | Control for Synchronization and Seamless Mode Switching | 622 |
| 8.4.6.4 | MPPT and Boost Converter Control of Solar PV Array | 622 |
| 8.4.6.5 | MPPT Control of WECS | 622 |
| 8.4.6.6 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 623 |
| 8.5 | MATLAB Based Modelling and Simulation of Solar PV Array and WECS Powered, Battery and Grid/DG set Supported EVCS | 623 |
| 8.5.1 | MATLAB Modelling of Single Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 623 |
| 8.5.2 | MATLAB Modelling of Three Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 624 |
| 8.5.3 | MATLAB Modelling of Single Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 625 |
| 8.5.4 | MATLAB Modelling of Three Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 625 |
| 8.5.5 | MATLAB Modelling of Single Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 626 |
| 8.5.6 | MATLAB Modelling of Three Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 626 |
| 8.6 | Hardware Implementation of Solar PV Array and WECS Powered, Battery and Grid/DG set Supported EV Charging Station | 627 |
| 8.7 | Results and Discussion | 629 |
| 8.7.1 | Performance of Single Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 629 |

| | | |
|---------|---|-----|
| 8.7.1.1 | Simulated Performance of Single Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 630 |
| 8.7.1.2 | Experimental Performance of Single Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 633 |
| 8.7.2 | Performance of Three Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 642 |
| 8.7.2.1 | Simulated Performance of Three Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 643 |
| 8.7.2.2 | Experimental Performance of Three Phase Grid/DG set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Directly on DC Link and Battery Through a Bi-directional DC-DC Converter | 647 |
| 8.7.3 | Performance of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 658 |
| 8.7.3.1 | Simulated Performance of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 659 |
| 8.7.3.2 | Experimental Performance of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 663 |
| 8.7.4 | Performance of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 671 |

| | | |
|---|--|-----|
| 8.7.4.1 | Simulated Performance of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 671 |
| 8.7.4.2 | Experimental Performance of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 676 |
| 8.7.5 | Performance of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 683 |
| 8.7.5.1 | Simulated Performance of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 683 |
| 8.7.5.2 | Experimental Performance of Single Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 688 |
| 8.7.6 | Performance of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 697 |
| 8.7.6.1 | Simulated Performance of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 698 |
| 8.7.6.2 | Experimental Performance of Three Phase Grid/DG Set Connected EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC Link | 701 |
| 8.8 | Conclusions | 711 |
| CHAPTER - IX MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK | | 713 |
| 9.1 | General | 713 |
| 9.2 | Main Conclusions | 713 |

| | |
|----------------------------------|-----|
| 9.3 Suggestions for Further Work | 718 |
| REFERENCES | 720 |
| LIST OF PUBLICATIONS | 745 |
| BIO-DATA | 749 |

LIST OF FIGURES

| | | |
|-----------|---|----|
| Fig. 3.1 | Tree diagram of configurations of charging stations | 35 |
| Fig. 3.2 | Single phase grid/DG set connected EVCS with directly connected battery | 36 |
| Fig. 3.3 | Three phase grid/DG set based EVCS with directly connected battery | 36 |
| Fig. 3.4 | Single phase grid/DG set connected EVCS with battery through a bidirectional DC-DC converter | 37 |
| Fig. 3.5 | Three phase grid/DG set connected EVCS with battery through a bidirectional DC-DC converter | 37 |
| Fig. 3.6 | Single phase grid connected EVCS with storage battery through a bidirectional converter and PV array without boost converter | 39 |
| Fig. 3.7 | Three phase grid connected EVCS with storage battery through a bidirectional converter and PV array without boost converter | 40 |
| Fig. 3.8 | Single phase grid connected EVCS with storage battery through a bidirectional converter and PV array with boost converter | 40 |
| Fig. 3.9 | Three phase grid connected EVCS with storage battery through a bidirectional converter and PV array with boost converter | 40 |
| Fig. 3.10 | Single phase grid connected EVCS with directly connected storage battery and PV array with boost converter | 41 |
| Fig. 3.11 | Three phase grid connected EVCS with directly connected storage battery and PV array with boost converter | 41 |
| Fig. 3.12 | Single phase grid/DG set connected EVCS with storage battery through a bidirectional converter and PV array without boost converter | 44 |
| Fig. 3.13 | Three phase grid/DG set connected EVCS with storage battery through a bidirectional converter and PV array without boost converter | 44 |
| Fig. 3.14 | Single phase grid/DG set connected EVCS with storage battery through a bidirectional converter and PV array with boost converter | 44 |
| Fig. 3.15 | Three phase grid/DG set connected EVCS with storage battery through a bidirectional converter and PV array with boost converter | 45 |
| Fig. 3.16 | Single phase grid/DG set connected EVCS with directly connected storage battery and PV array with boost converter | 45 |
| Fig. 3.17 | Three phase grid/DG set connected EVCS with directly connected storage battery and PV array with boost converter | 45 |
| Fig. 3.18 | Single phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 48 |
| Fig. 3.19 | Three phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 49 |

| | | |
|-----------|--|----|
| Fig. 3.20 | Single phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 49 |
| Fig. 3.21 | Three phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 49 |
| Fig. 3.22 | Single phase grid connected wind powered EVCS directly connected storage battery and PV array with boost converter | 50 |
| Fig. 3.23 | Three phase grid connected wind powered EVCS directly connected storage battery and PV array with boost converter | 50 |
| Fig. 3.24 | Single phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 53 |
| Fig. 3.25 | Three phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 53 |
| Fig. 3.26 | Single phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 53 |
| Fig. 3.27 | Three phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 54 |
| Fig. 3.28 | Single phase grid/DG set connected wind powered EVCS directly connected storage battery and PV array with boost converter | 54 |
| Fig. 3.29 | Three phase grid/DG set connected wind powered EVCS directly connected storage battery and PV array with boost converter | 54 |
| Fig. 4.1 | Single phase grid/DG set connected EVCS with directly connected battery | 60 |
| Fig. 4.2 | Three phase grid/DG set based EVCS with directly connected battery | 61 |
| Fig. 4.3 | Single phase grid/DG set connected EVCS with battery through a bidirectional DC-DC converter | 62 |
| Fig. 4.4 | Three phase grid/DG set connected EVCS with battery through a bidirectional DC-DC converter | 62 |
| Fig. 4.5 | IM and GCM/DGCM control of single phase EVCS with battery directly on DC link | 76 |
| Fig. 4.6 | Bidirectional DC-DC converter control for EVs | 78 |
| Fig. 4.7 | IM, GCM/DGCM control of Three phase EVCS with battery directly on DC link | 80 |
| Fig. 4.8 | Control of bidirectional converter for EV charging/discharging in three phase EVCS | 85 |
| Fig. 4.9 | IM and GCM/DGCM control of single phase EVCS with battery through a bidirectional DC-DC converter | 90 |
| Fig. 4.10 | Bidirectional DC-DC converter control for storage battery | 92 |

| | | |
|-----------|---|-----|
| Fig. 4.11 | Bidirectional DC-DC converter control for EVs | 94 |
| Fig. 4.12 | IM, GCM/DGCM control of Three phase EVCS with battery directly on DC link | 97 |
| Fig. 4.13 | Bidirectional DC-DC converter control for storage battery | 100 |
| Fig. 4.14 | MATLAB Model of Single Phase Grid/DG set Connected EV Charging Station with Battery Directly on DC link | 103 |
| Fig. 4.15 | MATLAB Model of Three Phase Grid/DG set Connected EV Charging Station with Battery Directly on DC link, (a) complete model, (b) VSC and battery connections | 104 |
| Fig. 4.16 | MATLAB Model of Single Phase Grid/DG set Connected EV Charging Station with Support of Battery Through a Bidirectional Converter | 105 |
| Fig. 4.17 | MATLAB Model of Three Phase Grid/DG set Connected EV Charging Station with Support of Battery Through a Bidirectional Converter | 106 |
| Fig. 4.18 | Hardware Configuration of digital controller | 107 |
| Fig. 4.19 | Photograph of hardware | 108 |
| Fig. 4.20 | Block diagram of voltage sensor signal conditioning circuitry | 110 |
| Fig. 4.21 | Block diagram of current sensor signal conditioning circuitry | 110 |
| Fig. 4.22 | Block diagram of opto-coupler conditioning circuitry | 110 |
| Fig. 4.23 | Photograph of hardware components, (a) dSPACE, (b) opto-coupler board, (c) voltage sensing board, (d) current sensing board | 111 |
| Fig. 4.24 | Simulated performance of single phase grid/DG set connected EV charging station with directly connected battery in islanded mode | 113 |
| Fig. 4.25 | Simulated performance of single phase grid/DG set connected EV charging station with directly connected battery in grid connected mode | 114 |
| Fig. 4.26 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 115 |
| Fig. 4.27 | Performance of charging station in islanded mode, (a) v_c , and i_e , (b) P_c , (c) harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_b and I_b , (f) P_b | 116 |
| Fig. 4.28 | Performance of charging station in grid connected mode, (a) v_s , and i_s , (b) P_s , (c) harmonic spectrum of i_s , (d) harmonic spectrum of v_s , (e) v_s and i_e , (f) P_{ev} , (g) harmonic spectrum of i_e , (h) i_c , (i) V_b and I_b , (j) I_b | 117 |
| Fig. 4.29 | Performance of charging station in DG set connected mode, (a) v_g , and i_g , (b) P_g , (c) harmonic spectrum of i_g , (d) harmonic spectrum of v_g , (e) v_g and i_e , (f) P_{ev} , (g) harmonic spectrum of i_e , (h) V_b , and I_b , (i) P_b | 118 |

| | | |
|-----------|---|-----|
| Fig. 4.30 | Dynamics during charging in islanded mode, (a) under change in DC charging (EV1) demand, (b) under change in AC charging (EV) demand | 119 |
| Fig. 4.31 | Dynamic performance in grid connected mode, (a)-(b) under change in AC (EV) charging demand | 119 |
| Fig. 4.32 | Dynamic performance in grid connected mode, (a)-(b) under charging/discharging of storage battery (S2G/G2S) | 120 |
| Fig. 4.33 | Dynamic performance in grid connected mode, (a)-(b) under charging/ discharging of EV1 battery (V2G/G2V) | 121 |
| Fig. 4.34 | Dynamic performance in DG set connected mode, (a)-(b) under change in AC (EV) charging demand | 121 |
| Fig. 4.35 | Automatic and uninterruptible mode switching of charging station, (a) voltage and current performance, (b) power performance | 122 |
| Fig. 4.36 | Performance of reactive power support to the grid and active filtering, (a) reactive power support to the grid, (b) active filtering | 123 |
| Fig. 4.37 | Simulated performance of three phase grid/DG set connected EV charging station with support of battery directly on DC link in islanded mode | 124 |
| Fig. 4.38 | Simulated performance of three phase grid/DG set connected EV charging station with support of battery directly on DC link in grid connected mode | 125 |
| Fig. 4.39 | Simulated performance of three phase grid/DG set connected EV charging station with support of battery directly on DC link in DG set connected mode | 126 |
| Fig. 4.40 | Power quality performance of three phase grid/DG set connected EV charging station with support of battery directly on DC link, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (d) harmonic spectrum of i_g in DGCM | 127 |
| Fig. 4.41 | Steady state performance of three phase grid/DG set connected EV charging station with support of battery directly on DC link in islanded mode, (a) v_{cab} , v_{cbc} , v_{cca} , and i_{ca} , i_{cb} , i_{cc} , (b) P_c , Q_c , S_c , pf, harmonic spectrum of i_{ca} , i_{cb} , and i_{cc} , and v_{cab} , v_{cbc} , v_{cca} , (c) V_b , and I_b , (d) P_b | 128 |
| Fig. 4.42 | Steady state performance of three phase grid/DG set based EVCS in GCM, (a) v_{sab} , v_{sbc} , v_{sca} , and i_{sa} , i_{sb} , i_{sc} , (b) P_s , Q_s , S_s , pf, harmonic spectrum of i_{sa} , i_{sb} , and i_{sc} , (c) v_{sab} , v_{sbc} , v_{sca} , and i_{ea} , i_{eb} , i_{ec} , (d) P_e , Q_e , S_e , pf, harmonic spectrum of i_{ea} , i_{eb} , and i_{ec} , (e) v_{sab} , v_{sbc} , v_{sca} , and i_{ca} , i_{cb} , i_{cc} , (f) P_c , Q_c , S_c , (g) V_b , and I_b , (h) P_b | 130 |

| | | |
|-----------|---|-----|
| Fig. 4.43 | Steady state performance of three phase grid/DG set based EVCS in DG set connected mode, (a) $v_{gab}, v_{gbc}, v_{gca}$, and i_{ga}, i_{gb}, i_{gc} , (b) P_g, Q_g, S_g , pf, harmonic spectrum of i_{ga}, i_{gb} , and i_{gc} and $v_{gab}, v_{gbc}, v_{gca}$, (c) $v_{gab}, v_{gbc}, v_{gca}$, and i_{ea}, i_{eb}, i_{ec} , (d) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb} , and i_{ec} , (e) $v_{gab}, v_{gbc}, v_{gca}$, and i_{ca}, i_{cb}, i_{cc} , (f) P_c, Q_c, S_c , (g) V_b , and I_b , (h) P_b | 131 |
| Fig. 4.44 | Dynamic performance in IM, (a) under EV current change, (b) under charging/discharging of EV battery | 132 |
| Fig. 4.45 | Dynamic performance in GCM, (a)-(b) under EV current change | 132 |
| Fig. 4.46 | Dynamic performance in GCM, (a)-(b) under charging/discharging of storage battery | 133 |
| Fig. 4.47 | Dynamic performance in GCM, (a)-(b) under charging/discharging of EV battery | 133 |
| Fig. 4.48 | Dynamic performance in GCM, (a)-(b) under unbalanced and distorted voltage conditions | 134 |
| Fig. 4.49 | Dynamic performance in GCM, (a) active power filtering-(b) reactive power support to grid | 135 |
| Fig. 4.50 | Dynamic performance in DGCM, (a)-(b) under change in EV current | 135 |
| Fig. 4.51 | Simulated performance in islanded mode of single phase EV charging station with battery a through bidirectional DC-DC converter | 137 |
| Fig. 4.52 | Simulated performance in grid connected mode of single phase EV charging station with battery a through bidirectional DC-DC converter | 138 |
| Fig. 4.53 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM, (d) harmonic spectrum of v_g in DGCM, (d) harmonic spectrum of i_g in DGCM | 139 |
| Fig. 4.54 | Islanded performance of single phase grid/DG set connected EV charging station with battery through a bidirectional DC-DC converter, (a) V_b , and I_b , (b) P_b , (c) v_c , and i_c , (d) P_c , (e) harmonic spectrum of i_c , (f) harmonic spectrum of v_c , (g) v_c and i_e , (h) P_e , (i) harmonic spectrum of i_e , (j) v_c , and i_h | 140 |
| Fig. 4.55 | GCM performance of single phase grid/DG set connected EV charging station with battery through a bidirectional DC-DC converter, (a) v_s , and i_s , (b) P_s , (c) harmonic spectrum of v_s , (d) harmonic spectrum of i_s , (e) v_s and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_s , and i_{h1} , (i) P_{h1} , (j) v_s , and i_{h2} , (k) P_{h2} | 141 |

| | | |
|-----------|---|-----|
| Fig. 4.56 | DG set connected mode performance of single phase grid/DG set connected EV charging station with battery through a bidirectional DC-DC converter, (a) v_g , and i_g , (b) P_g , (c) harmonic spectrum of i_g , (d) harmonic spectrum of v_g , (e) v_g and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_c , and i_c (i) v_a , and i_a , (j) P_a , (k) V_b , and I_b , (l) P_b | 142 |
| Fig. 4.57 | Dynamic performance in IM under EV charging variation | 144 |
| Fig. 4.58 | Dynamic performance in GCM, (a) under charging/discharging of storage battery (b) under change in EV current | 144 |
| Fig. 4.59 | Performance of reactive power support to the grid and active filtering, (a) active filtering (b) reactive power support to grid | 144 |
| Fig. 4.60 | Dynamic performance in DGCM, (a)-(b) under change in EV current | 145 |
| Fig. 4.61 | Simulated performance in islanded mode of three phase grid/DG set connected EV charging station with support of battery through a bidirectional DC-DC converter | 146 |
| Fig. 4.62 | Simulated performance in grid connected mode of three phase grid/DG set connected EV charging station with support of battery through a bidirectional DC-DC converter | 147 |
| Fig. 4.63 | Simulated performance in DG set connected mode of three phase grid/DG set connected EV charging station with support of battery through a bidirectional DC-DC converter | 149 |
| Fig. 4.64 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 150 |
| Fig. 4.65 | Steady state performance in IM, (a) $v_{cab}, v_{cbc}, v_{cca}$, and i_{ea}, i_{eb}, i_{ec} , (b) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb}, i_{ec} , and $v_{cab}, v_{cbc}, v_{cca}$ (c) V_b , and I_b , (d) P_b | 152 |
| Fig. 4.66 | Steady state performance in GCM, (a) $v_{sab}, v_{sbc}, v_{sca}$, and i_{sa}, i_{sb}, i_{sc} , (b) P_s, Q_s, S_s , pf, harmonic spectrum of i_{sa}, i_{sb} , and i_{sc} , (c) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ea}, i_{eb}, i_{ec} , (d) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb} , and i_{ec} , (e) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ca}, i_{cb}, i_{cc} , (f) P_c, Q_c, S_c , (g) V_b , and I_b , (h) P_b | 153 |
| Fig. 4.67 | Steady state performance in DGCM, (a) $v_{gab}, v_{gbc}, v_{gca}$, and i_{ga}, i_{gb}, i_{gc} , (b) P_g, Q_g, S_g , pf, harmonic spectrum of i_{ga}, i_{gb}, i_{gc} , and $v_{gab}, v_{gbc}, v_{gca}$ (c) $v_{gab}, v_{gbc}, v_{gca}$, and i_{ea}, i_{eb}, i_{ec} , (d) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb} , and i_{ec} , (e) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ca}, i_{cb}, i_{cc} , (f) P_c, Q_c, S_c , (g) V_b , and I_b , (h) P_b | 154 |
| Fig. 4.68 | Dynamic performance in IM under change in EV charging demand | 155 |

| | | |
|-----------|--|-----|
| Fig. 4.69 | Dynamic performance in grid connected mode, (a) charging/discharging of storage battery (b) under change in EV current | 156 |
| Fig. 4.70 | Dynamic performance in DG set connected mode, (a)-(b) under change in EV charging demand | 156 |
| Fig. 4.71 | Dynamic performance in grid connected mode under unbalanced and distorted voltage conditions | 157 |
| Fig. 4.72 | Dynamic performance in grid connected mode, (a) active power filtering-(b) reactive power support to grid | 157 |
| Fig. 5.1 | Single phase grid Connected EV charging station with solar PV array directly on DC link and battery through a bi-directional DC-DC converter | 160 |
| Fig. 5.2 | Three phase grid Connected EV charging station with solar PV array directly on DC link and battery through a bi-directional DC-DC converter | 161 |
| Fig. 5.3 | Single phase grid Connected EV charging station with solar PV through a boost converter and battery through a bi-directional DC-DC converter | 162 |
| Fig. 5.4 | Three phase grid Connected EV charging station with solar PV through a boost converter and battery through a bi-directional DC-DC converter | 163 |
| Fig. 5.5 | Single phase grid Connected EV charging station with solar PV through a boost converter and battery directly on DC link | 164 |
| Fig. 5.6 | Three phase grid Connected EV charging station with solar PV through a boost converter and battery directly on DC link | 165 |
| Fig. 5.7 | Operating Strategy of single phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 173 |
| Fig. 5.8 | IM and GCM control of single phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 174 |
| Fig. 5.9 | Bidirectional DC-DC converter control for storage battery | 181 |
| Fig. 5.10 | Control of bidirectional converter for EV charging/discharging | 183 |
| Fig. 5.11 | IM and GCM control of three phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 186 |
| Fig. 5.12 | Bi-directional dc-dc Converter Control of Storage Battery | 193 |
| Fig. 5.13 | Control of bidirectional converter for EV charging/discharging | 194 |
| Fig. 5.14 | IM/GCM control of single phase grid connected EVCS with solar PV array through a boost converter and battery through a bidirectional DC-DC converter | 195 |
| Fig. 5.15 | MPPT and Boost Converter Control of Solar PV Array | 199 |
| Fig. 5.16 | Bi-directional DC-DC Converter Control of Storage Battery | 200 |
| Fig. 5.17 | Bi-directional DC-DC Converter Control of Storage Battery | 201 |

| | | |
|-----------|--|-----|
| Fig. 5.18 | Operating strategy of three phase charging station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 201 |
| Fig. 5.19 | IM and GCM control of three phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 204 |
| Fig. 5.20 | Positive sequence estimation using double SOGI | 206 |
| Fig. 5.21 | MPPT and Boost Converter Control of Solar PV Array | 208 |
| Fig. 5.22 | Bi-directional dc-dc Converter Control of Storage Battery | 210 |
| Fig. 5.23 | Control of EV1 for CC/CV Charging and V2G Power Transfer | 211 |
| Fig. 5.24 | Islanded/grid connected mode control of single phase grid connected EVCS with solar PV array through a boost converter and battery directly on DC link | 212 |
| Fig. 5.25 | MPPT and Boost Converter Control of Solar PV Array | 215 |
| Fig. 5.26 | IM and GCM control of three phase EVCS with solar PV array through a boost converter and battery directly on DC link | 219 |
| Fig. 5.27 | MPPT and Boost Converter Control of Solar PV Array | 221 |
| Fig. 5.28 | MATLAB model of single phase grid connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 222 |
| Fig. 5.29 | MATLAB Model of three phase grid connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 223 |
| Fig. 5.30 | MATLAB Model of single phase EVCS with solar PV array through a boost converter and battery through a bidirectional DC-DC converter | 224 |
| Fig. 5.31 | MATLAB Model of three phase EVCS with solar PV array through a boost converter and battery through a bidirectional DC-DC converter | 225 |
| Fig. 5.32 | MATLAB Model of single phase grid connected EV charging station with solar PV array through a boost converter and battery directly on DC link | 226 |
| Fig. 5.33 | MATLAB Model of three phase grid connected EV charging station with solar PV array through a boost converter and battery directly on DC link | 226 |
| Fig. 5.34 | Experimental Components for Solar PV Array Based Charging Station | 228 |
| Fig. 5.35 | Simulated performance in islanded mode of single phase grid connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 230 |
| Fig. 5.36 | Simulated performance in grid connected mode of single phase grid connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 231 |

| | | |
|-----------|--|-----|
| Fig. 5.37 | Simulated performance during synchronization of single phase grid connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 232 |
| Fig. 5.38 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e | 233 |
| Fig. 5.39 | Steady state performance in islanded mode, (a)-(b) v_c, i_c and P_c , (c) harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_{PV}, I_{PV} and P_{PV} , (f) MPPT curve, (g)-(h) V_b, I_b and P_b | 233 |
| Fig. 5.40 | Steady state performance in grid connected mode, (a)-(b) V_{PV}, I_{PV} and P_{PV} , (c)-(d) v_e, i_e and P_e , (e)-(f) v_s, i_s and P_s , (g)-(i) harmonic spectrum of v_s, i_s and i_e , (j)-(k) V_b, I_b and P_b , (l)-(m) v_c, i_c and P_c | 235 |
| Fig. 5.41 | Dynamics during charging in islanded mode, (a)-(b) under solar irradiance change | 236 |
| Fig. 5.42 | Dynamics during charging in islanded mode, (a)-(b) under the change in household load | 237 |
| Fig. 5.43 | Dynamics during charging in islanded mode, (a)-(b) derating of MPPT | 237 |
| Fig. 5.44 | Dynamic performance in grid connected mode, (a)-(b) under change in household load | 238 |
| Fig. 5.45 | Dynamic performance in grid connected mode, (a)-(b) under change in solar irradiance | 239 |
| Fig. 5.46 | Dynamic performance in grid connected mode, (a)-(b) under change in charging/discharging of EV battery | 239 |
| Fig. 5.47 | Performance of charging station, (a) vehicle to grid reactive power support, (b) active power filter operation | 241 |
| Fig. 5.48 | Synchronization, mode switching and enabling signal generation | 241 |
| Fig. 5.49 | Simulated performance of three phase grid connected EV charging station with solar PV array directly on DC link and battery through a bidirectional DC-DC converter in islanded mode | 243 |
| Fig. 5.50 | Simulated performance of three phase grid connected EV charging station with solar PV array directly on DC link and battery through a bidirectional DC-DC converter in grid connected mode | 244 |
| Fig. 5.51 | Simulated performance of three phase grid connected EV charging station with solar PV array directly on DC link and battery through a bidirectional DC-DC converter during synchronization | 245 |

| | | |
|-----------|---|-----|
| Fig. 5.52 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM | 246 |
| Fig. 5.53 | Steady state performance in IM, (a) $v_{cab}, v_{cbc}, v_{cca}$, and i_{ea}, i_{eb}, i_{ec} , (b) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb} , and i_{ec} , (c) P_{EV1} , (d) P_b (e) V_{PV}, I_{PV} and P_{PV} , (f) MPPT curve | 248 |
| Fig. 5.54 | Steady state performance in GCM, (a) $v_{sab}, v_{sbc}, v_{sca}$, and i_{sa}, i_{sb}, i_{sc} , (b) P_s, Q_s, S_s , pf, harmonic spectrum of i_{sa}, i_{sb} , and i_{sc} , (c) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ea}, i_{eb}, i_{ec} , (d) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb} , and i_{ec} , (e) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ca}, i_{cb}, i_{cc} , (f) P_c, Q_c, S_c , (g) V_{EV1} , and I_{EV1} , (h) P_{EV1} (i) P_B | 249 |
| Fig. 5.55 | Steady state performance in GCM, (a) $v_{sab}, v_{sbc}, v_{sca}$, and i_{sa}, i_{sb}, i_{sc} , (b) P_s, Q_s, S_s , pf, harmonic spectrum of i_{sa}, i_{sb} , and i_{sc} , (c) V_b , and I_b , (d) P_b | 250 |
| Fig. 5.56 | Dynamic performance in IM, (a)-(b) under change in solar irradiance | 251 |
| Fig. 5.57 | Dynamic performance in islanded mode, (a)-(b) under connection/disconnection of EVs | 251 |
| Fig. 5.58 | Dynamic performance in grid connected mode, (a)-(b) under unbalanced charging of EV | 252 |
| Fig. 5.59 | Dynamic performance in grid connected mode, (a) under solar irradiance change, (b) under the change in DC charging current | 254 |
| Fig. 5.60 | Dynamic performance during synchronization and seamless mode switching | 254 |
| Fig. 5.61 | Dynamic performance in grid connected mode under unbalanced and distorted voltage conditions | 255 |
| Fig. 5.62 | Dynamic performance in grid connected mode, (a) active power filtering, (b) reactive power support | 255 |
| Fig. 5.63 | Simulated performance in islanded mode of single phase grid connected EV charging station with solar PV array through a boost converter and battery through a Bi-directional DC-DC converter | 257 |
| Fig. 5.64 | Simulated performance in grid connected mode of single phase grid connected EV charging station with solar PV array through a boost converter and battery through a Bi-directional DC-DC converter | 258 |
| Fig. 5.65 | Simulated performance during synchronization of single phase grid connected EV charging station with solar PV array through a boost converter and battery through a Bi-directional DC-DC converter | 260 |
| Fig. 5.66 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e | 261 |

| | | |
|-----------|---|-----|
| Fig. 5.67 | Steady state performance in IM, (a) v_c, i_e , (b) P_e , (c)harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_{PV}, I_{PV} and P_{PV} , (f) MPPT curve, (g) V_b, I_b , (h) P_b | 261 |
| Fig. 5.68 | Steady state performance in grid connected mode, (a) V_{PV}, I_{PV} and P_{PV} , (b) v_s, i_s , (c) P_s , (d) harmonic spectrum of i_s , (e) harmonic spectrum of v_s , (f) v_c, i_e , (g) P_e , (h) harmonic spectrum of i_e , (i) v_c, i_c , (j) P_c , (k) V_b, I_b , (l) P_b | 262 |
| Fig. 5.69 | Dynamic performance in islanded mode, (a)-(b) under change in EV charging current | 263 |
| Fig. 5.70 | Dynamic performance in IM, (a)-(b) under solar irradiance variation | 263 |
| Fig. 5.71 | Dynamic performance in GCM, (a) under charging/discharging of storage battery, (b) under variation of EV current, (c) under solar irradiance variation | 264 |
| Fig. 5.72 | Dynamic performance in GCM, (a) active filtering, (b) reactive power support | 265 |
| Fig. 5.73 | Simulated performance of three phase grid connected EV charging station with solar PV array through a boost converter and battery through a bidirectional DC-DC converter in islanded mode | 267 |
| Fig. 5.74 | Simulated performance of three phase grid connected EV charging station with solar PV array through a boost converter and battery through a bidirectional DC-DC converter in grid connected mode | 268 |
| Fig. 5.75 | Performance of three phase grid connected EV charging station with solar PV array through a boost converter and battery through a bidirectional DC-DC converter during synchronization | 269 |
| Fig. 5.76 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e | 270 |
| Fig. 5.77 | Steady state performance in islanded mode, (a) V_{PV}, I_{PV} and P_{PV} , (b) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ea}, i_{eb}, i_{ec} , (c) P_e, Q_e, S_e , pf, harmonic spectrum of v_{sab}, v_{sbc} , and v_{sca} , (d) V_b, I_b , (e) P_b | 271 |
| Fig. 5.78 | Steady state performance in grid connected mode, (a) V_{PV}, I_{PV} and P_{PV} , (b) MPPT curve, (c) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ea}, i_{eb}, i_{ec} , (d) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb} , and i_{ec} , (e) $v_{sab}, v_{sbc}, v_{sca}$, and i_{sa}, i_{sb}, i_{sc} , (f) P_s, Q_s, S_s , pf, harmonic spectrum of $v_{sab}, v_{sbc}, v_{sca}$, harmonic spectrum of i_{sa}, i_{sb}, i_{sc} , (g) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ca}, i_{cb}, i_{cc} , (f) P_c, Q_c, S_c | 272 |
| Fig. 5.79 | Steady state performance in grid connected mode, (a) $v_{sab}, v_{sbc}, v_{sca}$, and i_{ea}, i_{eb}, i_{ec} , (b) P_e, Q_e, S_e , pf, harmonic spectrum of i_{ea}, i_{eb} , and i_{ec} , (c) $v_{sab}, v_{sbc}, v_{sca}$, and i_{sa}, i_{sb}, i_{sc} , (d) P_s, Q_s, S_s , pf, harmonic spectrum of $v_{sab}, v_{sbc}, v_{sca}$, harmonic spectrum of i_{sa}, i_{sb}, i_{sc} | 273 |

| | | |
|-----------|---|-----|
| Fig. 5.80 | Dynamic performance in islanded mode, (a)-(b) under connection disconnection of EV and household load | 274 |
| Fig. 5.81 | Dynamic performance in IM, (a)-(b) under connection disconnection of EV battery | 274 |
| Fig. 5.82 | Dynamic performance in IM, (a)-(b) under change in solar irradiance | 275 |
| Fig. 5.83 | Dynamic performance in grid connected mode, (a) under change in solar irradiance, (b) V2G operation | 276 |
| Fig. 5.84 | Dynamic performance in GCM, (a)-(b) under load disturbance | 276 |
| Fig. 5.85 | Dynamic performance in grid connected mode, (a) active power filter operation and voltage correction(b) V2G reactive power support | 277 |
| Fig. 5.86 | Synchronization and seamless mode switching performance | 278 |
| Fig. 5.87 | Charging station performance under distorted and unbalanced voltage, (a)-(b) grid voltage and current under transition from without compensation to with compensation | 278 |
| Fig. 5.88 | Simulated performance in islanded mode of single phase charging station with storage battery directly on DC link and PV array through boost converter | 280 |
| Fig. 5.89 | Simulated performance in grid connected mode of single phase charging station with storage battery directly on DC link and PV array through boost converter | 281 |
| Fig. 5.90 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 282 |
| Fig. 5.91 | Steady state performance in islanded mode, (a)-(b) v_c, i_e and P_e , (c) harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_{PV}, I_{PV} and P_{PV} , (f) MPPT curve, (g) V_b, I_b , (h) P_b | 283 |
| Fig. 5.92 | Steady state performance in grid connected mode, (a) V_{PV}, I_{PV} and P_{PV} , (b)-(c) v_s, i_s and P_s , (d) harmonic spectrum of v_s , (e) harmonic spectrum of i_s , (f)-(g) v_s, i_e and P_e , (h) harmonic spectrum of i_e , (i)-(j) v_c, i_c and P_c , (k)-(l) V_b, I_b and P_b | 284 |
| Fig. 5.93 | Dynamic performance in IM under charging/discharging of EV battery | 285 |
| Fig. 5.94 | Dynamic performance in IM, (a)-(b) under variation in EV charging | 285 |
| Fig. 5.95 | Dynamic performance in IM, (a) under variation in solar irradiance | 286 |
| Fig. 5.96 | Dynamic performance in GCM under variation in EV charging | 286 |
| Fig. 5.97 | Dynamic performance in GCM, (a)-(d) under variation in solar irradiance | 287 |
| Fig. 5.98 | Dynamic performance in GCM under charging/discharging of EV battery | 288 |

| | | |
|------------|--|-----|
| Fig. 5.99 | Dynamic performance in GCM, (a) active power filtering, (b) reactive power support | 288 |
| Fig. 5.100 | Simulated performance of the three phase charging station in islanded mode with solar PV array through a boost converter and storage battery directly on DC link | 290 |
| Fig. 5.101 | Simulated performance of the three phase charging station in grid connected mode with solar PV array through a boost converter and storage battery directly on DC link | 291 |
| Fig. 5.102 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 292 |
| Fig. 5.103 | Steady state performance in islanded mode, (a) V_{PV} , I_{PV} and P_{PV} , (b) MPPT curve, (c)-(d) V_b , I_b , (e) P_b , (e) v_{cab} , v_{cbc} , v_{cca} , and i_{ea} , i_{eb} , i_{ec} , (f) P_e , Q_e , S_e , pf, harmonic spectrum of v_{cab} , v_{cbc} , v_{cca} , and i_{ea} , i_{eb} , i_{ec} | 293 |
| Fig. 5.104 | Steady state performance in GCM, (a) V_{PV} , I_{PV} and P_{PV} , (b) MPPT curve, (c)-(d) V_b , I_b , and P_b , (e) v_{sab} , v_{sbc} , v_{sca} , and i_{sa} , i_{sb} , i_{sc} , (f) P_s , Q_s , S_s , pf, harmonic spectrum of i_{sa} , i_{sb} , i_{sc} , and v_{sab} , v_{sbc} , v_{sca} , (g) v_{sab} , v_{sbc} , v_{sca} and i_{ea} , i_{eb} , i_{ec} , (h) P_e , Q_e , S_e , pf, harmonic spectrum of i_{ea} , i_{eb} , and i_{ec} , (i) v_{sab} , v_{sbc} , v_{sca} , and i_{ca} , i_{cb} , i_{cc} , (j) P_c , Q_c , S_c | 294 |
| Fig. 5.105 | Dynamic performance in IM under charging/discharging of storage battery (G2S/S2G) | 295 |
| Fig. 5.106 | Dynamic performance in islanded mode, (a)-(b) under variation in EV charging | 296 |
| Fig. 5.107 | Dynamic performance in IM, (a)-(c) under variation in solar irradiance | 297 |
| Fig. 5.108 | Dynamic performance in GCM, (a)-(c) under change in solar irradiance | 298 |
| Fig. 5.109 | Dynamic performance in GCM, (a)-(b) under charging/discharging of storage battery (G2S/S2G) | 298 |
| Fig. 5.110 | Dynamic performance in GCM, (a)-(b) under charging/discharging of EV battery (G2V/V2G) | 299 |
| Fig. 5.111 | Dynamic performance in GCM, (a)-(b) under change in the EV charging current | 300 |
| Fig. 5.112 | Dynamic performance in GCM, (a)-(b) under distorted and unbalanced voltage conditions | 300 |
| Fig. 5.113 | Dynamic performance in GCM, (a) reactive power support to grid, (b) active filtering | 301 |

| | | |
|-----------|--|-----|
| Fig. 6.1 | Single phase grid/DG Set based EV charging station with PV array directly on DC-link and storage battery through a bidirectional DC-DC converter | 304 |
| Fig. 6.2 | Three phase grid/DG set based EV charging station with PV array directly on DC-link and storage battery through a bidirectional DC-DC converter | 305 |
| Fig. 6.3 | Single phase grid/DG set based EV charging station with PV array through a boost converter and storage battery through a bidirectional DC-DC converter | 306 |
| Fig. 6.4 | Three phase grid/DG set based EV charging station with PV array through a boost converter and storage battery through a bidirectional DC-DC converter | 307 |
| Fig. 6.5 | Single phase grid/DG set based EV charging station with PV array through a boost converter and storage battery directly on DC link | 308 |
| Fig. 6.6 | Three phase grid/DG set based EV charging station with PV array through a boost converter and storage battery directly on DC link | 309 |
| Fig. 6.7 | IM and GCM/DGCM control of single phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 316 |
| Fig. 6.8 | Bidirectional DC-DC converter control for storage battery | 322 |
| Fig. 6.9 | Bidirectional DC-DC converter control for EVs | 324 |
| Fig. 6.10 | IM and GCM/DGCM control of single phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 327 |
| Fig. 6.11 | Bidirectional DC-DC converter control for storage battery | 331 |
| Fig. 6.12 | Bidirectional DC-DC converter control for EVs | 332 |
| Fig. 6.13 | IM and GCM/DGCM control of single phase EVCS with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 334 |
| Fig. 6.14 | PV array boost converter and boost converter control | 337 |
| Fig. 6.15 | Bidirectional DC-DC converter control for storage battery | 338 |
| Fig. 6.16 | IM and GCM/DGCM control of single phase EVCS with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 339 |
| Fig. 6.17 | PV array boost converter and boost converter control | 340 |
| Fig. 6.18 | Bidirectional DC-DC converter control for storage battery | 341 |
| Fig. 6.19 | IM and GCM/DGCM control of single phase EVCS with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 342 |
| Fig. 6.20 | PV array boost converter and boost converter control | 346 |
| Fig. 6.21 | IM and GCM/DGCM control of Three phase EVCS with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 347 |

| | | |
|-----------|---|-----|
| Fig. 6.22 | MATLAB model of single phase grid/DG set connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 351 |
| Fig. 6.23 | MATLAB model of three phase grid/DG set connected EV charging station with solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 352 |
| Fig. 6.24 | MATLAB model of single phase grid/DG set connected EV charging station with PV array through a boost converter and battery through a Bi-directional DC-DC converter | 353 |
| Fig. 6.25 | MATLAB model of three phase grid/DG set connected EV charging station with solar PV array through a boost converter and battery through a Bi-directional DC-DC converter | 353 |
| Fig. 6.26 | MATLAB model of single phase grid/DG set connected EV charging station with PV array through a boost converter and battery directly on DC link | 354 |
| Fig. 6.27 | MATLAB model of three phase grid/DG set connected EV charging station with solar PV array through a boost converter and battery directly on DC link | 354 |
| Fig. 6.28 | Experimental components for solar PV Array, battery, grid/DG set based EV charging station | 355 |
| Fig. 6.29 | Simulated performance in IM of single phase charging station with PV array directly on DC link and battery through a bidirectional DC-DC converter | 358 |
| Fig. 6.30 | Simulated performance in GCM of single phase charging station with PV array directly on DC link and battery through a bidirectional DC-DC converter | 359 |
| Fig. 6.31 | Simulated performance in DGCM of single phase charging station with PV array directly on DC link and battery through a bidirectional DC-DC converter | 360 |
| Fig. 6.32 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 361 |
| Fig. 6.33 | Performance of solar PV array feeding load, charging EVs and charging storage battery in IM, (a) V_{PV} , and I_{PV} , (b) P_{PV} , (c) V_b , and I_b , (d) P_b , (e) v_c , and i_e , (f) P_e , (g) harmonic spectrum of v_c , (h) harmonic spectrum of i_e | 362 |
| Fig. 6.34 | EV charging in GCM, (a) v_s , and i_s , (b) P_s , (c) harmonic spectrum of i_s , (d) harmonic spectrum of v_s , (e) v_c and i_c , (f) P_c , (g) v_s , and i_e (h) P_e , (i) harmonic spectrum of i_e | 363 |

| | | |
|-----------|--|-----|
| Fig. 6.35 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , (c)-(d) harmonic spectrum of i_g , v_g , (e) v_g and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_c , and i_c (i) P_c , (j) V_b , and I_b , (k) P_b , (l) v_a , and i_a , (m) P_a | 364 |
| Fig. 6.36 | Dynamics performance of charging station in IM, (a)-(b) under the change in EV charging demand | 365 |
| Fig. 6.37 | Dynamics performance of charging station in IM, (a)-(b) under the change in solar irradiance | 365 |
| Fig. 6.38 | Dynamics performance of charging station in GCM, (a)-(b) under the change in EV charging demand | 366 |
| Fig. 6.39 | Dynamics performance of charging station in GCM, (a)-(b) under the change in solar irradiance | 367 |
| Fig. 6.40 | Dynamics performance of charging station in GCM, (a)-(b) under change in storage battery current (charging (grid to storage (G2S))/discharging (storage to grid (S2G))) | 367 |
| Fig. 6.41 | Dynamics performance of charging station in GCM, (a) under reactive power compensation, (b) during synchronization | 368 |
| Fig. 6.42 | Dynamics performance of charging station in GCM, (a) during active filtering operation | 368 |
| Fig. 6.43 | Dynamics performance of DG set connected mode, (a)-(b) under the change in EV charging demand, (c) under change in solar irradiance | 369 |
| Fig. 6.44 | Simulated performance in IM of three phase charging station powered by PV array directly on DC link and storage battery through a bidirectional DC-DC converter | 371 |
| Fig. 6.45 | Simulated performance in GCM of three phase charging station powered by PV array directly on DC link and storage battery through a bidirectional DC-DC converter | 372 |
| Fig. 6.46 | Simulated performance in DGCM of three phase charging station powered by PV array directly on DC link and storage battery through a bidirectional DC-DC converter | 373 |
| Fig. 6.47 | Simulated performance during synchronization of three phase charging station powered by PV array directly on DC link and storage battery through a bidirectional DC-DC converter | 374 |
| Fig. 6.48 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 375 |

| | | |
|-----------|---|-----|
| Fig. 6.49 | EV charging in IM, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_c , (c) V_b and I_b , (d) P_b , V_{PV} , (e) I_{PV} , and P_{PV} , (f) MPPT curve | 376 |
| Fig. 6.50 | EV charging in GCM, (a) v_s , and i_s , (b) P_s , harmonic spectrum of i_s , harmonic spectrum of v_s , (c) v_s , and i_e , (d) P_e , harmonic spectrum of i_e , (e) v_s , and i_e , (f) P_c , (g) V_{PV} , I_{PV} and P_{PV} , (h) MPPT curve, (I) V_b and I_b , (j) P_b | 377 |
| Fig. 6.51 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , harmonic spectrum of i_g , harmonic spectrum of v_g , (c) v_g , and i_e , (d) P_e , harmonic spectrum of i_e , (e) v_g , and i_e , (f) P_c , (g) V_b and I_b , (h) P_b | 379 |
| Fig. 6.52 | Dynamics during charging in IM, (a)-(b) under change in solar irradiance | 380 |
| Fig. 6.53 | Dynamics during charging in IM, (a)-(b) under change in AC charging | 381 |
| Fig. 6.54 | Dynamics during charging in GCM, (a)-(d) under change in solar irradiance | 382 |
| Fig. 6.55 | Dynamics during charging in GCM, (a)-(d) under change in AC charging demand | 383 |
| Fig. 6.56 | Dynamics during charging in GCM, (a)-(c) under change in DC charging demand | 384 |
| Fig. 6.57 | Dynamics in GCM during, (a)-(d) under charging/discharging of storage battery | 385 |
| Fig. 6.58 | Dynamics in GCM during, (a) active power filtering, (b) reactive power support | 386 |
| Fig. 6.59 | Dynamics in GCM during synchronization and mode change | 386 |
| Fig. 6.60 | Dynamics in DGCM during, (a)-(b) change in AC charging demand | 387 |
| Fig. 6.61 | Simulated performance in IM of single phase EV charging station powered by solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 388 |
| Fig. 6.62 | Simulated performance in GCM of single phase EV charging station powered by solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 389 |
| Fig. 6.63 | Simulated performance during synchronization of single phase EV charging station powered by solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 390 |
| Fig. 6.64 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM | 391 |
| Fig. 6.65 | EV charging in IM, (a) v_c and i_e , (b) P_e , (c) harmonic spectrum of i_e , (d) harmonic spectrum of v_c , (e) V_b and I_b , (f) P_b , (g) V_{PV} , I_{PV} and P_{PV} , (h) MPPT curve | 392 |

| | | |
|-----------|---|-----|
| Fig. 6.66 | EV charging in GCM, (a) V_{PV} , I_{PV} and P_{PV} , (b) v_s , and i_s , (c) P_s , (d) harmonic spectrum of i_s , (e) harmonic spectrum of v_s , (f) v_s , and i_e , (g) P_e , (h) harmonic spectrum of i_e , (i) v_s , and i_c , (j) P_c , (k) V_b and I_b , (l) P_b | 393 |
| Fig. 6.67 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , (c) harmonic spectrum of v_g , (d) harmonic spectrum of i_g , (e) v_g , and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_g , and i_c , (i) P_c , (j) V_b and I_b , (k) P_b | 395 |
| Fig. 6.68 | Dynamics during charging in IM, (a)-(b) under change in AC charging demand | 396 |
| Fig. 6.69 | Dynamics during charging in IM, (a)-(b) under change in solar irradiance | 396 |
| Fig. 6.70 | Dynamic performance in GCM, (a) under change in storage battery current, (b) under change in EV charging demand, (c) under change in solar irradiance change | 397 |
| Fig. 6.71 | Dynamic performance in DGCM, (a)-(c) under change in EV charging demand, (d) under change in solar irradiance change | 398 |
| Fig. 6.72 | Simulated performance in IM of three phase EV charging station powered by solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 400 |
| Fig. 6.73 | Simulated performance in GCM of three phase EV charging station powered by solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 401 |
| Fig. 6.74 | Simulated performance during synchronization of three phase EV charging station powered by solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 402 |
| Fig. 6.75 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM | 403 |
| Fig. 6.76 | EV charging in IM, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_c , (c) V_b and I_b , (d) P_b , (e) V_{PV} , I_{PV} , P_{PV} , (f) MPPT curve | 404 |
| Fig. 6.77 | EV charging in GCM, (a) v_s , and i_s , (b) P_s , harmonic spectrum of i_s , harmonic spectrum of v_g , (c) v_s , and i_e , (d) P_e , harmonic spectrum of i_e (e) v_c and i_c , (f) P_c , (g) V_{PV} , I_{PV} , and P_{PV} (h) MPPT curve, (i) V_b and I_b , (j) P_b | 406 |
| Fig. 6.78 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , harmonic spectrum of i_g , harmonic spectrum of v_g , (c) v_g , and i_e , (d) P_e , harmonic spectrum of i_e (e) v_g and i_c , (f) P_c , (g) V_b and I_b , (h) P_b | 407 |
| Fig. 6.79 | Dynamics during charging in IM, (a)-(b) under change in solar irradiance | 408 |

| | | |
|-----------|--|-----|
| Fig. 6.80 | Dynamics during charging in IM, (a)-(b) under change in EV charging demand 409 | |
| Fig. 6.81 | Dynamics during charging in GCM, (a)-(b) under solar irradiance variation | 409 |
| Fig. 6.82 | Dynamics during charging in GCM, (a)-(b) under change in AC charging demand | 410 |
| Fig. 6.83 | Dynamics in GCM during charging/discharging of storage battery | 410 |
| Fig. 6.84 | Dynamics in GCM during, (a) active power filtering, (b) reactive power support 411 | |
| Fig. 6.85 | Dynamics during charging in DGCM, (a)-(b) under change in AC charging demand | 411 |
| Fig. 6.86 | Simulated performance in IM of single phase EV charging station powered by solar PV array through a boost converter and battery directly on DC link | 413 |
| Fig. 6.87 | Simulated performance in GCM of single phase EV charging station powered by solar PV array through a boost converter and battery directly on DC link | 414 |
| Fig. 6.88 | Simulated performance in DGCM of single phase EV charging station pow- ered by solar PV array through a boost converter and battery directly on DC link | 415 |
| Fig. 6.89 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (c) harmonic spectrum of i_g in DGCM | 416 |
| Fig. 6.90 | Performance of solar PV array feeding load, charging EVs and charging stor- age battery in IM, (a) v_c , and $i_e + i_h$, (b) total demand at PCC, (c) harmonic spectrum of v_c , (h) harmonic spectrum of $i_e + i_h$, (e) P_h , (f) v_c and i_e (g) P_e , (h) harmonic spectrum of i_e , (i) V_{PV} , and I_{PV} , (j) P_{PV} , (k) V_b , and I_b , (l) P_b | 417 |
| Fig. 6.91 | Performance of storage battery feeding load, and charging EVs in IM, (a) v_c , and $i_e + i_h$, (b) total demand at PCC, (c) harmonic spectrum of v_c , (d) harmonic spectrum of $i_e + i_h$, (e) V_b , and I_b , (f) P_b , (g) v_c , and i_e , (h) P_e , (i) v_c , and i_h , (j) P_h | 418 |
| Fig. 6.92 | Performance of charging station in grid connected mode, (a) v_s , and i_s , (b) P_s , (c) harmonic spectrum of v_s , (d) harmonic spectrum of i_s , (e) v_s and i_c , (f) P_c , (g) v_s , and i_e (h) P_e , (i) harmonic spectrum of i_e , (j) v_s , and i_h (h) P_h | 420 |
| Fig. 6.93 | EV charging in DG set connected mode, (a) v_g , and i_g , (b) P_g , (c) harmonic spectrum of v_g , (d) harmonic spectrum of i_g , (e) v_g and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_g , and i_h (i) P_h , (j) V_b , and I_b , (k) P_b , (l) v_a , and i_a , (m) P_a , (n) P_c | 421 |

| | | |
|------------|---|-----|
| Fig. 6.94 | Dynamics performance of charging station in IM, (a)-(b) under solar irradiance change | 423 |
| Fig. 6.95 | Dynamics performance of charging station in IM, (a)-(b) under change in DC charging | 423 |
| Fig. 6.96 | Dynamics performance of charging station in IM, (a)-(b) under change in AC charging demand | 423 |
| Fig. 6.97 | Dynamics performance of charging station in IM under EV connection/disconnection | 424 |
| Fig. 6.98 | Dynamics performance of charging station in GCM, (a)-(b) under change in AC charging demand | 425 |
| Fig. 6.99 | Dynamics performance of charging station in GCM, (a)-(b) under solar irradiance change | 425 |
| Fig. 6.100 | Dynamics performance of charging station in GCM under change in DC charging demand (V2G) | 426 |
| Fig. 6.101 | Dynamics during automatic and uninterruptible mode switching, (a) synchronization of grid voltage with PCC voltage, (b) generation of signal E=0/1 | 426 |
| Fig. 6.102 | Dynamics performance in GCM during, (a) V2G reactive power compensation, (b) active filtering | 427 |
| Fig. 6.103 | Dynamics performance of charging station in DGCM, (a)-(b) under change in AC charging demand | 427 |
| Fig. 6.104 | Simulated performance in IM of three phase EV charging station powered by solar PV array through a boost converter and battery directly on DC link | 428 |
| Fig. 6.105 | Simulated performance in GCM of three phase EV charging station powered by solar PV array through a boost converter and battery directly on DC link | 429 |
| Fig. 6.106 | Simulated performance in DGCM of three phase EV charging station powered by solar PV array through a boost converter and battery directly on DC link | 430 |
| Fig. 6.107 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 432 |
| Fig. 6.108 | EV charging in IM, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_e , (c) V_b and I_b , (d) P_b , (f) V_{PV} , I_{PV} and P_{PV} , (f) MPPT curve | 433 |
| Fig. 6.109 | EV charging in GCM, (a) v_s , and i_s , (b) P_s , harmonic spectrum of i_s , harmonic spectrum of v_g , (c) v_s , and i_e , (d) P_e , harmonic spectrum of i_e (e) v_c and i_c , (f) P_c , (g) V_{PV} , I_{PV} , and P_{PV} (h) MPPT curve, (i) V_b and I_b , (j) P_b | 434 |

| | | |
|------------|---|-----|
| Fig. 6.110 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , harmonic spectrum of i_g , harmonic spectrum of v_g , (c) v_s and i_e , (d) P_e , harmonic spectrum of i_e , (e) v_g and i_e , (f) P_c , (g) V_b , I_b , (h) P_b | 436 |
| Fig. 6.111 | Dynamics during charging in IM under change in EV current | 437 |
| Fig. 6.112 | Dynamics during charging in IM, (a)-(b) under change in AC charging (EV) demand | 437 |
| Fig. 6.113 | Dynamics during charging in IM, (a)-(c) under change in solar irradiance | 438 |
| Fig. 6.114 | Dynamics during charging in GCM, (a)-(c) under change in solar irradiance | 439 |
| Fig. 6.115 | Dynamics during charging in GCM, (a)-(b) under change in AC charging demand | 439 |
| Fig. 6.116 | Dynamics in GCM, (a)-(b) under charging/discharging of EV1 battery | 440 |
| Fig. 6.117 | Dynamics in GCM under charging/discharging of storage battery | 440 |
| Fig. 6.118 | Dynamics in GCM during, (a) active power filtering, (b) reactive power support | 441 |
| Fig. 6.119 | Dynamics during charging in DGCM, (a)-(b) under change in AC charging demand | 441 |
| Fig. 7.1 | Single phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 444 |
| Fig. 7.2 | Three phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 445 |
| Fig. 7.3 | Single phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 446 |
| Fig. 7.4 | Three phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 447 |
| Fig. 7.5 | Single phase grid connected wind powered EVCS directly connected storage battery and PV array with boost converter | 448 |
| Fig. 7.6 | Three phase grid connected wind powered EVCS directly connected storage battery and PV array with boost converter | 449 |
| Fig. 7.7 | IM and GCM control of single phase EVCS powered by wind through a boost converter, PV array directly on DC link and battery through a bi-directional DC-DC converter | 456 |
| Fig. 7.8 | Bidirectional DC-DC converter control for storage battery | 463 |
| Fig. 7.9 | Control of EV1 for CC/CV charging and V2G power transfer | 464 |
| Fig. 7.10 | Boost converter and MPPT control of WECS | 464 |

| | | |
|-----------|--|-----|
| Fig. 7.11 | IM and GCM control of three Phase EVCS Powered By WECS Through a Boost Converter, PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 465 |
| Fig. 7.12 | Scheme for estimating positive sequence voltage from unbalanced and distorted voltages | 468 |
| Fig. 7.13 | Control of bi-directional converter of storage battery | 471 |
| Fig. 7.14 | Control of EV1 for CC/CV charging and V2G power transfer | 473 |
| Fig. 7.15 | MPPT control of WECS | 473 |
| Fig. 7.16 | IM and GCM control of single Phase grid connected EV charging station powered by wind through a boost converter, solar PV array through a boost and battery through a bi-directional DC-DC converter | 474 |
| Fig. 7.17 | Control of Bi-directional converter of storage battery | 479 |
| Fig. 7.18 | Control of EV1 for CC/CV charging and V2G power transfer | 480 |
| Fig. 7.19 | Control of boost converter of PV array | 480 |
| Fig. 7.20 | MPPT control of WECS | 481 |
| Fig. 7.21 | IM and GCM control of three Phase EV charging station powered by wind through a boost converter, solar PV array through a boost and battery through a bi-directional DC-DC converter | 483 |
| Fig. 7.22 | Control of bidirectional converter for charging/discharging of storage battery | 486 |
| Fig. 7.23 | Control of bidirectional converter for charging/discharging of EV battery | 487 |
| Fig. 7.24 | Control of boost converter of PV array | 487 |
| Fig. 7.25 | MPPT control of WECS | 488 |
| Fig. 7.26 | IM and GCM Control of Single Phase EV Charging Station Powered By Wind Through a Boost Converter, Solar PV Array through a Boost Converter and Battery Directly on DC link | 490 |
| Fig. 7.27 | Control of boost converter of PV array | 493 |
| Fig. 7.28 | MPPT control of WECS | 493 |
| Fig. 7.29 | IM and GCM Control of Three Phase EVCS Powered By WECS Through a Boost Converter, PV Array through a Boost Converter and Battery Directly on DC link | 496 |
| Fig. 7.30 | Control of boost converter of PV array | 498 |
| Fig. 7.31 | Control of boost converter of PV WECS | 498 |
| Fig. 7.32 | MATLAB model of single phase grid connected EV charging station with WECS through a Boost converter, solar PV array directly on DC link and battery through a Bi-directional DC-DC converter, (a) complete model, (b) WECS model | 500 |

| | | |
|-----------|--|-----|
| Fig. 7.33 | MATLAB model of Three phase EV charging station with WECS through a Boost converter, solar PV array directly on DC link and battery through a Bi-directional DC-DC converter | 501 |
| Fig. 7.34 | MATLAB model of single phase grid connected EV charging station with WECS through a Boost converter, solar PV array through a boost converter and battery through a Bi-directional DC-DC converter | 502 |
| Fig. 7.35 | MATLAB model of three phase grid connected EV charging station with WECS through a Boost converter, solar PV array through a boost converter and battery through a Bi-directional DC-DC converter | 502 |
| Fig. 7.36 | MATLAB model of single phase grid connected EV charging station with WECS through a Boost converter, solar PV array through a boost converter and battery directly on DC link | 503 |
| Fig. 7.37 | MATLAB model of phase phase grid connected EV charging station with WECS through a Boost converter, solar PV array through a boost converter and battery directly on DC link | 504 |
| Fig. 7.38 | Simulated performance in IM of three phase charging station powered by wind through a boost converter, PV array through a boost converter and battery directly on DC link | 505 |
| Fig. 7.39 | Simulated performance in grid connected mode of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 507 |
| Fig. 7.40 | Simulated performance in grid connected mode of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 508 |
| Fig. 7.41 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 509 |
| Fig. 7.42 | EV charging in islanded mode, (a) v_c , and i_e , (b) P_e , (c) harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_b and I_b , (f) P_b , (g) V_{PV} , I_{PV} , and P_{PV} , (g) MPPT curve | 510 |
| Fig. 7.43 | EV charging in grid connected mode, (a) V_{PV} , I_{PV} and P_{PV} , (b) MPPT curve, (c) V_W , and I_W , (d) P_W , (e) v_s and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) V_b and I_b , (i) P_b , (j) v_s and i_s , (k) P_s , (l) harmonic spectrum of i_s | 511 |
| Fig. 7.44 | Dynamics during charging in IM, (a) under change in solar irradiance, (b) under change in WECS power, (c) under change in AC charging demand | 513 |
| Fig. 7.45 | Dynamic performance in GCM, (a)-(b) under change in solar irradiance | 514 |

| | | |
|-----------|--|-----|
| Fig. 7.46 | Dynamic performance in GCM, (a)-(c) under change in WECS power | 515 |
| Fig. 7.47 | Dynamic performance in GCM, (a)-(b) under change in DC charging (EV1) demand | 516 |
| Fig. 7.48 | Dynamic performance in GCM, (a)-(c) under change in AC (EV) charging demand | 516 |
| Fig. 7.49 | Dynamic performance in GCM during, (a) active power filtering, (b) reactive power support to grid | 517 |
| Fig. 7.50 | Synchronization and mode change from IM to GCM | 517 |
| Fig. 7.51 | Simulated performance in islanded mode of three phase charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bidirectional DC-DC converter | 519 |
| Fig. 7.52 | Simulated performance in grid connected mode of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and through a bidirectional DC-DC converter | 520 |
| Fig. 7.53 | Simulated performance in grid connected mode of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and through a bidirectional DC-DC converter | 522 |
| Fig. 7.54 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 523 |
| Fig. 7.55 | EV charging in islanded mode, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_c , (c) V_{PV} , I_{PV} , and P_{PV} , (d) MPPT curve, (e) V_W and I_W , (f) P_W , (g) V_b and I_b , (h) P_b | 524 |
| Fig. 7.56 | EV charging in grid connected mode, (a) v_s , and i_s , (b) P_s , harmonic spectrum of i_s , harmonic spectrum of v_s , (c) V_W and I_W , (d) P_W , (e) P_{PV} , I_{PV} , P_{PV} (f) P_b , (g) v_s , and i_e , (h) P_e , harmonic spectrum of i_e , harmonic spectrum of v_s , (i) v_s , and i_c , (j) P_c | 525 |
| Fig. 7.57 | Dynamics during charging in IM, (a) under change in solar irradiance, (b) under change in WECS power generation, (c) under change in AC charging | 526 |
| Fig. 7.58 | Dynamics during charging in GCM, (a)-(b) under change in storage battery current (S2G/G2S) | 527 |
| Fig. 7.59 | Dynamics during charging in GCM, (a)-(c) under change in solar irradiance | 527 |
| Fig. 7.60 | Dynamics during charging in GCM, (a)-(b) under change in WECS power generation | 528 |
| Fig. 7.61 | Dynamics in GCM under change in AC charging (EV) demand | 529 |

| | | |
|-----------|--|-----|
| Fig. 7.62 | Dynamics during charging in GCM, (a) under distorted voltage condition, (b) under active filtering operation, (c) under reactive power support to grid, (d) synchronization and seamless mode change | 530 |
| Fig. 7.63 | Simulated performance in islanded mode of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 531 |
| Fig. 7.64 | Simulated performance in grid connected mode of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 533 |
| Fig. 7.65 | Simulated performance during synchronization of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 534 |
| Fig. 7.66 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 535 |
| Fig. 7.67 | EV charging in IM, (a) V_{PV} , I_{PV} and P_{PV} , (b) MPPT curve, (c) V_W , I_W , (d) P_W , (e) v_c and i_e , (f) P_e , (g) harmonic spectrum of v_c , (h) harmonic spectrum of i_e , (i) V_b and I_b , (j) P_b | 536 |
| Fig. 7.68 | EV charging in GCM, (a) V_{PV} , I_{PV} and P_{PV} , (b) V_W , I_W , (c) P_W , (d) v_s , and i_s , (e) P_s , (f) harmonic spectrum of i_s , (g) v_s , and i_e , (h) P_e , (i) harmonic spectrum of i_e , (j) V_b and I_b , (k) P_b , (l) P_c | 537 |
| Fig. 7.69 | Dynamics during charging in IM, (a)-(b) under change in household load demand | 538 |
| Fig. 7.70 | Dynamics during charging in IM, (a) under change in DC charging (EV1) demand | 538 |
| Fig. 7.71 | Dynamics during charging in IM, (a) under change in WECS power | 539 |
| Fig. 7.72 | Dynamics during charging in IM, (a) under change in solar irradiance, (b) under WECS power change, (c) under change in household load demand | 540 |
| Fig. 7.73 | Dynamic performance in GCM, (a)-(b) under solar irradiance change | 541 |
| Fig. 7.74 | Dynamic performance in GCM, (a)-(b) under change in WECS power | 541 |
| Fig. 7.75 | Dynamic performance in GCM, (a) under change in household load variation, (b) under charging/discharging of EV1 battery (V2G/G2V) | 542 |
| Fig. 7.76 | Dynamic performance in GCM during, (a) reactive power support to grid, (b) active power filtering | 542 |
| Fig. 7.77 | Performance of synchronization and mode change from IM to GCM | 543 |

| | | |
|-----------|---|-----|
| Fig. 7.78 | Simulated performance in islanded mode of three phase charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 544 |
| Fig. 7.79 | Simulated performance in grid connected mode of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 546 |
| Fig. 7.80 | Simulated performance during synchronization of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 547 |
| Fig. 7.81 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 548 |
| Fig. 7.82 | EV charging in IM, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_c , (c) V_{PV} , I_{PV} , P_{PV} , (d) MPPT curve, (e) V_b and I_b , (f) P_b | 549 |
| Fig. 7.83 | EV charging in grid connected mode, (a) v_s , and i_s , (b) P_s , harmonic spectrum of i_s , harmonic spectrum of v_s , (c) v_s , and i_e , (d) P_e , harmonic spectrum of i_e , harmonic spectrum of v_s , (e) v_s and i_c , (g) P_b , (h) P_W | 550 |
| Fig. 7.84 | Dynamics during charging in IM, (a)-(b) under change in household load demand | 551 |
| Fig. 7.85 | Dynamics during charging in IM, (a)-(b) under change in DC charging (EV1) demand | 551 |
| Fig. 7.86 | Dynamics during charging in IM, (a)-(b) under change in WECS power | 552 |
| Fig. 7.87 | Dynamics during charging in IM, (a) under solar irradiance variation, (b) under variation in WECS power, (c) under change in household load | 553 |
| Fig. 7.88 | Dynamics during charging in GCM, (a) under solar irradiance variation, (b) under discharging of EV1 batter (V2G), (c) under change in household load, (d) under change in WECS power variation | 554 |
| Fig. 7.89 | Dynamics in GCM during, (a) active power filtering, (b) reactive power support of grid, (c) synchronization and seamless mode change | 555 |
| Fig. 7.90 | Simulated performance in IM of three phase CS powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 557 |
| Fig. 7.91 | Simulated performance in GCM of three phase EVCS powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 558 |

| | | |
|------------|--|-----|
| Fig. 7.92 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 560 |
| Fig. 7.93 | EV charging in IM, (a) v_c , and i_e , (b) P_e , (c) harmonic spectrum of i_e , (d)harmonic spectrum of v_e , (e) V_{PV} , I_{PV} and P_{PV} , (f) V_W , I_W , (g) P_W , (h) V_b and I_b , (i) P_b | 561 |
| Fig. 7.94 | EV charging in GCM, (a) v_s , and i_s , (b) P_s , (c)harmonic spectrum of v_s , (d)harmonic spectrum of i_s , (e) v_s and i_e , (f) P_e , (g)harmonic spectrum of i_e , (h) v_s and i_c , (i) P_c , (j) V_b , I_b , (k) P_b , (l) V_{PV} , I_{PV} and P_{PV} | 562 |
| Fig. 7.95 | Dynamics during charging in IM under change in EV1 current | 563 |
| Fig. 7.96 | Dynamics during charging in IM under change in EV current | 563 |
| Fig. 7.97 | Dynamics during charging in IM under solar irradiance change | 564 |
| Fig. 7.98 | Dynamics during charging in GCM under change in EV current | 564 |
| Fig. 7.99 | Dynamics during charging in GCM, (a)-(b) under change in solar irradiance | 565 |
| Fig. 7.100 | Dynamics during charging in GCM, (a)-(b) under change in storage battery current | 565 |
| Fig. 7.101 | Dynamics during charging in GCM, (a)-(b) under change in EV1 current | 566 |
| Fig. 7.102 | Dynamics in GCM during, (a) reactive power support to grid, (b) active power filtering | 566 |
| Fig. 7.103 | Performance of synchronization and seamless mode change from IM to GCM | 567 |
| Fig. 7.104 | Simulated performance in islanded mode of three phase charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 568 |
| Fig. 7.105 | Simulated performance in grid connected mode of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 570 |
| Fig. 7.106 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_h in GCM | 571 |
| Fig. 7.107 | EV charging in IM, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_e , (c) V_{PV} , I_{PV} and P_{PV} , (d) MPPT curve, (e) V_b and I_b , (f) P_b | 572 |
| Fig. 7.108 | EV charging in grid connected mode, (a) v_s , and i_s , (b) P_s , harmonic spectrum of i_s , harmonic spectrum of v_s , (c) v_s and i_e , (d) P_{ev} , harmonic spectrum of i_e , (e) v_s and i_c , (f) P_c , (g) V_{PV} , I_{PV} and P_{PV} , (h) V_W , I_W , (i) P_W , (j) P_b | 573 |
| Fig. 7.109 | Dynamics during charging in IM under change in storage battery current | 574 |

| | | |
|------------|--|-----|
| Fig. 7.110 | Dynamics during charging in IM, (a)-(b) under change in AC charging (EV) demand | 574 |
| Fig. 7.111 | Dynamics during charging in IM, (a)-(c) under change in solar irradiance | 575 |
| Fig. 7.112 | Dynamics during charging in GCM, (a)-(c) under change in WECS power | 576 |
| Fig. 7.113 | Dynamics during charging in GCM, (a)-(b) under change in solar irradiance level | 577 |
| Fig. 7.114 | Dynamics during charging in GCM, (a)-(c) under change in AC (EV) charging | 578 |
| Fig. 7.115 | Dynamics during charging in GCM under change in storage battery current | 578 |
| Fig. 7.116 | Dynamics during charging in grid connected mode, (a) active power filtering-(b) reactive power support to the grid, (c) synchronization and seamless mode change | 579 |
| Fig. 8.1 | Single phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 582 |
| Fig. 8.2 | Three phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 583 |
| Fig. 8.3 | Single phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 584 |
| Fig. 8.4 | Three phase grid/DG set connected wind powered EVCS boost converter | 585 |
| Fig. 8.5 | Single phase grid/DG set connected wind powered EVCS directly connected storage battery and PV array with boost converter | 586 |
| Fig. 8.6 | Three phase grid/DG set connected wind powered EVCS directly connected storage battery and PV array with boost converter | 587 |
| Fig. 8.7 | IM and GCM/DGCM control of single Phase grid/DG set connected EV charging station powered by wind through a boost converter, solar PV array directly on DC link and battery through a bi-directional DC-DC converter | 596 |
| Fig. 8.8 | Control of bi-directional converter of storage battery | 600 |
| Fig. 8.9 | Control of EV1 for CC/CV charging and V2G power transfer | 601 |
| Fig. 8.10 | MPPT control of WECS | 602 |
| Fig. 8.11 | IM and GCM/DGCM control of three Phase EVCS Powered By WECS Through a Boost Converter, PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 604 |
| Fig. 8.12 | IM and GCM/DGCM control of single Phase grid/DG set connected EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 608 |
| Fig. 8.13 | Control of Bi-directional converter of storage battery | 610 |
| Fig. 8.14 | Control of boost converter of PV array | 611 |

| | | |
|-----------|---|-----|
| Fig. 8.15 | IM and GCM/DGCM control of three Phase grid/DG set connected EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 612 |
| Fig. 8.16 | IM and GCM/DGCM control of single Phase grid/DG set connected EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 615 |
| Fig. 8.17 | IM and GCM/DGCM control of three Phase grid/DG set connected EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 619 |
| Fig. 8.18 | MATLAB model of single phase grid/DG set connected EV charging station with Wind through a boost converter, solar PV array directly on DC link and battery through a bi-directional DC-DC converter | 624 |
| Fig. 8.19 | MATLAB model of three phase grid/DG set connected EV charging station with Wind through a boost converter, solar PV array directly on DC link and battery through a bi-directional DC-DC converter | 624 |
| Fig. 8.20 | MATLAB model of single phase grid/DG set connected EV charging station with Wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 625 |
| Fig. 8.21 | MATLAB model of three phase grid/DG set connected EV charging station with Wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC converter | 626 |
| Fig. 8.22 | MATLAB model of single phase grid/DG set connected EV charging station with Wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 627 |
| Fig. 8.23 | MATLAB model of three phase grid/DG set connected EV charging station with Wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 627 |
| Fig. 8.24 | Experimental components for PV Array, WECS, battery, grid/DG set based EVCS | 628 |
| Fig. 8.25 | Simulated performance in IM of single phase EV charging station powered by wind through a boost converter, PV array directly on DC link and battery through a bidirectional DC-DC converter | 630 |
| Fig. 8.26 | Simulated performance in GCM of single phase Grid/DG set Connected EV charging station powered by wind through a boost converter, PV array directly on DC link and battery through a bidirectional DC-DC converter | 632 |

| | | |
|-----------|---|-----|
| Fig. 8.27 | Simulated performance in DGCM of single phase Grid/DG set Connected EV charging station powered by wind through a boost converter, PV array directly on DC link and battery through a bidirectional DC-DC converter | 633 |
| Fig. 8.28 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 634 |
| Fig. 8.29 | EV charging in IM, (a) v_c , and i_e , (b) P_e , (c) harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_b and I_b , (f) P_b , (g) V_{PV} , I_{PV} , and P_{PV} , (g) MPPT curve | 635 |
| Fig. 8.30 | EV charging in GCM, (a) v_s and i_s , (b) P_s , (c) harmonic spectrum of v_s , (d) harmonic spectrum of i_s , (e) v_s and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_c and i_c , (i) P_c , (j) V_b and I_b , (k) P_b , (l) V_{PV} , I_{PV} and P_{PV} | 636 |
| Fig. 8.31 | EV charging in DGCM, (a) v_g and i_g , (b) P_g , (c) harmonic spectrum of v_g , (d) harmonic spectrum of i_g , (e) v_g and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_c and i_c , (i) P_c , (j) V_b and I_b , (k) P_b | 637 |
| Fig. 8.32 | Dynamics during charging in IM, (a) under change in solar irradiance, (b) under change in WECS power | 638 |
| Fig. 8.33 | Dynamics during charging in IM, (a)-(b) under change in AC charging demand | 638 |
| Fig. 8.34 | Dynamic performance in GCM, (a)-(b) under change in solar irradiance | 639 |
| Fig. 8.35 | Dynamic performance in GCM, (a)-(b) under change in AC charging demand | 640 |
| Fig. 8.36 | Dynamic performance in GCM, (a)-(b) under change in storage battery current | 640 |
| Fig. 8.37 | Dynamic performance in GCM during, (a) reactive power support to the grid -(b) active power filtering | 641 |
| Fig. 8.38 | Dynamic performance in GCM during seamless mode transition | 641 |
| Fig. 8.39 | Dynamic performance in DGCM, (a)-(b) under change in AC charging demand | 642 |
| Fig. 8.40 | Dynamic performance in DGCM under change in solar irradiance | 642 |
| Fig. 8.41 | Simulated performance in IM of three phase EV charging station powered by wind through a boost converter, solar PV array directly on DC link and battery through a bi-directional DC-DC Converter | 644 |
| Fig. 8.42 | Simulated performance in GCM of three phase EV charging station powered by wind through a boost converter, solar PV array directly on DC link and battery through a bi-directional DC-DC Converter | 645 |

| | | |
|-----------|---|-----|
| Fig. 8.43 | Simulated performance in DGCM of three phase Grid/DG set Connected EV charging station powered by wind through a boost converter, PV array directly on DC link and battery through a bidirectional DC-DC converter | 646 |
| Fig. 8.44 | Simulated performance during synchronization of three phase EV charging station powered by wind through a boost converter, solar PV array directly on DC link and battery through a bi-directional DC-DC Converter | 648 |
| Fig. 8.45 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 649 |
| Fig. 8.46 | EV charging in islanded mode, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_c , (c) V_{PV} , I_{PV} , and P_{PV} , (d) V_b and I_b , (e) P_b | 650 |
| Fig. 8.47 | EV charging in GCM, (a) v_s , i_s , (b) P_s , harmonic spectrum of i_s and v_s , (c) v_s , and i_e , (d) P_e , harmonic spectrum of i_e , (e) v_s , i_c , (f) P_c , (g) V_W , I_W , (h) P_W , (i) V_b , I_b , (j) P_b | 651 |
| Fig. 8.48 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , harmonic spectrum of i_g , harmonic spectrum of v_g , (c) v_g , and i_e , (d) P_e , harmonic spectrum of i_e , (e) v_g , and i_c , (f) P_c , (g) V_b , I_b , (h) P_b | 652 |
| Fig. 8.49 | Dynamics during charging in IM, (a)-(b) under change in AC charging | 653 |
| Fig. 8.50 | Dynamics during charging in IM, (a)-(b) under change in solar irradiance | 654 |
| Fig. 8.51 | Dynamics during charging in GCM, (a)-(d) under change in solar irradiance | 655 |
| Fig. 8.52 | Dynamics during charging in GCM, (a)-(d) under change in AC charging demand | 656 |
| Fig. 8.53 | Dynamics during charging in GCM, (a)-(c) under charging/discharging of EV battery | 657 |
| Fig. 8.54 | Dynamics in GCM, (a)-(d) under charging/discharging of storage battery | 658 |
| Fig. 8.55 | Dynamics during charging in GCM under change in WECS power | 658 |
| Fig. 8.56 | GCM dynamics during, (a) active filtering, (b) reactive power support to grid | 659 |
| Fig. 8.57 | DGCM dynamics, (a)-(b) under change in AC charging demand | 659 |
| Fig. 8.58 | Simulated performance in IM of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 660 |
| Fig. 8.59 | Simulated performance in GCM of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 661 |

| | | |
|-----------|---|-----|
| Fig. 8.60 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM | 662 |
| Fig. 8.61 | EV charging in IM, (a) v_c , and i_e , (b) P_e , (c) harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_b and I_b , (f) P_b , (g) V_{PV} , I_{PV} , and P_{PV} , (g) MPPT curve | 663 |
| Fig. 8.62 | EV charging in GCM, (a) v_s and i_s , (b) P_s , (c) harmonic spectrum of v_s , (d) harmonic spectrum of i_s , (e) v_s and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_c and i_c , (i) P_c , (j) V_b and I_b , (k) P_b , (l) P_{PV} | 665 |
| Fig. 8.63 | EV charging in DGCM, (a) v_g and i_g , (b) P_g , (c) harmonic spectrum of v_g , (d) harmonic spectrum of i_g , (e) v_g and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_c and i_c , (i) P_c , (j) V_b and I_b , (k) P_b | 666 |
| Fig. 8.64 | Dynamics during charging in IM, (a)-(b) under change in AC charging demand | 667 |
| Fig. 8.65 | Dynamics during charging in IM, (a)-(b) under change in solar irradiance | 667 |
| Fig. 8.66 | Dynamics during charging in IM under change in WECS generation | 668 |
| Fig. 8.67 | Dynamic performance in GCM, (a)-(b) under change in solar irradiance | 668 |
| Fig. 8.68 | Dynamic performance in GCM under change in, (a) AC charging demand, (b) storage battery current, (c) WECS generation | 669 |
| Fig. 8.69 | Dynamic performance in DGCM, (a)-(c) under change in AC charging demand | 670 |
| Fig. 8.70 | Dynamic performance in DGCM, (a)-(b) under change in solar irradiance | 671 |
| Fig. 8.71 | Simulated performance in IM of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 672 |
| Fig. 8.72 | Simulated performance in GCM of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 673 |
| Fig. 8.73 | Simulated performance during synchronization of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery through a bi-directional DC-DC Converter | 674 |
| Fig. 8.74 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM | 675 |

| | | |
|-----------|---|-----|
| Fig. 8.75 | EV charging in islanded mode, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_c , (c) V_W , I_W , (d) P_W , (e) V_{PV} , I_{PV} , and P_{PV} , (f) V_b and I_b , (g) P_b | 676 |
| Fig. 8.76 | EV charging in GCM, (a) v_s , i_s , (b) P_s , harmonic spectrum of i_s , v_s , (c) v_s , i_e , (d) P_e , harmonic spectrum of i_e , (e) v_s , and i_c , (f) P_c , (g) V_W , I_W , (h) P_W , (i) V_b , I_b , (j) P_b | 678 |
| Fig. 8.77 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , harmonic spectrum of i_g , harmonic spectrum of v_g , (c) v_g , and i_e , (d) P_e , harmonic spectrum of i_e , (e) v_g , and i_c , (f) P_c , (g) V_b , I_b , (h) P_b | 679 |
| Fig. 8.78 | Dynamics during charging in IM, (a)-(b) under solar irradiance change | 680 |
| Fig. 8.79 | Dynamics during charging in IM, (a)-(b) under change in AC charging | 681 |
| Fig. 8.80 | Dynamics during charging in GCM, (a)-(b) under solar irradiance change | 681 |
| Fig. 8.81 | Dynamics during charging in GCM, (a)-(b) under change in AC charging | 682 |
| Fig. 8.82 | Dynamics during charging in GCM under change in storage battery current | 682 |
| Fig. 8.83 | Dynamics during charging in DGCM, (a)-(b) under change in AC charging | 683 |
| Fig. 8.84 | Simulated performance in IM of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 684 |
| Fig. 8.85 | Simulated performance in GCM of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 685 |
| Fig. 8.86 | Simulated performance in DGCM of single phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 686 |
| Fig. 8.87 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 687 |
| Fig. 8.88 | EV charging in IM, (a) v_c , and i_e , (b) P_e , (c) harmonic spectrum of v_c , (d) harmonic spectrum of i_e , (e) V_{PV} , I_{PV} , and P_{PV} , (f) V_b and I_b , (g) P_b | 688 |
| Fig. 8.89 | EV charging in GCM, (a) v_s and i_s , (b) P_s , (c) harmonic spectrum of v_s , (d) harmonic spectrum of i_s , (e) v_s and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_s and i_c , (i) P_c , (j) V_W and I_W , (k) P_W , (l) V_b and I_b , (m) P_b , (n) V_{PV} , I_{PV} and P_{PV} | 690 |

| | | |
|------------|---|-----|
| Fig. 8.90 | EV charging in DGCM, (a) v_g and i_g , (b) P_g , (c) harmonic spectrum of v_g , (d) harmonic spectrum of i_g , (e) v_g and i_e , (f) P_e , (g) harmonic spectrum of i_e , (h) v_c and i_c , (i) P_c , (j) V_b and I_b , (k) P_b | 691 |
| Fig. 8.91 | Dynamics during charging in IM, (a) under change in solar irradiance | 692 |
| Fig. 8.92 | Dynamics during charging in IM, (a) under change in AC charging demand | 693 |
| Fig. 8.93 | Dynamics during charging in IM under change in EV battery current | 694 |
| Fig. 8.94 | Dynamic performance in GCM under change in AC charging demand | 694 |
| Fig. 8.95 | Dynamic performance in GCM, (a) under change in solar irradiance | 695 |
| Fig. 8.96 | Dynamic performance in GCM, (a) under change in storage battery current | 696 |
| Fig. 8.97 | Dynamic performance in GCM, (a) under change in EV battery current | 696 |
| Fig. 8.98 | Dynamic performance in DGCM, (a) under change in AC charging demand | 697 |
| Fig. 8.99 | Dynamic performance in DGCM under change in solar irradiance | 697 |
| Fig. 8.100 | Simulated performance in IM of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 698 |
| Fig. 8.101 | Simulated performance in GCM of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 699 |
| Fig. 8.102 | Simulated performance in DGCM of three phase EV charging station powered by wind through a boost converter, solar PV array through a boost converter and battery directly on DC link | 701 |
| Fig. 8.103 | Power quality performance of charging station, (a) harmonic spectrum of v_c in IM, (b) harmonic spectrum of i_s in GCM, (c) harmonic spectrum of i_e in GCM, (d) harmonic spectrum of v_g in DGCM, (e) harmonic spectrum of i_g in DGCM | 702 |
| Fig. 8.104 | EV charging in islanded mode, (a) v_c , and i_e , (b) P_e , harmonic spectrum of i_e , harmonic spectrum of v_c , (c) V_b , I_b , (d) P_b , (e) V_{PV} , I_{PV} , and P_{PV} , (f) MPPT curve | 703 |
| Fig. 8.105 | EV charging in GCM, (a) v_s , i_s , (b) P_s , harmonic spectrum of i_s , v_s , (c) v_s , i_e , (d) P_e , harmonic spectrum of i_e , (e) v_s , and i_c , (f) P_c , (g) V_W , I_W , (h) P_W , (i) V_b , I_b , (j) P_b | 704 |
| Fig. 8.106 | EV charging in DGCM, (a) v_g , and i_g , (b) P_g , harmonic spectrum of i_g , harmonic spectrum of v_g , (c) v_g , and i_e , (d) P_e , harmonic spectrum of i_e , (e) v_g , and i_c , (f) P_c , (g) V_b , I_b , (h) P_b | 706 |
| Fig. 8.107 | Dynamics during charging in IM under charging/discharging of EV battery | 707 |

| | | |
|------------|---|-----|
| Fig. 8.108 | Dynamics during charging in IM, (a)-(b) under change in AC charging demand 707 | |
| Fig. 8.109 | Dynamics during charging in IM, (a)-(c) under change in solar irradiance | 708 |
| Fig. 8.110 | Dynamics during charging in GCM, (a)-(c) under change in WECS generation | 709 |
| Fig. 8.111 | Dynamics during charging in GCM, (a)-(c) under change in solar irradiance | 710 |
| Fig. 8.112 | Dynamics during charging in GCM, (a)-(c) under change in AC charging demand | 710 |
| Fig. 8.113 | Dynamics during charging in GCM under charging/discharging of storage battery | 711 |
| Fig. 8.114 | Dynamics during charging in DGCM, (a)-(b) under change in AC charging demand | 712 |

LIST OF TABLES

| | | |
|------------|--|----|
| Table 2.1 | Charging options for various vehicle categories | 19 |
| Table 2.2 | Charging standard and charging time in Indian scenario | 19 |
| Table 3.1 | Single phase and three phase Charging Station with Grid/DG set with Directly Connected Battery | 37 |
| Table 3.2 | Single Phase and Three Phase Charging Station with Grid/DG set and Battery through a Bidirectional DC-DC Converter | 38 |
| Table 3.3 | Single phase and three phase grid connected EVCS with storage battery through a bidirectional converter and PV array without boost converter | 41 |
| Table 3.4 | Single phase and three phase grid connected EVCS with storage battery through a bidirectional converter and PV array with boost converter | 42 |
| Table 3.5 | Single and three phase grid connected EVCS with directly connected storage battery and PV array with boost converter | 42 |
| Table 3.6 | Single and three phase grid/DG set connected EVCS with storage battery through a bidirectional converter and PV array without boost converter | 46 |
| Table 3.7 | Single and three phase grid/DG set connected EVCS with storage battery through a bidirectional converter and PV array with boost converter | 46 |
| Table 3.8 | Single and three Phase grid/DG set connected EVCS with directly connected storage battery and PV array with boost converter | 47 |
| Table 3.9 | Single and three phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 50 |
| Table 3.10 | Single and three phase grid connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 51 |
| Table 3.11 | Single and three phase grid connected wind powered EVCS directly connected storage battery and PV array with boost converter | 52 |
| Table 3.12 | Single and three phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array without boost converter | 55 |
| Table 3.13 | Single and three Phase grid/DG set connected wind powered EVCS with storage battery through a bidirectional converter and PV array with boost converter | 55 |
| Table 3.14 | Single and three phase grid/DG set connected wind powered EVCS directly connected storage battery and PV array with boost converter | 56 |
| Table 4.1 | Design of Grid/DG Set Connected and battery Supported EV charging Station | 66 |
| Table 4.2 | Design of Grid/DG Set Connected and battery Supported EV charging Station | 67 |
| Table 4.3 | Design of Grid/DG Set Connected and battery Supported EV charging Station | 69 |

| | | |
|-----------|---|-----|
| Table 4.4 | Design of Grid/DG Set Connected and battery Supported EV charging Station | 69 |
| Table 5.1 | Design of Single Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 167 |
| Table 5.2 | Design of Three Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 167 |
| Table 5.3 | Design of Single Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 169 |
| Table 5.4 | Design of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 169 |
| Table 5.5 | Design of Single Phase Grid Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Directly on DC link | 170 |
| Table 5.6 | Design of Three Phase Grid Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 171 |
| Table 5.7 | Design of Grid Connected and battery Supported EV charging Station | 227 |
| Table 6.1 | Design of Single Phase Grid/DG set Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 309 |
| Table 6.2 | Design of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 310 |
| Table 6.3 | Design of Single Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 311 |
| Table 6.4 | Design of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 312 |
| Table 6.5 | Design of Single Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Directly on DC link and Battery Directly on DC link | 313 |
| Table 6.6 | Design of Three Phase Grid/DG Set Connected EV Charging Station with Solar PV Array Through a Boost Converter and Battery Directly on DC link | 314 |
| Table 6.7 | Design of Grid/DG Set Connected and Battery Supported EV charging Station | 356 |

| | | |
|-----------|---|-----|
| Table 7.1 | Design of Single Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 450 |
| Table 7.2 | Design of Three Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 451 |
| Table 7.3 | Design of Single Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 452 |
| Table 7.4 | Design of Three Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 453 |
| Table 7.5 | Design of Single Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Directly on DC link | 454 |
| Table 7.6 | Design of Three Phase Grid Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 455 |
| Table 8.1 | Design of Single Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 588 |
| Table 8.2 | Design of Three Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Through a Bi-directional DC-DC Converter | 589 |
| Table 8.3 | Design of Single Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 590 |
| Table 8.4 | Design of Three Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Through a Bi-directional DC-DC Converter | 591 |
| Table 8.5 | Design of Single Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Directly on DC link and Battery Directly on DC link | 592 |
| Table 8.6 | Design of Three Phase Grid/DG Set Connected EV Charging Station with WECS Through a Boost Converter, Solar PV Array Through a Boost Converter and Battery Directly on DC link | 593 |

| | | |
|-----------|--|-----|
| Table 8.7 | Design of Grid/DG Set Connected and Battery Supported EV charging Station | 629 |
| Table 9.1 | Quantitative Performance of Charging Station Configurations in Terms of THDs | 714 |

LIST OF ABBREVIATIONS

| | |
|---------|---|
| EV | Electric Vehicle |
| CS | Charging Station |
| EVCS | Electric Vehicle Charging Station |
| PV | photovoltaic |
| WECS | Wind Energy Conversion System |
| SEIG | Self Excited Induction Generator |
| PMBLDCG | Permanent Magnet Brushless DC Generator |
| AC | Alternating Current |
| DC | Direct Current |
| V2G | vehicle-to-grid |
| G2V | Grid-to-Vehicle |
| S2G | Storage-to-Grid |
| G2S | Grid-to-Storage |
| V2H | Vehicle-to-Home |
| S2H | Storage-to-Home |
| S2V | Storage-to-Vehicle |
| V2S | Vehicle-to-Storage |
| PV2H | PV-to-Home |
| PV2V | PV-to-Vehicle |
| PV2G | PV-to-Grid |
| W2G | Wind-to-Grid |
| W2H | Wind-to-Home |
| W2V | Wind-to-Vehicle |
| DG | Diesel generator |
| IM | Islanded Mode |
| GCM | Grid Connected Mode |
| DGCM | DG Set Connected Mode |
| MPP | Maximum Power Point |

| | |
|--------------|--|
| MPPT | Maximum Power Point Tracking |
| V2V | vehicle-to-vehicle |
| IEEE | Institute of Electrical and Electronics Engineers |
| INC | Incremental Conductance |
| PCC | Point of Common Coupling |
| SS | Static Switch |
| PI | Proportional Integral |
| SOGI | Second Order Generalized Integrator |
| DSOGI | Dual Second Order Generalized Integrator |
| PLL | Phase Locked Loop |
| FLL | Frequency Locked Loop |
| S/H | Sample and Hold |
| THD | Total Harmonic Distortion |
| VSC | Voltage Source Converter |
| ZCD | Zero Crossing Detection |
| UPF | Unity Power Factor |
| IGBT | Insulated Gate Bipolar Transistor |
| ADC | Analog to Digital Converter |
| DAC | Digital to Analog Converter |
| PWM | Pulse Width Modulator |
| RC | Resistor-Capacitor |
| CC/CV | Constant Current/Constant Voltage |
| DSO | Digital Storage Oscilloscope |
| SMC | Sliding Mode Controller |
| SOGI-FLL-DRC | Second-Order Generalized Integrator-Frequency Locked Loop with DC Rejection Capability |
| SOC | State of Charge |
| APSA | Affine Projection Sign Algorithm |
| ILST | Improved Linear sinusoidal Tracer |

| | |
|--------------|--|
| CAPSA | Convex Combined Affine Projection Sign Algorithm |
| DPF | Displacement Power Factor |
| SS-LMSE | Variable Step Size Least Mean Switching Error |
| ANC | Adaptive Notch Cancellation |
| VLLMS | Variable Leaky Least Mean Square |
| AFF-SOGI-DRC | Adaptive Frequency Fixed Second Order Generalized Integrator with DC Offset Rejection Capability |

LIST OF SYMBOLS

| | |
|----------|---|
| C_{dc} | DC-link capacitor (F) |
| V_{dc} | DC-link voltage (V) |
| v_s | Single phase instantaneous grid voltage (V) |
| v_c | Single phase instantaneous PCC voltage (V) |
| v_g | Single phase instantaneous DG set voltage (V) |
| v_a | Single phase instantaneous DG set auxiliary winding voltage (V) |
| i_s | Single phase instantaneous grid current (A) |
| i_c | Single phase instantaneous PCC current (A) |
| i_g | Single phase instantaneous DG set current (A) |
| i_a | Single phase instantaneous DG set auxiliary winding current (A) |
| R_f | Ripple filter resistance (Ω) |
| C_f | Ripple filter capacitor (F) |
| i_e | Single phase instantaneous EV current (A) |
| i_h | Single phase instantaneous household load current (A) |
| E | Synchronizing signal |
| C_b | Storage battery capacitor (F) |
| C_e | EV battery capacitor (F) |
| I_b | Storage battery current (A) |
| I_{ev} | EV battery current (A) |
| V_{PV} | PV array voltage (V) |
| V_W | WECS rectified voltage (V) |
| I_{PV} | PV array current (V) |
| I_W | WECS rectified current (V) |
| P_s | Grid active power (kW) |
| Q_s | Grid reactive power (kVAR) |
| S | Grid apparent power (kVA) |
| ω | Angular frequency of grid (rad/s) |
| k | is safety factor |
| P_g | DG set active power (kW) |
| P_b | Storage battery active power (kW) |
| P_e | EV active power (kW) |
| P_{ev} | EV battery power (kW) |
| P_h | Household load active power (kW) |
| P_{PV} | PV array power (kW) |

| | |
|-------------------------------|--|
| P_W | WECS power (kW) |
| L_c | Interfacing inductor (H) |
| L_b | Interfacing inductor (H) |
| V_m | Amplitude pf PCC voltage |
| v_{ca}, v_{cb}, v_{cc} | Three phase instantaneous PCC voltage (V) |
| v_{sa}, v_{sb}, v_{sc} | Three phase instantaneous grid voltage (V) |
| v_{ga}, v_{gb}, v_{gc} | Three phase instantaneous DG set voltage (V) |
| i_{ca}, i_{cb} and i_{cc} | Three phase instantaneous PCC current (A) |
| i_{sa}, i_{sb} and i_{sc} | Three phase instantaneous grid current (A) |
| i_{ga}, i_{gb} and i_{gc} | Three phase instantaneous DG set current (A) |