Dr. Akhil Gupta

Solar Photovoltaics Engineering

A Power Quality Analysis Using Matlab Simulation Case Studies

Anchor Academic Publishing

disseminate knowledge

Gupta, Akhil: Solar Photovoltaics Engineering. A Power Quality Analysis Using Matlab Simulation Case Studies, Hamburg, Anchor Academic Publishing 2016

Buch-ISBN: 978-3-96067-082-7
PDF-eBook-ISBN: 978-3-96067-582-2
Druck/Herstellung: Anchor Academic Publishing, Hamburg, 2016

Bibliografische Information der Deutschen Nationalbibliothek:
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

Bibliographical Information of the German National Library:
The German National Library lists this publication in the German National Bibliography. Detailed bibliographic data can be found at: http://dnb.d-nb.de

All rights reserved. This publication may not be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Das Werk einschließlich aller seiner Teile ist urheberrechtlich geschützt. Jede Verwertung außerhalb der Grenzen des Urheberrechtsgesetzes ist ohne Zustimmung des Verlages unzulässig und strafbar. Dies gilt insbesondere für Vervielfältigungen, Übersetzungen, Mikroverfilmungen und die Einspeicherung und Bearbeitung in elektronischen Systemen.

Die Wiedergabe von Gebrauchsnamen, Handelsnamen, Warenbezeichnungen usw. in diesem Werk berechtigt auch ohne besondere Kennzeichnung nicht zu der Annahme, dass solche Namen im Sinne der Warenzeichen- und Markenschutz-Gesetzgebung als frei zu betrachten wären und daher von jedermann benutzt werden dürften.

Die Informationen in diesem Werk wurden mit Sorgfalt erarbeitet. Dennoch können Fehler nicht vollständig ausgeschlossen werden und die Diplomica Verlag GmbH, die Autoren oder Übersetzer übernehmen keine juristische Verantwortung oder irgendeine Haftung für evtl. verbliebene fehlerhafte Angaben und deren Folgen.

Alle Rechte vorbehalten

© Anchor Academic Publishing, Imprint der Diplomica Verlag GmbH
Hermannstal 119k, 22119 Hamburg
http://www.diplomica-verlag.de, Hamburg 2016
Printed in Germany

Acknowledgement

I am thankful to Dr. Saurabh Chanana, my Ph.d. supervisor at Department of Electrical Engineering, National Institute of Technology, Kurukshetra, Haryana, India, for his kind support which he rendered out of his busy schedule during the course of my earlier research work. His approach and ability to derive the solutions to any problem in this world has immensely helped me in increasing my ability during finding solutions to problems. It was only after my research work had been over, I was able to present this manuscript with a focused approach.

I am indebted to my parents, my wife Ms. Yachana Gupta and my children. Special thanks at extreme end to my wife for her valuable support time to time which made me free out of other social activities to give enough time in writing this book.

Finally,

A big Thanks are due to my other family members, my teachers, my students,

my colleagues, my friends and The God

Special Thanks to Diplomica-Verlag Publishing House

Dedicated to

MY FAMILY

Preface

This book comprises 10 chapters each of which covers the study on solar energy and its application in solar Photovoltaic grid connected systems. Power quality investigation has been carried highlighting the study of key power quality parameters. Author has made an endeavor to tailor the all chapters for an audience of university faculty members, students, researchers and practitioners in solar energy sector.

Chapter 1 mainly presents the world perspective and growth of electric power through conventional sources and its vis-à-vis comparative growth with various sources of renewable energy. It has been discussed that electric power has been one of the most critical component among others available required for infrastructure and crucial for economic growth and welfare of any nation. The growth of any developing nation mainly depends on various resources critically required in growth of infrastructure. This chapter also highlights the recent advancements recently taken place in renewable energy. The measures being adopted for building and supporting in the further renewable energy growth in developing and developed economies is also presented.

In Chapter 2, an introduction of a solar PV cell with its behavior with the help of its electrical circuits in ideal and practical conditions is presented. This description is carried out using its basic output current and output voltage equations. In addition, the various parameters as defined in a standard manufacturer data-sheet is discussed. The basic difference between a solar PV cell and a normal p-n junction diode is also described. The importance of MPP using *V-I* and *P-V* electrical characteristics is highlighted. In order to study any PV model, the dependence of a solar PV cell on variable solar radiation and ambient temperature is derived and discussed.

Chapter 3 has presented a discussion on advantages and limitations of crystalline and thin film technologies with their common features. This chapter has begun from by looking at the development of solar cells from the early stage. Then the commercial silicon wafer based solar cell technology is described. Special attention has been given to each thin film technology as its related material properties, fabrication techniques are discussed. The chapter has covered thin film technologies such as amorphous silicon, CdTe, CIGS, and thin film crystalline silicon solar cell technologies.

Chapter 4 has highlighted the needs of PV installation components other than PV panels. These components are jointly referred to as the Balance of System (BOS) and include the batteries, DC-DC converters, DC-AC converters for AC loads and grid connected systems. Since *P-V* and *V-I* curves of a solar panel are non-linear in nature, the need and importance of MPPT technique in extracting variable solar power at maximum points is described in PCS systems.

In chapter 5, the introduction of PQ and its concerns has been presented. The various PQ issues have been introduced and discussed according to IEEE and IEC standards. The effect of each of PQ issue has been described for a distribution system according to IEC standard. It is discussed that in electric power systems, hundreds of power generating stations and load centers are interconnected and operated. There are various PQ problems likewise, voltage sag, voltage swell, transients, voltage interruption, harmonics, noise and notching. Each PQ problem can be solved by the proper coordination among all power system components.

Chapter 6 has presented that Matlab is a software package, which can be used to perform analysis and solve mathematical and engineering problems. Introduction to various Matlab windows have been given and described. Simulink contains a library editor of tools from which we can build input/output devices and continuous and discrete time model simulations. Simulink has a comprehensive block library which can be used to simulate linear, non-linear or discrete systems. C codes can also be generated from Simulink models for embedded applications and rapid prototyping of control systems. This chapter also highlights the procedure for the operation of Simulink software with building blocks.

Chapter 7 has presented the modeling of solar PV single stage grid connected system at unity power factor. No transformer is used in the proposed system as it increases the level of harmonics in the overall system. The nature of real power generated by solar PV array through VSC has been shown and proved that whenever the power from grid is un-available, the real power requirement of the load is achieved by VSC. Data based MPPT is proposed through which behavior of actual DC link voltage is discussed.

In chapter 8, the simulation of the proposed system is performed under two different cases. In first case, the effect of changing power factor on active power, reactive power and THD values is observed. It is observed that the THD of grid current increases with increase in the phase angle of grid current VSC voltage. It affects the active power flow among VSC, load and utility grid. In the second case, the effect of changing frequency on active power, reactive power and THD

values is noticed. It is observed that the THD of VSC current increases whereas, the THD of grid current remains constant.

Chapter 9 has presented the analysis of two-stage solar PV grid connected system which is evaluated at linear *RLC* load. In DC-DC boost converter, the IC-MPPT technique which is capable to operate even under changing environmental conditions is implemented. Real and reactive power exchange is exchanged among VSC, load and utility grid. Voltage and current waveforms are presented. In order to evaluate the level of power quality, the THD analysis is carried out using FFT. It has been found that although level of harmonics generation from VSC is high, the control system is designed that level of harmonics is reduced for grid injected current.

Chapter 10 has discussed the system performance at P&O based MPPT technique for solar PV two-stage grid connected system. It has been found that harmonic level is reduced for converter current and grid injected current. However, this MPPT is not able to track the reference MPPT voltage accurately. This validates that this MPPT is not able to operate under wide range of changing environmental conditions. The behavior of voltage and current levels of VSC, load connected and utility grid has also been discussed. Active and reactive power exchange among VSC, load connected and utility grid has also been highlighted.

Table of Contents

Acknowledgement **5**

Preface **7**

List of Abbreviations **14**

List of Tables **16**

List of Figures **17**

CHAPTER I: ELECTRIC POWER - A WORLD PERSPECTIVE **21**

1.1. Introduction to Power Sector-A World Perspective 21

1.1.1 Coal 22

1.1.2 Natural gas 22

1.1.3 Petroleum and Other Liquid Fuels 22

1.1.4 Renewable Resources 22

1.2 Status of Indian Power Sector 23

1.3 Status of Global Renewable Energy 25

1.4 Conclusion 27

CHAPTER II: AN INTRODUCTION TO SOLAR PHOTOVOLTAIC CELL & MODELING **28**

2.1 Introduction 28

2.2 A Solar PV Cell-A p-n Junction Diode 28

2.3 Difference Between a Solar PV Cell and a p-n Junction Diode 30

2.4 Basic Parameters of Solar PV Cell 31

2.4.1 Voltage-Current (V-I) Characteristics 31

2.4.2 Short Circuit Current (I_{SC}) 32

2.4.3 Open-Circuit Voltage (V_{OC}) 32

2.4.4. Maximum Power Point (MPP) 33

2.4.5 Fill Factor (FF) 33

2.5 PV Module Arrangement 33

2.5.1 Typical Model of a Solar PV array 34

2.6 Conclusion 35

CHAPTER III: SOLAR CELL TECHNOLOGIES 36
3.1 Introduction 36
3.2 Classification of solar Photovoltaic Cells 36
3.2.1 Silicon Cells 37
3.2.2 Single-Crystal Silicon Cells 37
3.2.3 Multi-crystalline Silicon Cells 38
3.2.4 Thin Silicon (Buried Contact) Cells 38
3.2.5 Amorphous Silicon Cells 38
3.2.6 Gallium Arsenide Cells 39
3.2.7 Copper Indium (Gallium) Diselenide Cells 40
3.2.8 Cadmium Telluride Cells 40
3.3 Emerging Technologies 41
3.4 Conclusion 42
CHAPTER IV: MAXIMUM POWER POINT TRACKING IN POWER CONDITIONING SYSTEM 43
4.1 Introduction 43
4.2 Need of MPPT Technique 43
4.2.1 DC-AC Converter Systems 44
4.2.2. DC-DC Converter Systems 45
4.3 Power Voltage and Voltage Current Characteristics of a Typical PV Module 46
4.4 Classification of MPPT Techniques 47
4.4.1 P&O-MPPT Technique 47
4.4.2 IC-MPPT Technique 50
4.5 Analysis of Other MPPT Techniques 51
4.5.1 Fractional Open-Circuit Voltage Technique 52
4.5.2. Fractional Short-Circuit Current Technique 52
4.6 Conclusion 52

CHAPTER V: INTRODUCTION TO POWER QUALITY 54
5.1 Introduction 54
5.2 Sources of Poor Power Quality 55
5.3 Need of Power Quality Concerns 55
5.4 Power Quality Problems 55
5.5 Solutions Adopted to Improve Power Quality 59
5.6 Power Quality Standards 59
5.7 Standards Related with Voltage Characteristics 59
5.7.1. IEEE Standards 59
5.7.2. IEC Electromagnetic Compatibility Standards 60
5.7.3. The European Voltage Characteristics Standards 60
5.8 Standards Related With Current Characteristics 61
5.8.1. IEEE Standards 61
5.8.2. The International Electro Technical Commission 62
5.9 Conclusion 62
CHAPTER VI: MATLAB & SIMULINK SOFTWARE 63
6.1 Introduction 63
6.2 Introduction to Matlab Software 63
6.3 Matlab Windows 64
6.4 Matlab File Types 65
6.5 Simulink Software 65
6.5.1 Controlling Execution of a Simulation 72
6.5.2 Starting a Simulation 72
6.5.3 Ending a Simulink Session 73
6.6 Conclusion 73

CHAPTER VII: SOLAR PV GRID CONNECTED SYSTEM WITH MPPT CONTROL..75
7.1 Introduction 75
7.2 System Computation Model 75
7.2.1. Rotating Reference Frame Transformation 76
7.2.2 Real & Reactive Power Control.....77
7.2.3. Synchronization and Control of Three-Phase Grid Connected Inverter System 79
7.2.4. Generation of PWM Pulses.....80
7.3 Controlling Scheme of Voltage Source Converter 82
7.4 Data MPPT Control for Maximum Power Point 84
7.6 Conclusion 89
CHAPTER VIII: EVALUATION AT DIFFERENT POWER FACTOR & FREQUENCY.....91
8.1 Introduction 91
8.2 Simulation Results and Discussion.....91
8.2.1 Case I at different power factors and same frequency 91
8.2.2. Case II at different frequency and same power factors.....100
8.3 Conclusion 104
CHAPTER IX: MODEL ANALYSIS WITH INCREMENTAL CONDUCTANCE MPPT TECHNIQUE 106
9.1 Introduction 106
9.2 Voltage and Current Controllers.....107
9.3 Solar PV Computation Model 108
9.4 Simulations Results and Discussion 110
9.5 Conclusion 115
CHAPTER X: MODEL ANALYSIS WITH PERTURB & OBSERVE MPPT TECHNIQUE 116
10.1 Introduction 116
10.2 Proposed System Configuration 116
10.3 Simulation Results and Case Studies.....117
10.4 Conclusion 122
References 123

List of Abbreviations

Air Mass	(AM)
Balance of System	(BOS)
Basic Linear Algebra Subprograms	(BLAS)
Bipolar Junction Transistor	(BJT)
Building Integrated PV	(BIPV)
Clean Power Plan	(CPP)
Copper Indium Gallium Diselenide	(CIGS)
Conference of Parties	(COP)
Electromagnetic Compatibility	(EMC)
Energy Information Administration	(EIA)
European Nation	(EN)
Fast Fourier Transform	(FFT)
Gallium arsenide	(GaAs)
Gigawatts-Thermal	(GWth)
Incremental Conductance	(IC)
Individual Harmonic Distortion	(IHD)
Independent Power Producers	(IPP)
Institution of Electrical and Electronic Engineering	(IEEE)
International Energy Outlook	(IEO)
Intended Nationally Determined Contributions	(INDCs)
Integrated Development Environment	(IDE)
International Electro-technical Commission	(IEC)
kilo-watt-hour	(KWH)
Linear Algebra PACKage	(LAPACK)

MATrix LABoratory	(MATLAB)
Maximum Power Point	(MPP)
Maximum Power Point Tracking	(MPPT)
Metal Insulator Semiconductor Inversion Layer	(MIS-IL)
Metal Oxide Semiconductor Field Effect Transistor	(MOSFET)
Million Tonnes of Oil Equivalent	(MTOE)
Molybdenum	(Mo)
Organization for Economic Cooperation and Development	(OECD)
Perturb & Observe	(P&O)
Phase Locked Loop	(PLL)
Photovoltaic	(PV)
Power Quality	(PQ)
Power-Voltage	(P-V)
Power Conditioning System	(PCS)
Pulse Width Modulation	(PWM)
Root Mean Square	(rms)
Sine Pulse Width Modulation	(SPWM)
Standard Test Condition	(STC)
Sustainable Development Goal	(SDG)
Total Demand Distortion	(TDD)
Total Harmonic Distortion	(THD)
Transparent Conducting Oxide	(TCO)
United Nations Framework Convention on Climate Changes	(UNFCCC)
Voltage-Current	(V-I)
Voltage Source Converter	(VSC)
Watt-Peak	(Wp)