Operation of grid-connected photovoltaic power plants during voltage sags

Tafti, Hossein Dehghani

2017

Tafti, H. D. (2017). Operation of grid-connected photovoltaic power plants during voltage sags. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/73062>

<https://doi.org/10.32657/10356/73062>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**OPERATION OF GRID-CONNECTED
PHOTOVOLTAIC POWER PLANTS
DURING VOLTAGE SAGS**

HOSSEIN DEHGHANI TAFTI

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

2017

OPERATION OF GRID-CONNECTED PHOTOVOLTAIC POWER PLANTS DURING VOLTAGE SAGS

HOSSEIN DEGHANI TAFTI

School of Electrical and Electronic Engineering

A thesis submitted to Nanyang Technological University
in partial fulfillment of the requirement for the degree of
PhD of Engineering

2017

*To my devoted father and kind mother
as well as my beloved sister and brothers
and of course to all of my loving friends
without whom none of my success would be possible*

Acknowledgements

This thesis would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

First of all, I would like to express my special appreciation and thanks to my supervisor, Associate Professor Ali Iftekhar Maswood for giving me an opportunity to carry on pursuing my interest in research works under his valuable guidance. His inspiring spirit and enthusiasm as well as his given advices throughout the years are especially recognized and appreciated. It is an honor and pleasure to have him as my supervisor.

I would like to express my gratitude to my advisors, Dr. Georgios Konstantinou and Associate Professor Josep Pou for giving me the exchange opportunity in University of New South Wales. This period was the most successful part of my Ph.D., while all of my experimental results are achieved. Without their kind and sincere guidances, this research was not possible. They are very warm hearted, and willing to help whenever I have a problem with my research work.

Professor Frede Blaabjerg from Aalborg University has given me several constructive and wonderful suggestions on my research studies. I would like to express my special thanks to him for his kind effort and helps during his busy schedule.

My special thanks go to my Thesis Advisory Committee members, Assistant Professor Abhisek Ukil and Assistant Professor Anutosh Chakraborty for their invaluable guidance and encouragement throughout my research.

Electric Power Research Laboratory, NTU has been source of great knowledge and lifetime friends. My pursuit for PhD was happy and pleasurable. A special thanks to Gabriel H. P. Ooi and Ziyu Lim for their patience discussions and encourages during difficulties.

I would like to take this opportunity to extend my thanks to the laboratory staffs in Electric Power Research Laboratory (EPRL), Mr. Lim Kim Peow and Ms Jennifer Ng-Tan Siew Hong for their kind supportive in purchasing hardware components and also the IT technical assistance provided. I am also deeply thankful to Ms Chew-Sim Annie and Ms Chua-Goh Wei Jiuan for their technical support regarding joining and continuing my studies.

I also would like to thank and appreciate all my colleagues and lab managers from University of New South Wales, Professor. Vassilios G Agelidis, Dr. Pablo Acuna Rios, Dr. Ricardo Aguilera Echeverria, Dr Baburaj Karanayil, Dr. Mihai Ciobotaru and Dr. Minsoo Jang. Many thanks also to Dr. Christopher D. Townsend from University of Newcastle for his kind helps and advices during my studies.

Financial assistance provided by the A*STAR (Agency for Science, Technology and Research) and Nanyang Technological University in the form of Graduate Scholarship is thankfully acknowledgeable.

I cannot miss mentioning my friends in Nanyang Technological University: Karthik Kandasamy, Nandha Kumar Kandasamy, Khan Md Shafquat Ullah, Mohd Tariq, Harikrishna Raj Pinkymol, Mohammad Roomi, Nima Saadat, Faranak Golestaneh, Assel Sakanova, Indira Khakda, Marcin Rowinski, as well my friends in University of New South Wales: W. M. Harith Wickramasinghe, Damith W. Abeywardana, Roky Baidya, Milad Momayyezani, Leonardo Callegaro, Alireza Heidari, Abdollah Ahmadi, Ghias Farivar and Evripidis Karatsivos for making my life during PhD a very memorable one. Also, I should mention my Iranian friends in Singapore, whom their moral supports were a great help during this candidature: Zahra Marvi, ALireza Barzegar, Sajjad Seifozakerini, Sajjad Maghare, Narjes Allahverdi, Amin Kiani, Mohammad Akbari, Hossein Nejati, Mohammad Khavari, Mahan Qava and all whom I might have forgotten to mention their name here.

Last but not least, I would like to thank my loving family. Words cannot express how grateful I am to my devoted father, my dear mother, lovely sister and brothers for all of the sacrifices that youve made on my behalf. Your prayer for me was what sustained me thus far.

Abstract

Renewable energy sources are occupying an increasing share in the global power generation market. Among various renewable energy sources, photovoltaic (PV) technology has been in the focus of many governments and, supported substantial subsidies has resulted a steep increase in the installed capacity. Moreover, with the decreasing trend in the PV panel costs from \$4.90/W in 1998 to \$0.3/W in 2015, the rate of growth of new PV installations is expected to remain at a high level. With high penetration of installed distributed generation (DG) units, power system operators (PSOs) are facing new challenges such as reliability, availability and power quality. In order to maintain the power quality and reliability of the power system, medium- and large-scale grid-connected photovoltaic power plants (GCPVPPs) should possess low-voltage ride-through (LVRT) capability, as regulated by new standards and grid codes. Therefore, improved GCPVPP structures with LVRT capabilities in combination with efficient control strategies are necessary. Accordingly, the detailed operation of medium- and large-scale GCPVPPs during voltage sags is studied in this thesis.

A typical two-stage multi-string PVPP consists of a dc/dc converter in each PV string and one central inverter. It is commonly recognized as one of state of the art configurations for medium- and large-scale GCPVPPs, due to its inherent advantages. Multilevel converters have emerged as the most viable solutions for high power energy conversion applications due to their capability of delivering excellent power quality with low harmonic contents and better efficiency, compared to the two-level converters. Therefore, multilevel converters have been proposed and discussed for multi-string GCPVPPs in this thesis.

Firstly, the operation of the GCPVPP with three-level neutral-point-clamped (3L-NPC) inverter with balanced current injection to the grid during voltage sags is investigated. An algorithm for the calculation of current references, in the dq-frame, during voltage sags is introduced, which considers the inverter current limitation, grid code requirements and the amount of extracted power from photovoltaic strings. The proposed algorithm uses the full current capacity of the inverter in injecting

active or reactive powers to the grid during voltage sags, which leads in a better grid voltage enhancement. The performance of proposed control strategy is investigated on a 150-kVA GCPVPP connected to the 12.47-kV medium-voltage test-case system simulation model during different voltage sag conditions. An experimental setup of the 3.3-kVA grid-connected three-level neutral-point-clamped inverter with a dc/dc converter illustrates and validates the performance of the controller in injecting required active/reactive power and supporting the network voltage.

Secondly, the operation of GCPVPPs during unbalanced voltage sags with the injection of unbalanced currents to the grid is studied. This control strategy results into the zero active power oscillation during unbalanced voltage sags. An analytical expression for the calculation of active and reactive power references of a grid-tied inverter is proposed, which limits the peak current of the inverter during voltage sags. The key novelty is that the active/reactive power references are analytically calculated based on the dc-link voltage and grid codes, while they do not depend on the implemented current reference calculation algorithm and, as a general formulation, can be implemented in combination with various current reference calculation algorithms. Furthermore, based on the inverter nominal current and the injected reactive power to the grid during voltage sags, an analytical algorithm is introduced for the calculation of the active power reference, which can be extracted from PV strings. The proposed algorithm ensures that the maximum current capability of the inverter is used for the enhancement of the grid voltages during voltage sags, while it always complies with the reactive power injection requirement of grid codes and avoids increasing the dc-link voltage excessively. Experimental results of a grid-connected 3.3-kVA, 3L-NPC inverter laboratory prototype under several voltage sag conditions are presented to demonstrate the effectiveness of the proposed controller.

The proposed unbalanced current injection algorithm is a general algorithm, which can be applied in various multilevel inverter topologies, however additional consideration on the operation of the inverter and voltage balancing of capacitors is required. Multilevel Cascaded H-Bridge (CHB) converters are one of the promising solutions for medium- and large-scale GCPVPPs. However, there is a lack of a complete study about their operation during voltage sags in the literature. Accordingly, a flexible control strategy is introduced for the operation of photovoltaic grid-connected CHB inverters during unbalanced voltage sags. The key novelty is that the proposed strategy is able to inject both active and reactive powers to the grid under

either balanced or unbalanced currents, while ensuring that all dc-link capacitor voltages remain balanced. A zero-sequence voltage injection algorithm is proposed for inter-phase balancing, which allows for energy exchange between various phases. For inter-bridge balancing, the extracted power from different bridges of one phase is changed by modifying bridge voltage references. A feedforward compensator is also applied to decrease the inverter transient current at the beginning of the voltage sag. The performance of the proposed control strategy is investigated on a 10-MVA photovoltaic power plant connected to a 6.6-kV medium-voltage test-case system simulation model. An experimental setup of a 9-kVA grid-connected seven-level CHB illustrates and validates the performance of the proposed strategy for the operation of the grid-connected CHB during different unbalanced voltage sags.

One of the issues of the operation of GCPVPPs during voltage sags, is the reduction of the extracted power from PV strings to a certain power reference. During the voltage sag, both active and reactive power are injected to the grid through the inverter, therefore the amount of the injected active power is reduced compared to the grid normal operation. In order to obtain a constant dc-link voltage in the GCPVPP, the extracted power from PV strings should be equal to the injected power to the grid in all operating conditions (excluding power losses). Consequently, a constant power generation (CPG) algorithm from PV strings is introduced in this thesis, which reduces the extracted power from the PV string to the required power reference. An algorithm for the calculation of the photovoltaic panel voltage reference, which generates a constant power from the GCPVPP, is suggested. The key novelty of the proposed algorithm is its applicability for both single- and two-stage GCPVPPs and flexibility to move the operation point to the right- or left-side of maximum power point. Furthermore, the frequency of operation for the algorithm and voltage increments between consecutive operating points are modified based on a hysteresis band controller in order to obtain fast dynamic response under transients and low power oscillation during steady-state operation. The performance of the proposed algorithm for both single- and two-stage GCPVPPs is examined on a 50-kVA simulation setup of these topologies. Moreover, experimental results on a 1-kVA PV system validate the effectiveness of the proposed algorithm under various operating conditions, demonstrating the proposed CPG algorithm functionalities.

The key contributions of this thesis can be summarized as:

- A control strategy for the multi-string GCPVPP with neutral-point-clamped

(NPC) inverter with LVRT capability is developed.

- An active/reactive power control of photovoltaic grid-connected inverters with peak current limitation and zero active power oscillation during unbalanced voltage sags is proposed.
- A flexible control of photovoltaic grid-connected cascaded H-bridge converters during unbalanced voltage sags is suggested.
- A general constant power generation algorithm for photovoltaic systems is introduced.

The proposed control strategies in this thesis enable the operation of medium- and large-scale GCPVPPs during voltage sags, while they achieve LVRT capability and comply with grid codes.

Table of Contents

Abstract	iv
Table of Contents	vii
List of Figures	xii
List of Tables	xvi
List of Acronyms	xvii
1 Introduction	1
1.1 Background and Motivations	1
1.2 Research Objectives	7
1.3 Major Contributions	9
1.4 Thesis Organization	11
2 Literature Review	15
2.1 Photovoltaic Power Conversion Topologies	15
2.2 Photovoltaic Power Plant Structures	18
2.2.1 Module Inverter	18
2.2.2 Central Inverter	19
2.2.3 String inverter	19
2.2.4 Multi-string inverter	20
2.2.5 Discussion about Various Issues of GCPVPPs	23
2.3 Investigated Topologies for Medium- and Large-Scale Photovoltaic Power Plants with Multilevel Inverters	25
2.3.1 Multi-string Photovoltaic Power Plant with Neutral-Point-Clamped Inverter	25
2.3.2 Multi-string Photovoltaic Power Plant with Cascaded H-Bridge Inverter	27
2.4 Grid Codes	28
2.4.1 Grid Requirements during Normal Operation	29
2.4.2 Grid Requirements during Voltage Sags	31

2.5	Conventional Control Strategies for GCPVPPs during Normal Operation	35
2.5.1	Direct-Power Control	37
2.5.2	Voltage-Oriented Control	38
2.5.2.1	Current Control in abc -Frame	39
2.5.2.2	Current Control in dq -Frame	40
2.5.2.3	Current Control in $\alpha\beta$ -Frame	40
2.5.2.4	Comparison of Current Control Strategies	41
2.5.3	Comparison of Voltage-Oriented and Direct-Power Controller Structures	42
2.6	Conventional Control Strategies for GCPVPPs during Voltage Sags .	45
2.6.1	Active/Reactive Power with Balanced Current Injection Strategies	47
2.6.2	Active/Reactive Power with Unbalanced Current Injection Strategies	47
2.6.3	Conventional Control Strategies of Grid-Connected CHB Inverter	48
2.6.4	Conventional Constant Power Generation Algorithms in GCPVPPs	49
2.7	Summary	52
3	Balanced Current Injection Strategy of PV Grid-Connected Inverter	55
3.1	Introduction	56
3.2	Control Strategy for GCPVPP with 3L-NPC Inverter during Normal Operation	56
3.3	Proposed Balanced Current Injection Control Strategy during voltage sags	60
3.3.1	Voltage Sag Detection	60
3.3.2	Adaptive Phase-Locked-Loop Control	61
3.3.3	Proposed Control Strategy for Inverter and dc-dc Converter during Voltage Sags	62
3.4	Simulation Results	67
3.4.1	Dynamic performance of the proposed controller	69
3.4.2	Grid voltage support during voltage sags	72
3.5	Experimental Evaluation	75
3.6	Summary	81
4	Unbalanced Current Injection Strategy for Grid-Connected Inverter	83
4.1	Introduction	83
4.2	Unbalanced Active/Reactive Power Theory	85

4.3	Proposed Active/Reactive Power Control Strategy during Unbalanced Voltage Sags	86
4.3.1	Proposed Active/Reactive Power Reference Calculation	87
4.3.2	Proposed Unbalanced Current Reference Calculation Algorithm with Zero Active Power Oscillation	90
4.3.3	Current Controller during Unbalanced Voltage Sags	91
4.3.4	dc-dc Converter Controller during Voltage Sags	93
4.3.5	Discussion on the Proposed PV String Control Algorithms	97
4.4	Experimental Evaluation	98
4.5	Discussion on the Proposed Balanced and Unbalanced Current Injection Algorithms	103
4.6	Summary	103
5	Operation of PV grid-connected CHB Inverter during Voltage Sags	105
5.1	Introduction	105
5.2	Proposed Control Strategy for Grid-Connected PV CHB Inverter	106
5.2.1	Feedforward Compensation	108
5.2.2	Proposed Inter-Phase Balancing Strategy	110
5.2.3	Inter-Bridge Balancing Strategy	112
5.3	dc-dc Converter Controller during Voltage Sags	113
5.4	Simulation Results	114
5.4.1	Simulation Results on the 10-MVA GCPVPP	115
5.4.2	Simulation Results on the 9-kVA GCPVPP	118
5.5	Experimental Evaluation	123
5.6	Summary	130
6	A General Constant Power Generation Algorithm in GCPVPPs	131
6.1	Introduction	131
6.2	Power Reduction Principles	133
6.3	Proposed Voltage Reference Calculation Algorithm	136
6.3.1	Proposed Time- and Voltage-Step Calculation Algorithm	137
6.3.2	Proposed Voltage Reference Calculation Algorithm	139
6.4	Simulation Results	142
6.5	Experimental Evaluation	153
6.6	Discussion on the Stability of the Proposed CPG Algorithm	158
6.7	Summary	160
7	Conclusion and Future Work	161

7.1	Conclusions	161
7.2	Recommendations for Future Research	165
List of Publications		169
References		173

List of Figures

1.1	Total global energy potential	2
1.2	Solar price and installation history between 1975 and 2015	3
1.3	Estimated renewable energy share of global electricity production, 2015	3
1.4	Solar global capacity and annual additions 2005 - 2015	4
1.5	Solar energy capacity additions, shares of top 15 countries and rest of the world, 2015	5
2.1	Various PV power conversion topologies	16
2.2	GCPVPP structure with module inverter.	19
2.3	GCPVPP structure: (a) Central inverter and (b) string inverter. . .	20
2.4	Different multi-string topologies	21
2.5	Grid-connected multi-string photovoltaic power plant with 3L-NPC inverter	26
2.6	Circuit configuration for a grid-connected photovoltaic power plant with CHB converter and dc-dc converters.	27
2.7	LVRT requirements defined in different countries covering a wide range of applications	33
2.8	Grid reactive current requirement for GCPVPPs connected to medium- voltage grid.	34
2.9	Basic Control Structure for multi-string GCPVPP with 3L-NPC inverter.	35
2.10	Direct-power control (DPC) structure.	37
2.11	Voltage-oriented control (VOC) structure.	38
2.12	abc -frame current controller.	39
2.13	dq -frame current controller.	40
2.14	$\alpha\beta$ -frame current controller	41
3.1	Control algorithm of GCPVPP with 3L-NPC inverter during grid <i>Normal</i> <i>operation</i>	57
3.2	Space vector representation of the 3L-NPC inverter.	58

3.3	Circuit diagram and current path for vectors of one vector pair in ASVM technique.	59
3.4	Voltage sag detection algorithm.	61
3.5	Schematic diagram of adaptive phase-locked-loop (PLL) algorithm. . .	62
3.6	Proposed current controller for multi-string GCPVPP with 3L-NPC inverter during voltage sags.	63
3.7	Power reduction strategy from PV strings during <i>Sag I</i>	65
3.8	Schematic diagram of the medium-voltage test-case network.	70
3.9	Dynamic performance of the multi-string GCPVPP with three PV strings during various operation modes	71
3.10	Dynamic current controller performance of the grid-connected 3L-NPC inverte	73
3.11	Voltage enhancement of the proposed active/reactive power injection strategy during different fault cases	74
3.12	Experimental setup of the grid-connected 3L-NPC inverter	76
3.13	Experimental results: <i>Sag I</i> - 36% two-phase voltage sag	78
3.14	Experimental results: <i>Sag II</i> - 70% three-phase voltage sag	80
4.1	Proposed current controller for grid-connected 3L-NPC inverter. . . .	91
4.2	Proposed current reference calculation algorithm during unbalanced voltage sags.	92
4.3	Proposed PV strings control algorithm.	94
4.4	(a) Power-voltage curve of the PV string and (b) dc-dc boost converter controller during voltage sags.	95
4.5	Simulation results of multi-string GCPVPP with three PV string during various operation modes	97
4.6	Experimental results: <i>Sag I</i>	101
4.7	Experimental results: <i>Sag II</i>	102
5.1	Proposed control strategy for grid-connected CHB inverter during voltage sags.	107
5.2	Feedforward compensation principle for the grid-connected CHB inverter	109
5.3	Proposed inter-phase balancing algorithm for grid-connected CHB inverter	111
5.4	Proposed inter-bridge voltage balancing algorithm: (a) Schematic of the proposed algorithm, (b) voltages vector diagram during unbalanced dc-link voltages in phase a.	112
5.5	Simulation results of GCPVPP 7L-CHB inverter with isolated dc-dc converters: <i>Case I</i> - 40% single-phase voltage sag with balanced current injection	117

5.6	Simulation results of GCPVPP 7L-CHB inverter with isolated dc-dc converters: <i>Case II</i> - 60% two-phase unbalanced voltage sag with unbalanced current injection	119
5.7	Simulation results of 9-kVA grid-connected 7L-CHB inverter: <i>Case I</i> - 30% single-phase voltage sag with unbalanced current injection	121
5.8	Simulation results of 9-kVA grid-connected 7L-CHB inverter: <i>Case II</i> - 70% three-phase voltage sag with balanced current injection	122
5.9	Simulation results of 9-kVA grid-connected 7L-CHB inverter: <i>Case III</i> - 70% long-duration three-phase voltage sag with unbalanced current injection	123
5.10	Experimental verification of the grid-connected CHB inverter	124
5.11	Experimental results of grid-connected 7L-CHB inverter: <i>Case I</i> - 30% single-phase voltage sag with unbalanced current injection	126
5.12	Experimental results of grid-connected 7L-CHB inverter: <i>Case II</i> - 70% three-phase voltage sag with balanced current injection	127
5.13	Experimental results of grid-connected 7L-CHB inverter: <i>Case III</i> - 70% long-duration three-phase voltage sag with unbalanced current injection	128
6.1	Various topologies of photovoltaic power plants: (a) Single-stage power conversion structure and (b) two-stage power conversion structure. . .	132
6.2	Power-voltage curve of the PV string	134
6.3	Proposed voltage reference calculation strategy.	136
6.4	Proposed voltage- and time-step calculation strategy	138
6.5	Proposed voltage reference calculation strategy	140
6.6	Control diagram of the single- and two-stage PVPP topologies.	142
6.7	Simulation results: (a) Implemented irradiance profile and (b) available power from the PV module at <i>MPP</i>	144
6.8	Simulation results - <i>Case I</i> : Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the left-side of <i>MPP</i>	146
6.9	Simulation results - <i>Case II</i> : Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the right-side of <i>MPP</i>	147
6.10	Simulation results - <i>Case III</i> : Constant power generation of the PV module in the single-stage topology with the movement of the voltage reference to the right-side of <i>MPP</i>	149
6.11	Simulation results - <i>Case V</i> : Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the right-side of <i>MPP</i>	150

6.12	Simulation results - <i>Case IV</i> : Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the left-side of <i>MPP</i>	151
6.13	Simulation results - <i>Case VI</i> : Constant power generation of the PV module connected in the single-stage topology with the movement of the voltage reference to the right-side of <i>MPP</i>	152
6.14	Experimental verification: (a) Schematic diagram of the dc-dc converter test system and (b) setup of the experiment.	154
6.15	Experimental results: <i>Case I</i> - Behavior of the proposed power reduction method under change of the power reference.	156
6.16	Experimental results: <i>Case II</i> - Behavior of the proposed power reduction method under change of the irradiance	157
7.1	Circuit configuration for the grid-connected PV power plant with full-row connected H-Bridge converter and isolated dc/dc converters. . . .	166
7.2	Circuit configuration for the grid-connected PV power plant with 4-leg NPC inverter.	167
7.3	High diurnal PV power variability in a typical day for Australia, January 2013.	167

List of Tables

1.1	List of ten largest installed photovoltaic power plants in the world . .	5
1.2	The association between thesis chapters and list of key contributions of the thesis	11
1.3	The association between thesis chapters and author publications ² . .	14
2.1	Comparison of various PV power conversion topologies.	17
2.2	Various Issues of GCPVPPs.	24
2.3	IEEE 1547 and IEC 61727 maximum current harmonics for GCPVPPs.	29
2.4	EN 50160 public distribution grid voltage harmonics.	30
2.5	Limits of injected dc current for different standards.	31
2.6	Standard disconnection time for voltage variations.	32
2.7	Standard disconnection time for frequency variations.	32
2.8	Comparison of various current controllers.	43
2.9	Comparison of VOC and DPC control structures.	45
3.1	Sharp NU-U235F1 electrical characteristics.	68
3.2	Simulation parameters of the GCPVPP with NPC inverter	68
3.3	PCC voltage enhancement under various fault conditions	75
3.4	Experimental Parameters of the GCPVPP with NPC inverter	77
4.1	Experimental parameters for grid-connected 3L-NPC inverter	99
5.1	Simulation and Experimental Parameters of the GCPVPP with CHB inverter	116
6.1	Simulation parameters of the grid-connected inverter with <i>CPG</i> capa- bility	143
6.2	Parameters of the experimental setup of dc-dc converter	155

List of Acronyms and Notations

A. List of Acronyms

ASVM	Adaptive Space Vector Modulation
CHB	Cascaded H-Bridge converter
CPG	Constant Power Generation
DG	Distributed Generation
GCPVPP	Grid-Connected Photovoltaic Power Plant
HFT	High-Frequency Transformer
INC	Incremental Conductance
LVRT	Low-Voltage Ride-Through
LFT	Low-Frequency Transformer
MV	Medium Voltage
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NPC	Neutral-Point-Clamped converter
O.C.	Open Circuit
P	Active Power
PCC	Point of Common Coupling
PI controller	Proportional Integral controller
PR controller	Proportional Resonant controller
PV	Photovoltaic
PWM	Pulse-Width Modulation
PSPWM	Phase-Shifted Pulse-Width Modulation
P&O	Perturb and Observe
PSO	Power System Operator
Q	Reactive Power
RP	Reduced Power operation mode
RES	Renewable Energy Source
SOGI	Second Order Generalized Integrator

STATCOM	Static Synchronous Compensator (S
SVM	Space Vector Modulation
3L-NPC	Three-Level Neutral-Point-Clamped converter
7L-CHB	Seven-Level Cascaded H-Bridge converter

B. List of Notations

C_u/C_l	dc-link upper/lower capacitor
C_{pv}	PV panel capacitor
f_0	Fundamental frequency
f_s	Switching frequency
FF	PV panel filling factor
Ir	Solar irradiation
i_d	d-axis current
i_q	q-axis current
i_α	α -axis
i_β	β -axis
i_{abc}	Three-phase current
i_{mpp}	PV panel maximum power point current
k_1	Ratio of the positive-sequence active power
k_2	Ratio of the positive-sequence reactive power
L_f	Inductor filter
p	Active power
P^+	Positive-sequences of the average active power
P^-	Negative-sequences of the average active power
Δp_{th}	Threshold power
q	Reactive power
p_{mpp}	PV panel maximum power
v_{dc}	dc-link voltage
v_{mpp}	PV panel maximum power point voltage
v_d	d-axis voltage
v_q	q-axis voltage
V_{ref}	Calculated voltage reference through the MPPT/CPG algorithm
$\hat{v}_{min}$	Minimum phase voltage amplitude
$ v_{pcc} $	PCC voltage

$ v_{pcc}^+ $	Amplitude of PCC voltage positive-sequence
$ v_{pcc}^- $	Amplitude of PCC voltage negative-sequence
Δv_{pv}	PV string voltage
$V_{step-mppt}$	<i>MPPT</i> mode voltage-step
$V_{step-cpg-st}$	Steady-state <i>CPG</i> mode voltage-step
$V_{step-cpg-tr}$	Transient <i>CPG</i> mode voltage-step
S	Apparent power
T	Temperature
T_0	Fundamental frequency grid voltage period
T_{step}	Voltage calculation execution time-step of MPPT/ <i>CPG</i> algorithm
$T_{step-mppt}$	<i>MPPT</i> mode time-step
$T_{step-cpg-st}$	Steady-state <i>CPG</i> mode time-step
$T_{step-cpg-tr}$	Transient <i>CPG</i> mode time-step
t	Time

Chapter 1

Introduction

This chapter presents the trends of energy consumption in the world, while tendencies towards the application of solar energy for electricity production are also described. The historical developing road map of photovoltaic (PV) power plants and PV panel costs are expressed. Finally, the motivations of the present research and its contributions are discussed.

1.1 Background and Motivations

With the fast increase in the world energy demand a huge amount of resources, economical and human are invested to develop new technologies for energy production. Electricity has a lot of advantages among all varieties of energy types, like easy transmission and easy conversion to other types of energy. Therefore, it has become the dominant type of energy used by industry and domestic units. The need of independence from fossil fuels and increasing rate of fossil fuel prices have led the research and industry towards developing cheaper energy resources. On top of that, because of the global warming issues, renewable and clean energy systems are necessary for a sustainable energy in the future. Renewable energy (RE) is defined as the energy that is extracted from resources, which can naturally be reproduced on a human time-scale. There are several types of renewable energy sources (RESs) like wind, sunlight, rain, tides, waves and geothermal heat. Renewable energy can also be seen as a clean energy, because it does not produce greenhouse gases. Furthermore, the renewable energy is a critical part of the energy portfolio in order to achieve a sustainable and secure energy production in the future.

Among various types of renewable energy sources, wind and solar are most widely extended. Other RESs like geothermal or wave energy are still developing. Wind energy is more widely used by electric power system, however the solar energy is also growing rapidly in the recent years.

Solar irradiation is available all over the world and is the main source of all other energy resources. Fig. 1.1 represents the global energy potential that can be produced by various energy resources [1]. The total energy consumption is 16 TW-year. Among non-renewable energy sources, coal has the biggest potential in energy production with 900 TW-year. The total amount of the oil and natural gas potential is around 455 TW-year and if these two sources are used as the only source of energy, they can provide energy for the world only for 28 years. This figure shows the importance of using renewable energy sources, which are replenished during a human age scale. Solar energy has the most potential of energy production compared to all types of primary energy resources. The potential amount of solar energy is 23,000 TW-year. On top of that, solar energy has some benefits compared to other RESs. It does not require moving parts for producing electricity and needs less maintenance. Following development in material science, the cost of PV panels is decreasing drastically, as shown in Fig. 1.2. The PV panel cost is reduced from \$4.90/W in 1998 to \$0.3/W in 2015. On top of that with improved material designs, the energy conversion efficiency of PV panels is increasing, resulting in higher amount of extracted electric power

Figure 1.1: Total global energy potential [1].

Figure 1.2: Solar price and installation history between 1975 and 2015 [2].

from solar irradiation. Consequently, the global solar panel installation is increased to 64,892 MW in 2015 [2].

Nowadays many countries are increasing the amount of electricity production from RESs. The estimated share of various energy resources for producing electricity in 2015 is illustrated in Fig. 1.3. In this year, more than 76% of the electricity is produced from non-renewable energy resources, while an estimated amount of 16.6% is generated from hydropower [3]. Among other RESs, the wind energy participated in producing around 3.7% of electricity, while 1.2% is devoted to the solar energy. This statistical data shows that renewable energy production will be the most impor-

Figure 1.3: Estimated renewable energy share of global electricity production in 2015 [3].

tant challenge in the upcoming years for the electricity production. Therefore, new technologies and novel designs are necessary to improve the conventional structure and improve the efficiency, availability and reliability of renewable energy production. Furthermore, it can be seen from Figs. 1.1 and 1.3 that the solar energy has the largest potential capacity in the electricity production, however, it is not still utilized as a major resource in producing electricity. Consequently, higher efforts are necessary from researchers and engineers for developing solar energy conversion facilities.

Fig. 1.4 presents the world total installed PV power plant capacity [3]. The amount of installed PV capacity is increased drastically from 5.1 GW in 2005 to 227 GW in 2015, which shows a growth rate of 8000% over 10 years. Furthermore, the rate of growth is also doubled from 2012 to 2015, which was 50 GW. The solar capacity addition share of top 15 countries is illustrated in Fig. 1.5 [3]. China is on the top with 30% share of the global solar installed capacity, while Japan and United States are ranked as second and third with 22% and 15% solar addition share, respectively. In addition to the increasing rate of installed solar capacity in the world, the capacity of installed grid-connected photovoltaic power plants (GCPVPPs) has also been increased drastically, in the recent years. Solar power plants have grown from rooftop domestic capacities to large PV farms with capacity of more than 800 MW. The list of the ten largest installed GCPVPPs in the world in 2016 is presented in

Figure 1.4: Solar global capacity and annual additions 2005 - 2015 [3].

Figure 1.5: Solar energy capacity additions, shares of top 15 countries and rest of the world in 2015 [3].

Table 1.1 [4]. Two of the largest installed PV power plants according to 2016 data are the "Longyangxia Dam Solar Par" and the "Kamuthi Solar Power Project" in China and India with 850 MW and 648 MW capacity, respectively. "Longyangxia Dam Solar Park", completed in 2015, is integrated with a hydroelectric power station. The park is coupled to one of the hydroelectric turbines, which automatically regulates the output to balance the variable generation from solar before dispatching power to the grid. This limits the problems caused by variable solar generation, while it helps to conserve water. For a comparison of this GCPVPP capacity, it can be noted that the largest electric power plant from other energy resources is the hydroelectric "Three Gorges Dam" with capacity of 22,500 MW in China.

Table 1.1: List of ten largest installed photovoltaic power plants in the world [4]

Name	Capacity (MW _p)	Annual Generation(GWh)	Location	Year
Longyangxia Dam Solar Park	850	6000	China	2015
Kamuthi Solar Power Project	648	1300	India	2016
Solar Star (I and II)	597	1664	U.S.A	2015
Topaz Solar Farm	550	1301	U.S.A	2014
Desert Sunlight Solar Farm	550	1287	U.S.A	2015
Huanghe Hydropower Golmud Solar Park	500	317	China	2014
Copper Mountain Solar Facility	458	1086	U.S.A	2015
Quaid-e-Azam Solar Park	400	1000	Pakistan	2015
Yanchi Solar Park	380	525	China	2016
Charanka Solar Park	345	400	India	2012

It should be mentioned that all of the presented data are for PV power plants which directly produce electricity through PV panels. In other types, the extracted energy from the sun is converted to the thermal energy by concentrating the solar radiation into some especial points. This study focuses on the PV power plants which directly produce electricity using PV panels.

In summary, GCPVPPs have several advantages, which lead their increasing growth in the power system

- + Solar energy, which is the source of energy for GCPVPPs, has the largest potential for producing energy compared to all other primary sources of energy and is also available in almost all parts of the world.
- + GCPVPP utilizes the solar energy, which is a non-polluting and renewable source of energy.
- + GCPVPP can be installed quickly and is easily portable.
- + Moving parts do not exist in GCPVPPs and they do not produce noise.
- + Operation and maintenance cost of the GCPVPP is relatively low compared to other types of power plants.
- + GCPVPP have long operation period or lifespan (25 years).
- + Stand-alone photovoltaic power plants (PVPPs) can be installed in remote areas, where the cost of grid connection is excessively high.
- + GCPVPPs can be greatly effective in supplying peak energy demand during the day, because the peak generation time of PV power plants is usually same as daily peak demand time, especially during summer.
- + PV panel costs are drastically decreasing during recent years and currently the electric generation cost from GCPVPPs is relatively competitive to the electric generation cost of other power plants.
- + Since PV energy is renewable and clean, various governments regulate encouraging policies like reducing tax and etc. for PVPP owners.

Despite of the mentioned advantages of solar power plants, they also have various disadvantages, which can the pathway of research in this area:

- Despite the fact that solar power conversion is excessively enhanced during the recent years, the energy conversion efficiency is still low in comparison to other types of power plants. In this area, design of high efficient PV modules with new materials and other improvements are required.
- The output power of PV power plants is dependent on the weather conditions and accurate forecast methods are necessary for planning and supplying loads during cloudy conditions.
- Partial shading of PV panels affect the efficiency of the PV power plant and methods for extracting maximum power from the GCPVPP are required to be improved.
- High penetration of the installed PV power plants and other renewable energy sources in the power system results in various challenges and difficulties in terms of reliability, availability, power quality and protection.

According to the presented data for RESs and solar energy, it can be easily seen that medium- and large-scale GCPVPPs will play a major role in the future energy mix globally. Therefore, research on new designs and operation methods of these types of power plants in order to improve their efficiency, reliability and availability, is necessary to achieve a sustainable and secure energy for the future. These factors motivate the research on various topologies and control strategies of medium- and large-scale GCPVPPs.

1.2 Research Objectives

High penetration of distributed generators (DG) in the power system, results in new challenges for power system operators (PSOs). DGs can exacerbate the power quality of the grid by injecting current harmonics. Also the probabilistic characteristic of generated power of a DG unit reduces the reliability of the electricity for customers. Initially, low-voltage ride-through (LVRT) capability was introduced by PSOs in order to withstand voltage sags and maintain the connection to the grid and avoid loss of power generation [5,6]. Later, reactive power injection was added in grid

codes with the intention of supporting the grid voltage and reducing the possibility of voltage collapse during network faults. Furthermore, negative-sequence current injection appears to be a new important requirement of next generation of grid codes for enhancing the DG capabilities in supporting unbalanced voltage sags [7]. Consequently an improvement in the design of DG units is necessary to maintain the power quality and reliability of the power system.

Among various DG units, GCPVPPs have recently achieved a drastic increase in the installed capacity due to the decreased module prices and favorable incentive policies [8]. As a result, LVRT became a necessary requirement for medium- and large-scale GCPVPPs. Several studies have been performed on LVRT capability of single- and two-stage GCPVPPs considering the injection of balanced active/reactive currents to the grid during voltage sags [9,10].

Unbalanced voltage sags are more common in power systems, causing several adverse effects including overloading of distribution transformers, higher losses and lower stability of the power system. The negative-sequence component of the voltage results in double fundamental frequency oscillation of the injected active or reactive power to the grid. On the other hand, injection of balanced reactive currents during unbalanced grid voltage sags, may result in overvoltage of nonfaulty phases [11–13]. Therefore, the design of the controller of the grid-connected inverter becomes more challenging during unbalanced grid voltage sags.

During the voltage sags, due to the required reactive power injection to the grid. The amount of injected active power should be reduced. Accordingly, the extracted power from PV strings is regulated to a specific reference value to prevent the increase of the dc-link voltage. Accordingly, the controller of the dc-dc converters should be modified in order to be able to extract a constant power from PV strings, instead of maximum power. The implemented constant power generation algorithm, should also be capable of operation during partial shading of PV strings, which result in multiple maximum power points.

The main objectives of this thesis are:

- Suggestion of a control strategy for GCPVPP in order to enable the LVRT capability and inject the required reactive power to the grid based on grid codes.
- Minimization of the output active power oscillation of the GCPVPP inverter

during voltage sags, with the aim of reduction of dc-link capacitor voltage ripples.

- Analysis the performance of various types of multilevel converters for GCPVPP and implementation of required control strategies for their stable and fast operation during voltage sags.
- Suggestion of a novel control strategy, which reduces the extracted power from PV strings to a certain level during voltage sags, in order to achieve the stable operation of GCPVPP during various operation modes, including partial shading of PV strings.

1.3 Major Contributions

Based on the presented objectives, research work has been conducted and reported in this thesis. The major contributions of this thesis are as follows. The associated author publication to each contribution is also referred¹.

1. **Control strategy for the multi-string GCPVPP with neutral-point-clamped (NPC) inverter with LVRT capability**

*Author publication number*¹: [1], [9], [10] and [11].

The main novelty of this control strategy is that it complies with grid codes in injecting the required reactive power to the grid during voltage sags, while it uses the full current capacity of the inverter by injecting active power during voltage sags. Consequently, a higher voltage enhancement at point of common coupling (PCC) is achieved compared to conventional algorithms. Furthermore, a control algorithm is introduced for the dc-dc converter of the multi-string GCPVPP, which reduces the extracted power from PV strings to the amount of power which can be injected to the grid during voltage sags. The proposed control strategy ensures the stable operation of the GCPVPP with grid-connected NPC inverter during various voltage sags.

2. **Active/reactive power control of photovoltaic grid-connected inverters with peak current limitation and zero active power oscillation during unbalanced voltage sags**

¹Refer to page 169 for Author List of Publications.

Author publication number: [4] and [6].

An analytical expression for the calculation of active and reactive power references of a grid-tied inverter is introduced, which limits the peak current of the inverter during voltage sags. The key novelty is that the active/reactive power references are analytically calculated based on the dc-link voltage and grid codes, while they do not depend on the implemented current reference calculation algorithm and, as a general formulation, can be implemented in combination with various current reference calculation algorithms. Furthermore, based on the inverter nominal current and the injected reactive power to the grid during voltage sags, an analytical algorithm is introduced for the calculation of the active power reference, which can be extracted from PV strings. The proposed algorithm ensures that the maximum current capability of the inverter is used for the enhancement of the grid voltages during voltage sags, while it always complies with the reactive power injection requirement of grid codes and avoids increasing the dc-link voltage excessively. An unbalanced current injection algorithm is also applied for the grid-tied inverter which results in zero active power oscillation.

3. Flexible control of photovoltaic grid-connected cascaded H-bridge converters during unbalanced voltage sags

Author publication number: [3], [7] and [8].

A flexible control strategy is proposed for the operation of photovoltaic grid-connected Cascaded H-Bridge (CHB) inverters during unbalanced voltage sags. The key novelty is that the proposed strategy is able to inject both active and reactive powers to the grid with either balanced or unbalanced currents, while ensuring that all dc-link capacitor voltages remain balanced. A zero-sequence voltage injection algorithm is proposed for inter-phase balancing, which allows for energy exchange between various phases. For inter-bridge balancing, the extracted power from different bridges of one phase is changed by modifying bridge voltage references. A feedforward compensation is also applied to decrease the inverter transient current at the beginning of the voltage sag.

4. A general constant power generation algorithm for photovoltaic systems

Author publication number: [2] and [5].

An algorithm is introduced for the calculation of the photovoltaic panel voltage

reference, which generates a constant power from the PVPP. The key novelty of the proposed algorithm is its applicability for both single- and two-stage PVPPs and flexibility to move the operation point to the right- or left-side of maximum power point. Furthermore, the frequency of execution for the algorithm and voltage increments between consecutive operating points are modified based on a hysteresis band controller in order to obtain fast dynamic response under transients and low power oscillation during steady-state operation.

The association between the chapters of the thesis and the above-mentioned list of key contributions is provided in Table 1.2.

Table 1.2: The association between thesis chapters and list of key contributions of the thesis

Chapter number	Contribution number
3	1
4	2
5	3
6	4

1.4 Thesis Organization

This thesis comprises seven chapters, and the organization of which are summarized as follows:

Chapter 1 provides the statistical information about solar energy generation and its growth in the recent years. The issues of high penetration of DG units in the power system are also discussed, while the importance of research in this area is presented. The motivations, objectives and contributions of the research work along with the organization of this thesis are also discussed in this chapter.

Chapter 2 reports a brief literature review of the works related to this study. Various topologies of GCPVPPs are discussed, while their advantages and disadvantages for large-scale GCPVPPs are explained. Moreover, grid code requirements are presented, followed by a brief explanation of various control strategies of grid-connected inverters. Their characteristics during different operation modes are analyzed, while a sample control structure for the operation of GCPVPP with the NPC inverter is

illustrated. Finally, the issues of the available control strategies in the literature for the operation of GCPVPPs during voltage sags are deeply investigated. Based on these issues, the importance of this research study is also presented.

Chapter 3 proposes an algorithm for calculating dq -axis current references during voltage sags based on inverter current limitation, grid code requirements and the amount of extracted power from PV strings. The proposed algorithm injects balanced currents to the grid during various types of voltage sags. It ensures that the full current capacity of the inverter is used in injecting active/reactive power to the grid during voltage sag in order to enhance the grid voltage during voltage sags. In order to obtain a constant dc-link voltage and maintain the active and reactive power injection during voltage sags, a coordinated maximum power point tracking (MPPT) algorithm is also implemented for the dc-dc converters of the multi-string PVPP, which reduces the extracted power from PV strings to the amount of active power that can be injected to the grid according to the inverter nominal current and the injected reactive current. The simulation and experimental results supporting the applicability of the proposed algorithm are also provided.

Chapter 4 derives an analytical expression for calculating active/reactive power references which limits the inverter peak current during voltage sags. The proposed algorithm injects unbalanced currents to the grid during unbalanced voltage sags, which results in zero active power oscillation. Additionally, an analytical expression is introduced which calculates the required active power from PV strings during voltage sags. This method ensures that the inverter current remains within its nominal operation range and also keeps the dc-link voltage at its nominal value. In order to obtain a constant dc-link voltage and maintain the active and reactive power injection during voltage sags, a coordinated maximum power point tracking (MPPT) algorithm is also implemented for the dc-dc converters of the multi-string GCPVPP, which reduces the extracted power from PV strings to the amount of active power that can be injected to the grid according to the inverter nominal current and the injected reactive current. The performance of the proposed algorithm is evaluated using simulation and experimental tests and results are provided.

Chapter 5 introduces a flexible control strategy for the operation of grid-connected

PV cascaded H-bridge (CHB) inverter during unbalanced voltage sags. The proposed strategy is capable of balancing dc-link voltages while injecting both active and reactive powers with either balanced or unbalanced currents. A zero-sequence voltage injection algorithm is proposed for inter-phase balancing, which allows for energy exchange between various phases. For inter-bridge balancing, the extracted power from different bridges of one phase is changed by modifying bridge voltage references. A feedforward compensation is also applied to decrease the inverter transient current at the beginning of the voltage sag. The performance of the proposed control strategy is investigated on a 10-MVA GCPVPP simulation setup under various voltage sags, while experimental results of a 9-kVA grid-connected 7L-CHB inverter setup are also presented, which validate the capability of the proposed algorithm for the operation of the grid-connected CHB inverter during voltage sags. Unbalanced voltage sags are more common compared to balanced voltage sags and the operation of the grid-connected PV CHB inverter during balanced voltage sags or normal grid condition is also easier to deal with. Therefore, unbalanced voltage sags are taken into consideration in all of the investigated case studies in this chapter, while the proposed control strategy can also be used during grid normal operation or balanced voltage sags.

Chapter 6 proposes a general algorithm for the calculation of the PV panel voltage reference, which leads to generation of a constant power from the PV panel during voltage sags. The proposed algorithm is an adaptation of the perturb and observe (P&O) algorithm, based on the characteristics of the power-voltage (P-V) curve of the PV panel. During the constant power generation (CPG), the typical MPPT algorithm is replaced with the proposed algorithm to calculate the voltage reference based on the required power reference and as a result no modification is made in the controller of the dc-dc converter. Unlike the presented studies in the literature, the proposed algorithm is flexible to move the operation point of the PV panel to the right- or left-side of the *MPP* and is also applicable in both single- or two-stage PVPPs. A hysteresis band controller is proposed to change the frequency of execution for the algorithm (time-step) and voltage increments between consecutive operating points (voltage-step) in order to achieve fast dynamic response and low power oscillation during steady-state operation of the controller. The generality and flexibility of the proposed algorithm is evaluated using simulation and experimental validation on various PVPP topologies and different irradiance and power reference curves.

Chapter 7 presents the overall assessment of this research work as well as the recommendations for future work. Followed by this chapter are the List of authors publications and Bibliography related to this research work.

The association between the chapters of the thesis and the author publications is as follows².

Table 1.3: The association between thesis chapters and author publications²

Chapter number	Author publication number
2	[1] - [11]
3	[2], [9], [10], [11]
4	[4], [6]
5	[3], [7], [8]
6	[1], [5]

²Refer to page 169 for Author List of Publications.

Chapter 2

Literature Review

This chapter reviews the available research studies in the literature about GCPVPPs. Firstly, various topologies of GCPVPPs and their characteristics are stated, followed by a discussion on the selection of the suitable architecture for medium- and large-scale GCPVPPs. Afterwards, investigated GCPVPP topologies in this thesis are introduced, followed by a brief description of grid codes. Several control strategies of GCPVPPs are explained in conjunction with their characteristics during various operation conditions. Finally, the issues of available control strategies for GCPVPPs operation during voltage sags are explained and accordingly, the requirements for the improvements, introduced this thesis, are presented.

2.1 Photovoltaic Power Conversion Topologies

The dc output voltage of the PV panel should be converted to the ac voltage, suitable for connection to the grid. Therefore, always a dc/ac power conversion is necessary to adapt the electrical characteristics of the PV panel with the grid. As shown in Fig. 2.1, various topologies can be used for this purpose [14,15]. It should be mentioned that in Fig. 2.1, a PV panel symbol can be a represent for one PV panel or a number of series and/or parallel connected PV panels.

Some topologies, like Fig. 2.1(a), (c) and (e), utilize only one dc/ac power conversion stage. In this design, the dc/ac converter should extract the maximum power from the PV module. Moreover, the dc/ac converter should control the grid current to regulate the injected power to the grid with the extracted power from PV panels.

In Fig. 2.1, topologies (b), (d) and (f) use a dc/dc conversion stage beside the dc/ac inverter. In this topology, the dc/dc converter extracts the maximum power from the PV strings. The extracted power is transferred to the dc-bus. The dc/ac inverter controls the grid injected current based on the extracted power from PV modules. The multi-string PV power plant is based on the dual stage energy conversion architecture. However dual stage energy conversion structure can be used in all PV power plant structures. The main reason of using the dc/dc converter, is adding a freedom to the controller for extracting the maximum power in all environmental conditions including partial shading.

Another issue in PV power plants is the earth leakage current, which may cause safety issues. As a result, all of the PV power plants should include earth leakage current elimination methods based on standards. Earth leakage current can be limited using two different methods. Some topologies use the advantage of isolation transformers in eliminating the earth leakage current. Other topologies apply extra

Figure 2.1: Various PV power conversion topologies: (a) dc/ac, (b) dc/dc-dc/ac, (c) dc/ac with LFT, (d) dc/dc-dc/ac with LFT, (e) dc/ac-ac/ac with HFT and (f) dc/dc-dc/ac with HFT.

Table 2.1: Comparison of various PV power conversion topologies.

Characteristic	dc/ac	dc/ac with LFT	dc/ac-ac/ac with HFT	dc/dc-dc/ac	dc/dc-dc/ac with LFT	dc/dc-dc/ac with HFT
Figure number	Fig. 2.1(a)	Fig. 2.1(c)	Fig. 2.1(e)	Fig. 2.1(b)	Fig. 2.1(d)	Fig. 2.1(f)
Reference	[16–20]	[21–23]	[14]	[24–27]	[28, 29]	[30]
Isolation	Earth-leakage current should be controlled	Yes	Yes	Earth-leakage current should be controlled	Yes	Yes
dc component of the injected current	It has to be controlled	No	No	It has to be controlled	No	No
MPPT is implemented in	dc/ac inverter	dc/ac inverter	dc/ac inverter	dc/dc converter	dc/dc converter	dc/dc converter
Transformer	No	Conventional, high weight and volume	High-frequency, low weight and volume	No	Conventional, high weight and volume	High-frequency, low weight and volume
Efficiency	Very good	Medium	Good	Good	Medium	Good
Power range	Low	High	High	Medium - High	High	Medium - High

controller to the dc/dc or dc/ac converter to reduce the earth leakage current.

Table 2.1 compares the characteristics of various PV energy conversion topologies. dc/ac and dc/dc-dc/ac topologies apply extra controller to reduce the earth leakage current. Several studies employed low-frequency transformer (LFT) on the ac side. This transformer operates at grid frequency and boosts the output voltage of the inverter to the grid voltage level. Since the LFT is operating at the grid frequency, it requires large core, which is heavy and bulky. Also, the total losses are increased in the topology with LFT, which reduces the overall efficiency of the GCPVPP.

High-frequency transformers (HFT) are smaller than LFTs for similar power ratings. On top of that, the application of HFT reduces the overall losses compared to LFT. As a result, some recent studies apply the HFT in the PV energy conversion architecture. The HFT can be implemented in the dc/dc or dc/ac converter. dc/ac-ac/ac with HFT applies a matrix converter to convert the high frequency voltage to the voltage with grid frequency. In this topology, the HFT is implemented in the dc/dc converter. As shown in Fig. 2.1(f), the output voltage of the PV panel is converted to a high frequency voltage, which flows through the isolation HFT. Afterwards, by using diode bridge rectifier, the high frequency voltage is rectified to the dc voltage. Finally, the dc/ac inverter transfers the dc power of dc-bus to the

grid. It can be seen from table that dc/dc-dc/ac with HFT topology shows better performance in efficiency and size and can be applied for medium and high power applications. Consequently, this topology is the state of the art for multi-string PV power plants [31].

It should be noted the dc-dc converters produce additional power losses. Nevertheless, the overall output power of the GCPVPP increases by extracting the maximum power from all of the PV strings and decoupling the second harmonic voltage ripple from them. Additionally, safety standards regulate the inclusion of an isolation transformer in the GCPVPP, which can be complied with the inclusion of high-frequency transformers.

2.2 Photovoltaic Power Plant Structures

Usually, the output power of commercial PV panel products is less than 300 W and is not sufficient to supply big loads. Therefore, it is necessary to connect certain number of PV panels in series and/or parallel to achieve an acceptable output power. Various structures are proposed in the literature for GCPVPPs. Some of them connect several PV panels in series and/or parallel and apply a dc-dc converter to boost the voltage and some of them do not utilize dc-dc converters [32, 33]. These structures can be categorized into four main types, which are explained in the following subsections.

2.2.1 Module Inverter

Module inverter structure is depicted in Fig. 2.2 [14]. Each PV panel is connected to an individual inverter that transfers the power from the PV panel to the grid. As mentioned, the normal power rating of a PV panel is less than 300 W and as a result this topology can only be used for domestic applications or small loads. There is no mismatch problem and inverter can easily extract the maximum power from the PV panel under various environmental conditions. The modular topology simplifies the modification of the whole system because of its plug & play characteristic and can be operated with domestic users who do not have enough knowledge about its operation principles. On the other hand, for generating large amount of power, high number of modules should be connected in parallel with a more complicated control structure. On top of that, the necessity of high voltage amplification can increase the cost of

the inverter and reduce the overall efficiency of this topology [14].

Figure 2.2: GCPVPP structure with module inverter.

2.2.2 Central Inverter

In the central inverter topology, PV panels are connected as parallel strings. Each string consists of a certain number of series connected PV panels. As shown in Fig. 2.3(a), all of the paralleled strings are connected to one central inverter. The inverter extracts the power from PV panels and transfers it to the grid. This topology is used for large-scale or utility-scale GCPVPPs like the 750-kW power station in [34]. Usually, the dc-bus voltage is 550-850 V and as a result a certain number of PV panels should be connected in series in each string to achieve the required dc-voltage. Due to the partial shading or mismatch between PV panels, extracting the maximum power from the PV plant is challenging. String diodes are applied to avoid the reverse current in shaded PV panels. The power loss of these blocking diodes, reduces the overall efficiency of this structure. Furthermore, the reliability of the GCPVPP depends on the only available central inverter. This increases the failure probability. The required long high-voltage dc cables between PV modules and the central inverter also increases the power losses [14].

2.2.3 String inverter

String inverter topology consists of a series connection of PV panels with an individual inverter (Fig. 2.3(b)). Voltage amplification can be eliminated by sufficient number of series connected PV panels. In some countries like Germany and Spain, the galvanic isolation transformer also can be avoided which results in higher energy

Figure 2.3: GCPVPP structure: (a) Central inverter and (b) string inverter.

conversion efficiency. The maximum power of the string can be extracted by its individual inverter and partial shading of parallel strings does not affect the maximum power extraction. In comparison to the central inverter structure, no blocking diode is required in strings and as a result losses of the diode is avoided. This topology reduces the power plant price in comparison to module inverters [35].

2.2.4 Multi-string inverter

Multi-string topology is a modified version of the centralized inverter topology. In this structure an individual dc-dc converter is utilized in each string. This topology is an intermediate solution between string inverter topology and module inverter and it combines the advantages of both of them. This topology increases the modularity of the GCPVPP and hence different PV panels with different nominal data, orientation, inclination and weather condition (solar irradiation) can be combined in one PV power plant. dc-dc converters extract the maximum power from PV strings and transfer it to the common dc-bus. Various topologies of multi-string inverter are illustrated in Fig. 2.4

Because PV strings and their individual dc-dc converters are operating independently, the system can be modified easily. The central inverter transfers the total extracted power from PV strings to the grid. Due to its inherent advantages, as follows, the multi-string GCPVPP structure is considered in this study for medium-

Figure 2.4: Different multi-string topologies: (a) A single 2L-VSI, (b) modular multi-string with parallel 2L-VSIs and (c) a single multilevel inverter

and large-scale GCPVPPs [15, 31, 36–42].

- The maximum power from all PV strings can be extracted during all environmental conditions. In the single-stage power conversion topology with a central inverter, the mismatch between PV strings, resulted from clouds or shadows, dust covering and also temperature differences, aging, or manufacturing imperfections, reduces the extracted power from all of the PV strings. The PV module with lowest output current limits the current of all of the PV modules

in that string. Also, the voltage of maximum power point can be different in various PV strings, however all of the parallel PV strings experience the same voltage and hence maximum power cannot be extracted from all of the PV strings.

- Due to the low irradiation during the sunrise/sunset or cloudy sky, the voltage of maximum power point of the PV panels is small. In the single-stage topology, since the dc-link voltage is equal to the voltage of the PV arrays, the grid-connected inverter cannot produce the required voltage for grid connection during such conditions. Consequently, it disconnects from the grid and the available power from PV panels during sunset/sunrise or cloudy sky, cannot be extracted. However, in the double-stage multi-string topology, the dc/dc converters can step up the voltage of PV strings to the dc-link nominal voltage. Hence, the available power from PV panels during sunset/sunrise or cloudy sky can be injected to the grid.
- The modular structure of the multi-string topology, allows the GCPVPP to be scaled up without the need of changing the installed PV panels. Furthermore, various types of PV panels can be installed due to independent operation of dc/dc converters in each PV string.
- The low frequency bulky transformer can be eliminated by applying isolated dc/dc converters with high frequency transformers. As a result, the required voltage boost can be achieved besides providing isolation required by some standards.

Three different multi-string topologies of medium- and large-scale GCPVPPs are illustrated in Fig. 2.4:

- (a) **Multi-string topology with a single two-level voltage-source-inverter (2L-VSI):** High-voltage and high-power semiconductor devices should be used in this topology to deliver the large amount of power to the grid. Beside the limitations on the voltage and power of the semiconductor devices, the technology is not still very mature and their reliability is low.
- (b) **Multi-string topology with parallel connection of several 2L-VSIs:** In this topology several 2L-VSIs are connected in parallel to transfer the large amount of power from the GCPVPP to the grid. The semiconductor switches

with lower power ranges, compared to the topology a, can be used in each 2L-VSI in this topology. Due to the parallel connection, the reliability of the systems is higher compared to topology a. On the other hand, due to high number of semiconductor devices, the price is high, while it requires a control system with high complexity. Another disadvantage of this topology is the circulating current between parallel branches, which reduces the overall efficiency of the system.

- (c) **Multi-string topology with a single multilevel converter:** In this type, a single multilevel inverter is applied to connect the GCPVPP to the grid. The number of voltage levels and semiconductor switches can be designed based on the required power and voltage of the GCPVPP. This topology does not require high-voltage and high-current semiconductor switches. Hence, it has higher reliability compared to the topology a. It also needs a control systems with lower complexity compared to the topology b. Furthermore, circulating current does not exist in this topology and it can achieve higher efficiency compared to the topology b. The required inductor filter size for this topology is smaller than topologies a and b, due to the multilevel output voltage of the converter with lower harmonics.

Based on the above-mentioned discussions, the multi-string GCPVPP with multilevel inverter (topology c), has higher reliability and efficiency, lower harmonic distortion and lower control complexity and cost compared to the other topologies. Additionally, high-power scales can be achieved by this topology. Accordingly, this topology is state of the art for medium- and large-scale GCPVPPs and is addressed in this thesis.

2.2.5 Discussion about Various Issues of GCPVPPs

There are various issues, which should be considered in the design of GCPVPPs: Common mode voltage, parasitic capacitance and earth leakage current. The following table summarizes the causes and solutions for these issues.

Table 2.2: Various Issues of GCPVPPs.

Issue	Causes	Solutions
Common mode voltage	<ul style="list-style-type: none"> • Unbalanced capacitor voltages in multilevel inverters, which connect the GCPVPP to the grid. • Unbalanced currents which consist zero sequence component. 	<ul style="list-style-type: none"> • Design of voltage balancing algorithms to balance the capacitors voltages of the multilevel inverters • Elimination of the zero-sequence current injection to the grid by implementing the current controller in dq or $\alpha\beta$ frames.
Parasitic capacitance	<ul style="list-style-type: none"> • The electrical structure of the PV panel. 	<ul style="list-style-type: none"> • Designing improved PV panel structures with lower parasitic capacitances. • Isolating the PV panel installations from the earth
Earth leakage current	<ul style="list-style-type: none"> • Parasitic capacitance of the PV strings. • Common mode voltage. 	<ul style="list-style-type: none"> • Using grid-frequency isolation transformer between the inverter and grid • Applying isolated dc-dc converters with high-frequency isolation transformer between the PV strings and grid-connected inverter. • Isolating the PV panel installations from the earth.

2.3 Investigated Topologies for Medium- and Large-Scale Photovoltaic Power Plants with Multi-level Inverters

Multilevel converters are a promising solution for medium- and large-scale grid-connected photovoltaic power plants (GCPVPPs), because of their ability to produce high-quality output voltage and current waveforms at medium/high-voltage ranges, while they require lower voltage rated power semiconductors and dc capacitors. As stated in the above section, the multi-string structure is among state-of-the-art configurations for medium- and large-scale GCPVPPs. This thesis considers two multi-string-based GCPVPP topologies with multilevel inverters:

- Neutral-point-clamped (NPC) inverter
- Cascaded H-bridge (CHB) inverter

The detailed explanation of these structures and their characteristics are presented in the following sections.

2.3.1 Multi-string Photovoltaic Power Plant with Neutral-Point-Clamped Inverter

The first GCPVPP structure, which is investigated in this thesis is the multi-string structure with three-level NPC (3L-NPC) inverter with single dc-bus. Fig. 2.5 represents the details of the proposed structure. Each PV string is connected to a dc-dc boost converter. All of the PV strings are connected to a single dc-bus. This topology improves the maximum power extraction during partial shading, because each PV string is controlled independently from other PV strings and therefore MPPT controller can extract the maximum power from the PV string in all irradiation conditions. Furthermore, in the case of failure of some PV strings, all other PV strings can continue their normal operation.

Several types of multi-level inverters are presented in the literature. Three-level flying capacitor inverter utilizes several flying capacitors which increases the size and cost of the system and reduces the reliability. However, NPC inverter shows higher reliability by eliminating the flying capacitors and reduces the size. On top of that,

Figure 2.5: Grid-connected multi-string photovoltaic power plant with 3L-NPC inverter

there are various commercialized NPC inverter products with different power rating and they can be used for high power conversion applications.

The grid-tied 3L-NPC inverter consists of two pairs of IGBT switches (S_{a1} and S_{a2}) including the complementary ($S_{a1'}$ and $S_{a2'}$) in each phase. The 3L-NPC operates with three different switching states to synthesize the three output pole voltage levels at $V_{dc}/2$, 0 and $V_{dc}/2$ with respect to the midpoint m of dc-link. More details about 3L-NPC inverter can be found in [43].

Despite the increasing demands of renewable energy resources, several regulations such as IEEE Std. 1547-2003 and IEEE Std. 929-2000 [44, 45] must be complied strictly to ensure the power quality of the renewable grid-connected system. Therefore, lower current harmonic distortion can be achieved with the aid of output filter, which are connected between the inverter and the grid, as shown in Fig. 2.5. Due to the intelligent synthesis of three-level output voltage waveforms, the filter size can be much smaller compared to the conventional two-level inverters. The resistance of the inductor filter is usually smaller than 10% of its impedance. Especially for high-current inductor filters, which are used in medium- and large-scale GCPVPPs, the resistance is smaller. Hence, the effect of the resistance on the controller is negligible. Accordingly, the resistance of the inductor filter is neglected in the drawings of the thesis.

Figure 2.6: Circuit configuration for a grid-connected photovoltaic power plant with CHB converter and dc-dc converters.

2.3.2 Multi-string Photovoltaic Power Plant with Cascaded H-Bridge Inverter

Among various multilevel converter topologies, the multilevel cascaded H-bridge (CHB) converter, shown in Fig. 2.6, has been introduced as a potential candidate for medium- and large-scale GCPVPPs in several studies [38, 46–52], because:

- Switching frequency of each H-bridge semiconductor can be decreased close to the fundamental frequency, which results in the reduction of semiconductor losses and achievement of higher power conversion efficiency, while maintaining a high-quality (low total harmonic distortion) output voltage.
- If connecting to medium-voltage grids, the bulky and expensive line-frequency transformer can be eliminated by directly connecting the converter to the grid.
- The use of multiple dc-links and dc-dc converters allows implementing multiple maximum power point tracking (MPPT) algorithms and therefore the ability to maximize the extracted power from all photovoltaic (PV) strings.

Various topologies of isolated dc-dc converters are introduced in the literature for medium- and large-scale GCPVPPs [53, 54]. Each dc-dc converter reduces the oscillation of the extracted power from PV strings, which exists in the direct connection of PV strings to dc-links (without dc-dc converters) as a consequence of the existence of

second harmonic oscillation in dc-link voltages. Moreover, the isolated dc-dc converters eliminate the leakage current of PV modules, which is the result of the common mode voltage across the parasitic capacitance between PV modules and ground.

The inductor filters are connected in the output of the inverter to reduce the current harmonics and comply with grid standards. This topology is designed for the direct connection of the GCPVPP to the medium- or high-voltage grid. The inductor filter is usually used for the connection of power converters to medium- or high-voltage grids, due to challenges in the design of high-voltage capacitors and their low-reliability [38, 46-52]. Hence, the inductor filter is considered in this thesis for the connection of CHB inverter to the grid. The design of the tuned arm filter is to eliminate the high-frequency current harmonic from the injected current to the grid. The design of the cut-off frequency for this type of filter, is normally 10 times larger than the fundamental frequency. The frequency bandwidth of voltage sags is in the range of fundamental frequency. Hence, the performance of the proposed control algorithm does not change while LCL filter is connected between the CHB inverter and grid.

The implementation of a high-power isolated dc-dc converter is very challenging. However, in the implemented GCPVPP, parallel dc-dc converters are applied to transfer the large amount of power from PV strings to the dc-link of each H-bridge. In this case, the available high-power isolated dc-dc converters, as mentioned in the following references, can be used in the implementation of the GCPVPP. For example, a 166-kW/20-kHz prototype of isolated dc-dc converter has been implemented in [55]. Several other designs are also proposed in [56–58] for high-power dc-dc converters.

2.4 Grid Codes

Increasing the size and number of renewable power plants results in new challenges about power quality and reliability for power system operators (PSOs). Therefore, PSOs and standardization institutions regulate new requirements and rules for grid-connected renewable power plants in order to maintain the power quality and reliability of the power system. As an important source of DG, GCPVPPs should also comply these standards and regulations. Design of the grid-connected inverter is very sensitive to the grid requirements. For example, in United States, transformerless PV

Table 2.3: IEEE 1547 and IEC 61727 maximum current harmonics for GCPVPPs.

Individual harmonic order (odd)*	$h < 11$	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$35 \leq h$	THD
%	4.0	2.0	1.5	0.6	0.3	5%

*Even harmonics are limited to 25% of the odd harmonic limits above.

power plants are not popular because of the regulated standards or in Euro the mini-central inverters are mostly designed in the range of 8-15 kW as a reason of limited feed-in tariff to this level.

Based on the grid condition, be normal operation or fault situation, different requirements are regulated for GCPVPPs. Following subsections briefly represent these requirements [44, 59, 60].

2.4.1 Grid Requirements during Normal Operation

During the grid normal operation, the main concern of PSOs is the power quality of the grid. Therefore, the main parameters, which are required by PSOs for GCPVPPs during grid normal operation, are:

- ✓ Total harmonic distortion (THD) and individual harmonic current levels
- ✓ Level of injected dc current
- ✓ Power factor
- ✓ Voltage and frequency of normal range
- ✓ Islanding identification and operation
- ✓ Automatic synchronization and reconnection
- ✓ Earth leakage current and grounding

Various international standards that deal with GCPVPPs are:

Table 2.4: EN 50160 public distribution grid voltage harmonics.

Odd harmonics				Even harmonics	
Not Multiple of three		Multiple of three			
Order h	Relative voltage(%)	Order h	Relative voltage(%)	Order h	Relative voltage(%)
7	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6-24	0.5
13	3	21	0.5		
17	2				
19	1.5				
23	1.5				
25	1.5				

- IEEE 1547.1-2005, Standard for conformance test procedures for equipment interconnecting distributed resources with electric power system [44]. This is a new standard that specifies the type, production and commissioning tests that shall be performed to demonstrate the interconnection functions and equipment of the distributed resources conform to the IEEE Std. 1547.
- IEC 61727 (2002), characteristics of the utility interface for photovoltaic (PV) systems [59].
- EN 50160 (1999), Voltage characteristics of public distribution system [60].

Most of the standards are related to the current total harmonic distortion (THD) during the normal operation. Table 2.3 and Table 2.4 represent the requirements of the mentioned standards on the harmonic distortion of the injected current. It can be seen that for higher order harmonics, the permitted amplitude of the injected harmonic current is smaller.

Regarding the dc current injection, various standards regulate various limitations

Table 2.5: Limits of injected dc current for different standards.

	IEC 61727	VDE 0126-1-1	IEEE 1547	EN 6100-3-2	IEEE 929-2000
dc current injection	< 1% of rated output current	< 1 A	< 0.5% of rated output current	< 0.22 A corresponds to 50-W half-wave rectifier	< 0.5% of rated output current

as summarized in Table 2.5 [14]. In all of the standards, the permitted dc-current injection is considered to be very small, in order to prevent the saturation of grid transformers and other problems, caused by dc-currents.

2.4.2 Grid Requirements during Voltage Sags

To ensure the safety of utility maintenance personnel and general public and to avoid the damage of equipment during the reconnection, GCPVPPs should be disconnected from the grid during abnormal grid conditions.

Abnormal condition refers to the variation of voltage or frequency from their normal range. Table 2.4.2 represents the disconnection time for different voltage ranges for IEEE 1547, IEC 61727 and VDE 0126-1-1 standards. It can be seen that for larger voltage variations, the disconnection time is smaller, because the probability of damage to grid equipment for larger voltage variations is larger. Standard disconnection times for different frequency variations are stated in Table 2.4.2. In IEEE 1547 standard, the normal grid frequency is 60 Hz and the nominal frequency value for VDE 0126-1-1 is 50 Hz. It can be seen that VDE0126-1-1 allows a much lower frequency limit and thus frequency adaptive synchronization is necessary by this standard.

In addition to requirements for disconnection during grid abnormal conditions, some countries like Germany, Italy and Japan regulate some policies for renewable power plants to stay connected during grid voltage disturbances and inject the reactive power in order to improve the voltage quality of the grid. The reason of regulating these new policies, is the high penetration of renewable power plants in the power system. Since large amount of electricity is supplied by distributed generation (DG) units, disconnecting all of them during a voltage sag can exacerbate the situation of the grid and may cause power system blackout. Hence, two new requirements are presented by grid codes:

Table 2.6: Standard disconnection time for voltage variations [61].

IEEE 1547		IEC 61727		VDE 0126-1-1	
Voltage range %	Disconnection time (s)	Voltage range %	Disconnection time (s)	Voltage range %	Disconnection time (s)
$V < 50$	0.16	$V < 50$	0.10	$V < 85$	0.20
$50 \leq V < 88$	2.00	$50 \leq V < 88$	2.00	$110 \leq V$	0.20
$110 \leq V < 120$	1.00	$110 \leq V < 135$	2.00		
$120 \leq V$	0.16	$135 \leq V$	0.05		

Table 2.7: Standard disconnection time for frequency variations [61].

IEEE 1547		IEC 61727		VDE 0126-1-1	
Frequency range (Hz)	Disconnection time (s)	Frequency range (Hz)	Disconnection time (s)	Frequency range (Hz)	Disconnection time (s)
$59.3 \leq f < 60.5^*$	0.16	$f_n - 1 \leq f < f_n + 1$	0.20	$47.5 \leq f < 50.2$	0.20

* For systems with power < 30 kW the lower limit can be adjusted to in order to allow participation in the frequency control.

- Staying connected to the grid during voltage sag/swell
- Injecting reactive power to improve the grid voltages.

Fig. 2.7 represents the grid requirements of Germany, Japan and Italy for DGs to stay connected during the fault. It can be seen that according to Italy grid code, DGs with total power of more than 6 kW should stay connected to the grid for 0.15 s during 0 pu voltage level of the grid. The nominal voltage that the DG unit should permanently stay connected to the grid for Germany is 0.9 pu; however this nominal value for Italy is 0.85 pu and for Japan is 0.8 pu. As a reason of fast growing of DGs in Japan, the policies will be changed after 2016 and more restricted policies will be applied for DG units [62, 63].

Dynamic voltage support and LVRT capability is necessary for GCPVPPs connected to the medium-voltage (MV) grid. GCPVPPs are required to stay connected to the grid during voltage sags for a specific period of time, and also inject reactive power for grid support. Moreover, GCPVPPs should be able to restore the active power injection with limited ramp after grid voltage sag clearance [64].

Figure 2.7: LVRT requirements defined in different countries covering a wide range of applications [62].

The reactive current requirement of MV grid-connected DGs according to the German grid codes is depicted in Fig. 2.8 [65]. The shaded area in which $-10\% < \Delta V_g/V_n < 10\%$, relates to the voltage amplitude between 0.9 pu and 1.1 pu, which is considered as the normal grid condition, and active power is only required to be injected to the grid. During this operation mode, the amount of injected reactive power to the grid is zero and the grid-connected inverter operates at unity power factor. The voltage amplitude between 0.9 pu and 1.1 pu is considered as the normal grid condition, and only active power is required to be injected to the grid. However, during any abnormal grid conditions, the GCPVPPs are required to support the grid voltage by injecting reactive power, as depicted in Fig. 2.8.

$$I_q^* = \begin{cases} 0, & 0.9 \text{ pu} \leq \hat{V}_{min} < 1.1 \text{ pu} \\ k \frac{\Delta V}{\hat{V}_N} I_{N_{dq}} + I_{q0}, & 0.5 \text{ pu} \leq \hat{V}_{min} < 0.9 \text{ pu} \\ -I_{N_{dq}} + I_{q0}, & \hat{V}_{min} < 0.5 \text{ pu}, \end{cases} \quad (2.1)$$

where

Figure 2.8: Grid reactive current requirement for GCPVPPs connected to medium-voltage grid [65].

$\hat{V}_N$: The nominal amplitude of the PCC phase voltage.

ΔV : $\hat{V}_{min} - \hat{V}_N$.

$\hat{V}_{min}$: The minimum phase voltage amplitude.

$I_{N_{dq}}$: $\sqrt{3}I_N$.

I_N : The nominal rms current of the inverter.

I_{q0} : The initial reactive current of the inverter before the voltage sag.

It should be noted that $\hat{V}_{min}$ is calculated dynamically through the controller. $I_{N_{dq}}$ denotes the transformed nominal inverter current to dq -axis. k is a constant value defined according to the agreement between PSO and GCPVPP operator and is usually larger or equal to 2 [5]. In this study, k is considered to be equal to 2.

Since three different operation conditions are defined by grid codes, the proposed controllers in this thesis are also divided into three operation modes. If $\hat{V}_{min}$ is between 0.9 pu and 1.1 pu, the controller operates normally (*Normal*). If $\hat{V}_{min}$ is between 0.5 pu and 0.9 pu, the inverter is required to inject both active and reactive power to the grid simultaneously (*Sag I*). Finally, when $\hat{V}_{min}$ is smaller than 0.5 pu,

Figure 2.9: Basic Control Structure for multi-string GCPVPP with 3L-NPC inverter.

the inverter should inject only reactive current to the grid (*Sag II*).

2.5 Conventional Control Strategies for GCPVPPs during Normal Operation

As mentioned, multi-string structure is selected in this study for large-scale GCPVPPs. This section investigates various control strategies, which can be implemented for multi-string GCPVPPs during grid normal operation. Fig. 2.9 depicts the basic control structure of the multi-string GCPVPP. The controller can be divided into two main parts: input-side control and grid-side control [66].

The input-side controller is implemented on the dc-dc boost converter and extracts the maximum power from PV strings by adjusting the PV string voltage (v_{st}) to the maximum power point voltage of the PV string. It should be mentioned that during the grid normal operation, the boost converter doesn't control the dc-link voltage and instead of that, grid-side controller should regulate the dc-link voltage to its reference value. Grid-side controller is responsible for the operation of the grid-connected inverter. Various tasks which should be performed during the grid normal operation are as below:

- Calculating of the grid voltage angle to synchronize the output current with

the grid.

- Adjusting the dc-bus voltage to its voltage reference and accordingly calculating the inverter output current references.
- Calculating switching signals of the grid-connected inverter.
- Balancing the dc-link capacitors voltage.

Calculation of the grid voltage angle is implemented by the phase locked loop (PLL) controller. Since the main contribution of this study is not the PLL controller, a conventional PLL controller is applied in the simulated multi-string PV power plant. More details on the implementation of the PLL controller can be found in [67, 68].

The grid-tied inverter controller adjusts the dc-link voltage to its reference value by regulating the inverter output reference currents and voltages. Accordingly, the controller generates the switching signals by considering the strategy of the voltage balancing of dc-link capacitors.

As represented in Fig. 2.9, inverter three-phase currents, grid three-phase voltages and the dc-link capacitor voltages are the inputs of the grid-tied inverter controller and it generates the inverter switching signals. It should be mentioned that the grid-tied inverter doesn't control the output voltage during the grid-connected operation mode. During islanding, which the PV power plant is disconnected from the grid, the control scheme should be converted to the voltage control mode. This study investigates the operation of the inverter during the grid-connected operation. During the grid-connected operation mode, the output voltage of the inverter is specified by the grid, and therefore, the inverter can only control its output current. The reference value of the output current, which indicates the injected power to the grid, is calculated based on the dc-link voltage.

Various control strategies are introduced in the literature for the grid-tied inverter which can be classified into two main categories: direct power control (DPC) and voltage oriented control (VOC). The following subsections briefly describe these control strategies.

2.5.1 Direct-Power Control

The detailed structure of the direct-power control (DPC) is illustrated in Fig. 2.10. Active and reactive power references are calculated by the power estimator block, while the dc-link power is calculated by multiplying the dc-link current and voltage. Usually, during the grid normal operation, the reactive power reference (Q^*) is set to zero in order to achieve the unity power factor operation.

The calculated error between the instantaneous power and its reference value is fed into a hysteresis controller, which provides h_p and h_q . The calculated h_p and h_q parameters along with θ are the input parameters of the switching table. The switching signals are generated based on this switching table. The detailed description of this algorithm including the details of the switching table and hysteresis block can be found in [69, 70].

It can be seen that this method doesn't contain a modulation stage. Additionally, it has non-linear behavior due to the application of the hysteresis block. This algorithm achieves fast dynamic response. However, it can not be used for the operation of grid-connected inverters during voltage sags with unbalanced current injection, because the voltage of each phase is not controlled individually.

Figure 2.10: Direct-power control (DPC) structure.

2.5.2 Voltage-Oriented Control

A detailed structure of the VOC structure is shown in Fig. 2.11. The summation of v_{c1} and v_{c2} , which equals to v_{dc} , is compared with the dc-voltage reference (V_{dc}^*) and the calculated error is fed into the PI controller. The output of the PI controller is the d-axis current reference (i_d^*), which is relevant to the inverter active power. The amount of q-axis current reference (i_q^*) is calculated based on grid codes as explained in (2.1). Based on grid code, during the grid *Normal* operation, i_q^* is set to zero in order to achieve the unity power factor operation. Therefore, the inverter injects the maximum active power to the grid with its nominal current [69].

Figure 2.11: Voltage-oriented control (VOC) structure.

The output phase currents are transformed to the synchronous rotating (d-q) frame using Clarke and Park transformations, while PLL calculates the required voltage angle from the grid phase voltages. The current controller adjusts the instantaneous d-q axis currents with their reference values and calculates the stationary frame (α - β frame) voltage references. The existing current control strategies are investigated in the following subsections. The modulation block generates the switching signals according to the voltage references, while it also performs the dc-link capacitor voltage balancing [69].

As shown in Fig. 2.11, the VOC consists of two cascaded controllers. The ex-

ternal controller adjusts the dc-link voltage to its reference value and calculates the current references. The internal current loop, which has faster dynamic response, is responsible to adjust the instantaneous currents of the inverter to their reference values. The internal current controller is responsible for power quality issues and current protection. Therefore harmonic compensation and dynamic response are the most important properties of the internal current controller. Three different current control strategies are introduced in the literature for grid-tied inverter, which are explained briefly in the following subsections [66].

2.5.2.1 Current Control in abc -Frame

The idea of natural-frame control is to have a separate control on each phase current. Fig. 2.12 depicts a possible implementation structure for the natural-frame current controller. The output of the dc-link voltage controller, which is i_d^* , together with the calculated q-axis current reference (i_q^*) is converted to the equivalent current references by using the inverse Park and Clarke transforms. Three-phase current references (i_a^* , i_b^* and i_c^*) are compared with their instantaneous values and calculated errors are fed into three separate PI controllers. The outputs of these controllers are the phase voltage references and are fed into the pulse-width modulation (PWM) block to generate the intended switching signals [71].

Various methods of power system configuration like delta and star, with or without isolated neutral are existed and each system needs its special control structure. For example in the situation of isolated neutral point, only two controllers for two phases are required, because in this configuration the third phase current is the summation of two phase currents.

Figure 2.12: abc -frame current controller.

2.5.2.2 Current Control in dq -Frame

In the synchronous-rotating-frame current controller, which is also called dq -controller, the instantaneous phase currents of the inverter are transformed to the dq -frame using the Park and Clarke transformation. As shown in Fig. 2.13, the calculated instantaneous dq -currents are compared with their reference values which are computed by dc-link voltage and reactive power controllers. The outputs of these controllers which are reference synchronous frame voltage values, are transformed to their equivalent natural frame values thorough inverse Park and Clarke transformation.

The use of Park and Clarke transformation increases the steady state error of this structure, as a reason of the existing error in the calculated voltage angle by the PLL controller. On the other hand, applying several frame transformations increases the computational complexity of this controller. More information about the implementation and its characteristics can be found in [72].

Figure 2.13: dq -frame current controller.

2.5.2.3 Current Control in $\alpha\beta$ -Frame

Fig. 2.14 depicts the detailed structure of the current controller in the stationary-frame ($\alpha\beta$ -frame). d -axis and q -axis current references are transformed to their equivalent values in the stationary-frame. The measured instantaneous phase currents are also transformed to the stationary-frame by using the Clarke transformation. In the stationary-frame the proportional-resonant (PR) controller is applied to adjust the instantaneous stationary currents with their reference values. It calculates the stationary voltage references. The inverse Clarke transformation is applied to convert

Figure 2.14: $\alpha\beta$ -frame current controller

the calculated voltage references to their equivalent natural frame values. Finally, the PWM block generate the intended switching signals based on the reference voltages. A detailed execution process of this control structure is presented [73].

2.5.2.4 Comparison of Current Control Strategies

Table 2.8 represents various advantages and disadvantages of the presented current control strategies. Natural-frame control structure controls the phase current separately and the configuration of the power system is important in its implementation. Additionally, this structure has higher implementation complexity, especially in the case of using hysteresis controller. Since the PI controller is applied in the synchronous-rotating frame structure, it is simple for implementation, but it has high steady state error, because it cannot eliminate low-order harmonics. Furthermore, the necessity of multiple frame transformation, increases the computational complexity of this algorithm.

Stationary-frame current control structure uses the advantages of both synchronous frame and natural frame control structures. It is not necessary to obtain the current angle and filtered grid voltage angle can be applied in the Park transformation. Additionally, multiple frame transformation is avoided, resulting in lower computational complexity. On the other hand, the PR current controller shows also faster dynamic response. As a reason of the mentioned advantages of the stationary frame control structure, this study applies it for the PV grid-tie inverter. As a summary, the PR controller has the following advantages compared to PI or PID controllers [10, 13, 74]:

- It does not require the multiple frame transformation, like the PI controller.

This reduces the computational complexity.

- It achieves fast dynamic performance.
- It can achieve zero steady-state error.

2.5.3 Comparison of Voltage-Oriented and Direct-Power Controller Structures

As mentioned previously, all of the control structures of grid-tied inverters can be classified into two main structures. In the DPC structure, the switching signals are generated by the use of a switching table, while in the VOC, modulation stage generates the required switching signals. Table 2.9 represents several advantages and disadvantages of each structure. It can be seen that the DPC has simpler structure with nonlinear performance which results in the faster dynamic operation of this structure. On the other hand, it is sensitive to the line inductance and has variable switching frequency which results in larger filter inductor. Another disadvantage of the DPC is the lack of modulation stage which makes difficulties for implementation of this method in multilevel inverters.

VOC results into constant switching frequency for the converter and it can be implemented with smaller filter size, compared to DPC with variable switching frequency. Moreover, it is not sensitive to the variation of the line inductance. The main disadvantage of VOC, compared to DPC, is its slower dynamic response. One of the problems of the inverter during grid faults, is the unbalance voltage of the dc-link capacitors, which may result into overvoltage and activation of the protection system. VOC performs the voltage balancing by generating the proper switching signals according to the dc-link capacitor voltages, however it is difficult to be implemented in the DPC structure [66].

It should be mentioned that one of the main objectives of this study is to design a controller for grid-tied inverter with LVRT capability, and therefore VOC is suitable for the grid-tied inverter. Additionally, this study intends to improve the dynamic response of VOC, while it also tries to improve the harmonic suppression capability of the controller.

In addition to the mentioned reasons for selecting the VOC, the inverter should inject unbalanced currents to the grid to improve the grid voltage during unbalance

Table 2.8: Comparison of various current controllers [69].

Technique	Advantages	Disadvantages
Natural-frame current control	<ul style="list-style-type: none"> • Separate control on each phase current. • Phase current angle is not a necessity and Park transformation can be implemented by filtered phase voltages. 	<ul style="list-style-type: none"> • Different controllers for different power system configuration. • High complexity, especially when hysteresis band controller is used. • Unbalanced current control is difficult to be implemented.
Synchronous rotating current control	<ul style="list-style-type: none"> • Simple implementation. 	<ul style="list-style-type: none"> • Phase current angle is necessary. • Higher computational complexity due to the required frame transformation blocks. • Low compensation capability of low-order harmonics
Stationary-frame current control	<ul style="list-style-type: none"> • Phase current angle is not a necessity and Park transformation can be implemented by filtered phase voltages • Elimination of steady state error. • Faster dynamic response. 	<ul style="list-style-type: none"> • More difficult implementation than synchronous rotating PI controllers.

voltage sags. The DPC structure doesn't have the ability to inject the unbalanced currents to the grid, however it can be implemented in the VOC by setting the current references to the required unbalanced values.

In summary, due to the following reasons, the VOC strategy is chosen for the control of grid-connected inverters in this thesis:

- VOC has constant switching frequency, while DPC has variable switching frequency, which requires larger filter sizes.
- The voltage and current of each phase can be controlled individually in the VOC strategy and it is capable of injecting unbalanced currents to the grid, while in DPC strategy the voltage and current of each phase is not controlled individually.
- DPC strategy is sensitive to line inductor and the variation of the line inductor changes its performance.
- Due to the lack of modulation stage in the DPC algorithm, its implementation on multilevel converters with voltage balancing requirements is challenging.
- The only disadvantage of VOC, compared to DPC, is its slower dynamic response. This issue of VOC is addressed in this thesis by adding the feedforward voltage controllers.

Table 2.9: Comparison of VOC and DPC control structures [69].

Technique	Advantages	Disadvantages
VOC	<ul style="list-style-type: none"> • Fixed switching frequency • Advanced PWM strategies • Cheaper A/D converters • No sensitivity to line inductance variation 	<ul style="list-style-type: none"> • Coordinate transformation and decoupling between active and reactive components are required • Complex algorithm • Lower input power factor
DPC	<ul style="list-style-type: none"> • No separate PWM modulation block • No current regulation loop • No coordinate transformation • Good dynamic performance • Decoupled active and reactive power control 	<ul style="list-style-type: none"> • High values of inductance and sampling frequency are required. • Power and voltage estimation should be avoided at the moment of switching (it yields high errors) • Variable switching frequency • No DC-link capacitor voltage balancing strategy • Fast microprocessor and A/D converters required.

2.6 Conventional Control Strategies for GCPVPPs during Voltage Sags

High penetration of distributed generation (DG) units in the power system has resulted in new electricity regulation requirements, particularly during grid voltage sags. Initially, low-voltage ride-through (LVRT) capability was introduced by power system operators in order to withstand voltage sags and maintain the connection to the grid and avoid loss of power generation [5,75]. Later, reactive power injection was added in grid codes with the intention of supporting the grid voltage and reducing the possibility of voltage collapse during network faults. Furthermore, negative-sequence

current injection appears to be a new important requirement of next generation of grid codes for enhancing the DG capabilities in supporting unbalanced voltage sags [7].

Among various DG units, grid-connected photovoltaic power plants (GCPVPPs) have recently achieved a drastic increase in the installed capacity due to the decreased module prices and favorable incentive policies [8]. As a result, LVRT became a necessary requirement for medium- and large-scale GCPVPPs. Several studies have been performed on LVRT capability of single- and two-stage GCPVPPs considering the injection of balanced active/reactive currents to the grid during voltage sags [9, 10].

Various control structures of the GCPVPPs during grid *Normal* operation are explained in previous section. Some modifications are required in these controllers for operation of GCPVPP during voltage sags. Various algorithms are proposed in the literature. Based on the organization of this thesis, these methods are divided into four parts. Some of the presented algorithms in the literature, aim to inject balanced active/reactive currents to the grid during unbalanced voltage sags. The purpose of these controllers is to use the full current capacity of the inverter in enhancing the voltage of the grid. Other methods aim to inject unbalanced currents to the grid during unbalanced voltage sags in order achieve zero active/reactive power oscillation.

The main focus of these algorithms is the current reference calculation algorithm for different purposes and they not consider the special control requirements for various multilevel converters, especially voltage balancing of capacitors. Accordingly, the available control structures for the grid-connected CHB inverter are presented beside their issues for the operation of CHB during voltage sags.

In addition to the above issues, extracting a constant power from PV strings is required during voltage sags. The reduction of the extracted power to a constant value is due to the current limitation of the inverter. Several available control strategies for extracting constant power from PV strings are presented subsequently. Based on that the requirement for a general constant power generation algorithm from PV strings is explained.

2.6.1 Active/Reactive Power with Balanced Current Injection Strategies

Several studies have been performed on LVRT capability of single- and two-stage GCPVPPs considering the injection of balanced active/reactive currents to the grid during voltage sags [9, 10]. Moreover, various methods are presented for the injection of unbalanced currents to the grid during unbalanced voltage sags [7, 11, 76, 77]. These studies have proposed different algorithms for calculating the current references (balanced or unbalanced) according to a certain amount of active/reactive power references, which are empirically determined only based on the rated apparent power of the inverter [7, 9–11, 76, 77]. However, if the nominal apparent power of the inverter is considered during voltage sags, due to the smaller voltage amplitude of the grid, the amplitude of the calculated current references will be larger than the nominal current of the inverter. On the other hand, by setting the active/reactive power references to a fixed value which is smaller than the nominal apparent power of the inverter, during voltage sags, the full current capacity of the inverter is not utilized in enhancing the grid voltage.

2.6.2 Active/Reactive Power with Unbalanced Current Injection Strategies

Unbalanced voltage sags are more common in power systems, causing several adverse effects including overloading of distribution transformers, higher losses and lower stability of the power system. The negative-sequence component of the voltage results in double fundamental frequency oscillation of the injected active or reactive power to the grid. On the other hand, injection of balanced reactive currents during unbalanced grid voltage sags, may result in overvoltage of nonfaulty phases [11–13]. Therefore, the design of the controller of the grid-connected inverter becomes more challenging during unbalanced grid voltage sags.

Various flexible active power injection algorithms have been implemented in [78, 79] with the ability to minimize oscillations of either active or reactive power during unbalanced voltage sags. However, injection of reactive power during voltage sags can be more beneficial in voltage enhancement of point of common coupling (PCC) [11]. A number of studies have been carried out on flexible active/reactive power

injection to the grid during unbalanced voltage sags with various control aims such as oscillating power control [13, 80], grid voltage support [11], maximizing inverter power capability [81] and in-phase current compensation [77].

The peak current limitation during voltage sags is taken into consideration in few studies [7, 82–87]. The active power injection is considered in [82], while the reactive power injection is studied in [84, 85]. Several control strategies are also introduced in [86], however few of them satisfy the peak current limitation. The active and reactive power injection with peak current limitation is investigated in [87], however only positive sequence current injection is applied. Finally, an active/reactive positive/negative sequence power injection method with peak current limitation is investigated in [7], where the amount of injected reactive power is calculated based on the injected active power and nominal current of the inverter. The injection of the active power is given priority to the reactive power in [7], although based on the grid codes and standards [5], during voltage sags, the injection of the reactive power should be given priority to the active power.

2.6.3 Conventional Control Strategies of Grid-Connected CHB Inverter

The detailed explanation of the GCPVPP with CHB inverter is presented in Section 2.3.2. In addition to the problems and solutions described above, a grid-connected PV CHB inverter may experience inter-phase imbalance, which occurs when each phase generates a different amount of power as a result of the unbalanced phase currents or partial shading; and an additional inter-bridge imbalance which happens when each bridge in the same phase leg generates a different amount of power as a consequence of unequal power generation from the PV strings [38, 50]. These imbalances result in several issues:

- The output voltage quality of the converter deteriorates.
- The voltage of one dc-link may increase beyond its normal range, which can activate the dc-link over-voltage protection relay, while disconnects the converter from grid.
- In the single-stage power conversion topology (without dc-dc converters), the deviation of dc-link voltages from their average value ($\overline{V_{dc}}$), which is set to the

voltage of PV strings maximum power point (v_{mpp}), decreases the extracted power from PV strings [41].

With respect to the above mentioned issues, several algorithms are introduced in [38, 47, 50, 51] under partial shading and bridge failure. The main goal of these studies is the zero-sequence voltage injection for achieving inter-phase balancing and injecting active power (p) with balanced currents to the grid during grid normal operation. An inter-bridge balancing through the modification of bridge voltage references is also presented in [51].

During unbalanced voltage sags, a grid-connected PV CHB inverter experiences inter-phase imbalance as a result of unbalanced phase currents; further inter-phase and inter-bridge imbalance can simultaneously occur as a result of unequal power generation from the PV strings (depending on irradiance conditions). Accordingly, various strategies are presented in [88–90], which achieve low-voltage ride-through capability for the CHB-based static synchronous compensator (STATCOM). Moreover, zero-sequence and negative-sequence current injection of the CHB-based STATCOM during grid disturbances are also taken into consideration in [91, 92]. The main disadvantage is that only reactive power injection is implemented on the grid-connected inverter in these studies, however, modern grid codes [5] also require simultaneous active power injection with either balanced or unbalanced currents from grid-connected PV inverters. On top of that, a deep consideration with respect to the inter-phase and inter-bridge balancing is required. Therefore there is a need for a flexible control strategy, which can ensure dc-link voltage balancing, for the grid-connected PV CHB inverter during voltage sags, however, it is not investigated in the literature [38, 41, 46–51, 88–92].

2.6.4 Conventional Constant Power Generation Algorithms in GCPVPPs

Current-voltage characteristics and output power of photovoltaic (PV) strings vary with changes of solar irradiance and temperature. Accordingly, maximum power point tracking (MPPT) techniques are applied in most of applications in order to maximize the extracted power from a given PV system and increase the overall power conversion efficiency [93]. Several MPPT algorithms, varying in approach and complexity, have been introduced in the literature [94–99]. Each method has various

advantages and disadvantages in different aspects like computational efficiency, speed of tracking the maximum power point, operation under partial shading and power oscillations during steady-state. Among all MPPT algorithms, perturb and observe (P&O) [100, 101] and incremental conductance (INC) [102, 103] algorithms are the most commonly used. It is shown in [104] that the tracking performance of these two algorithms is similar under both static and dynamic conditions.

The focus of most of the research studies in the literature is on the extraction of maximum power from PV panels, however, there are several cases in which the control of the PV panel output active power to a certain power reference is necessary. The active power control of the PV panel is referred as constant power generation (*CPG*) in this study. One of these cases, is the adaptation of GCPVPPs with new grid code regulations in which a constant power injection to the grid is requested. The grid codes aim to avoid the adverse effects of the high penetration of installed GCPVPPs in the power system, like overloading the power grid [105]. Another case is their operation during voltage sags with the requirement of simultaneous injection of active and reactive power to the grid with the aim of enhancing the voltage of the PCC. In this case, the extracted power from PV modules should be limited to a certain value in order to satisfy the inverter current limitations. Therefore, a general and flexible algorithm that achieves *CPG* with fast dynamic response and low power oscillation during steady-state is essential for all different topologies of GCPVPPs.

Several algorithms are introduced in the literature to achieve *CPG* for different topologies of GCPVPPs. The basic principles of *CPG* are introduced in [105–109] with the focus on the stability issues and necessary maintenance costs of GCPVPPs with variable output voltage. This idea is implemented on a single-stage GCPVPP with the ability to control of the output active power of the grid-connected inverter in order to comply with grid code requirements [110]. Moreover, a voltage reference calculation method is also introduced based on the perturb and observe (P&O) algorithm to calculate the voltage reference related to the required active power. Due to the single-stage topology, the operation point is moved to the right-side of maximum power point (*MPP*) during the *CPG* mode. Moving the operation point to the right-side of *MPP* in [107, 110] reduces the robustness of these algorithms, because the operation point may go beyond the open-circuit voltage of the PV panel under the fast reduction of irradiance.

To avoid the mentioned drawback, the two-stage GCPVPP topology is considered

in [111] with the ability to achieve *CPG* operation during voltage disturbances. A multi-mode operation including MPPT, *CPG* and short-circuit current control is also implemented on the interleaved dc-dc converter. Similar *CPG* algorithms are also investigated in [10] based on dc-link voltage control. In these studies, the *CPG* operation is implemented by modifying the controller of the dc-dc converter to regulate the dc-bus voltage at its reference during grid disturbances. These methods need the initialization of the controllers during change of operation modes and also show slow dynamic performance.

According to the power-voltage (P-V) characteristics of the PV panel, an algorithm for the calculation of the voltage reference during *CPG* operation of the two-stage GCPVPP is presented and investigated in [112–114]. In this approach, the implementation of the *CPG* algorithm does not require any modification in the controller of the dc-dc converter. Accordingly, the calculated voltage reference from this algorithm is replaced by the voltage reference of the MPPT operation mode. As shown in [112], P&O based *CPG* control results in a faster response compared to INC algorithm under fast changes of irradiance. Moreover, in order to avoid the operation of the PV panel beyond the open-circuit voltage of the PV panel during fast changes of the irradiance, the operation point of the PV panel is moved to left-side of MPP, which limits its application only for two-stage GCPVPPs. Therefore, there is a need for a general algorithm for calculation of the voltage reference of the PV panel during *CPG* operation, which can be used for both single- and two-stage GCPVPPs during grid voltage disturbances or normal operation.

2.7 Summary

A brief history of development and theoretical operation principle of a PV panel has been presented in this chapter. The usual power rating of commercial PV modules is between 200 W and 300 W. The specification of 235-W PV module, which is used in this study is stated and verification results of the modelled PV panel have been provided. The irradiation and temperature are two main parameters affecting the output voltage and power of a PV panel. Increasing the irradiation, results in an increment in the maximum power of the PV panel, and on the contrary increasing the temperature decreases the maximum power of the PV panel.

Various PV power plant structures are presented in the literature. Module inverter topology is suitable for small domestic PV modules. String inverter topology and central inverter topology suffers from the maximum power extraction during the partial shading. Multi-string topology has a lot of advantages like higher modularity and higher energy conversion efficiency. Consequently, this topology has become the state-of-the-art for large-scale GCPVPPs. Furthermore, several energy conversion structures are introduced for PV power plant in the literature. Each structure shows various advantage and disadvantages. dc/dc-dc/ac with HFT structure shows a better performance compared to other topologies. In this topology, HFT which is implemented in the dc-dc converter of each string, provides the electrical isolation and eliminates the earth leakage current. Additionally, HFT has smaller size and lower losses compared to LFT, which results in higher energy conversion efficiency and power density than other topologies.

Various grid codes and standards, regulated for GCPVPPs have been presented, subsequently. These standards and grid codes deal with the power quality and reliability of the power system during normal and abnormal grid conditions. During abnormal condition, the PV inverter should inject reactive power to the grid in order to enhance the voltage quality of the grid. The design of the inverter controller, current filter and storage system is affected by these regulations and this study deals with an improved design of the GCPVPPs to comply with grid requirements.

Various control structures of the grid-connected inverters during grid *Normal* operation have been explained and their characteristics have been compared. It is concluded that VOC structure shows better performance for GCPVPPs, especially during voltage sags, because it consists of a current controller and the current ref-

erences can be chosen to achieve special characteristics during voltage sags. Subsequently, available control algorithms for balanced current injection of the grid-connected inverter during voltage sags are reviewed, followed by algorithms that inject unbalanced currents to the grid. The necessity of a novel and general controller for balanced/unbalanced current injection of the grid-connected inverter during voltage sags is also explained. A review of the Control algorithms of the grid-connected CHB inverter has been presented afterwards, followed by the necessity of a novel controller for its operation during voltage sags. Finally, constant power generation from PV panels has been explained in addition to different available strategies, while the requirement for a general algorithm that can be used for both single- and two-stage GCPVPPs.

The following chapters explain the details of the proposed algorithms for the operation of GCPVPPs during voltage sags, by considering the mentioned issues of the available algorithms in the literature.

Chapter 3

Balanced Current Injection Strategy for Photovoltaic Grid-Connected Inverter during Voltage Sags

The chapter focuses on the control of photovoltaic grid-connected neutral-point-clamped inverters with balanced current injection to the grid during voltage sags. An introduction to the GCPVPP topology is given in the following section. A control strategy for the operation of the GCPVPP during Normal grid condition is explained in Section 3.2. A detailed implementation of the proposed dq-coordinate current reference calculation, voltage sag detection, adaptive phase-locked-loop (PLL), current controller and implemented method for controlling the dc-link voltage during grid voltage sags are presented in Section 3.3. Simulation results of the performance of the proposed controller on a 150-kVA multi-string GCPVPP during various voltage sag conditions along with the obtained voltage enhancements of the point of common coupling (PCC) are illustrated in Section 3.4. Experimental results on a 3.3-kVA laboratory grid-connected 3L-NPC are provided in Section 3.5 and the conclusions are summarized in Section 3.6.

3.1 Introduction

The operation of the GCPVPP with 3L-NPC inverter is investigated in this chapter. The schematic of this power plant is explained in Section 2.3.1. As mentioned in Section 2.6.1, several algorithms are presented in the literature for the balanced current injection of GCPVPPs during voltage sags, however they do not consider the relation between the extracted power for PV strings and injected active/reactive power from the inverter.

Based on the scenario described in Section 2.6.1, this chapter proposes an algorithm for calculating dq -axis current references during voltage sags based on inverter current limitation, grid code requirements and the amount of extracted power from PV strings. The proposed method ensures that the full current capacity of the inverter is used in injecting active/reactive power to the grid during voltage sag in order to enhance the grid voltage during voltage sags. In order to obtain a constant dc-link voltage and maintain the active and reactive power injection during voltage sags, a coordinated MPPT algorithm is also implemented for the dc-dc converters of the multi-string GCPVPP, which reduces the extracted power from PV strings to the amount of active power that can be injected to the grid according to the inverter nominal current and the injected reactive current. Simulation and experimental results are presented to validate the performance of the proposed algorithm.

3.2 Control Strategy for GCPVPP with 3L-NPC Inverter during Normal Operation

The connected dc-dc converters to each PV string, in Fig. 2.5, extract the maximum power from PV strings during *Normal* operation. The implemented control algorithm for the operation of the GCPVPP with 3L-NPC inverter is shown in Fig. 3.1. The dc-link voltage (v_{dc}) is regulated to its reference value, using the PI controller, which calculates the d-axis current reference. The outer loop maintains v_{dc} to its reference value by adjusting the inverter output power. The amount of output reactive power is calculated using the q-axis current reference (i_q^*), which is usually set to zero for unity power factor operation. Hereafter, the dq -axis current references (i_d^* and i_q^*) are converted to obtain their equivalent stationary-frame current references (i_α^* and i_β^*) using inverse Park transformation.

Figure 3.1: Control algorithm of GCPVPP with 3L-NPC inverter during grid *Normal* operation.

The respective $\alpha\beta$ current errors are then obtained by subtracting the stationary-frame current references with the instantaneous stationary-frame currents (i_α and i_β), obtained from the measured three-phase inverter currents through inverse Clarke transformation. Lastly, the stationary-frame voltage references (v_α^* and v_β^*) are acquired directly from the two independent proportional-resonant (PR) controllers without the need of inverse Park transformation. The transfer function of the PR controller is:

$$G_{PR} = K_p + \frac{K_i}{S^2 + \omega^2}. \quad (3.1)$$

where:

G_{PR} : The transfer function of the PR controller.

K_p : The proportional gain.

K_i : The integral gain.

ω : The resonant frequency.

The resonant term provides an infinite gain at the resonant frequency that minimizes the steady-state error to zero. Therefore, the steady-state current error can be minimized by having the resonant frequency matching with the grid frequency.

It should be noted that the implementation of the ideal PR controller with infinite gain in the experimental setup is not practical, because:

- The grid frequency is not exactly 50 Hz in the practical system and it varies within the standard margin.

Figure 3.2: Space vector representation of the 3L-NPC inverter.

- The voltage measurement contains some errors and does not measure the exact instantaneous value of the voltage.
- A delay exists in the calculation of the processor.

Although, the ideal performance can not be achieved in the practical system, the PR controller is implemented in several research studies due to its fast dynamic performance and zero steady-state error [115–118].

The output voltage waveforms of the 3L-NPC inverter are synthesized using the adaptive space vector modulation (ASVM) technique. The space vector representation for the 3L-NPC inverter is shown in Fig. 3.2. It can be observed that there are several pairs of vectors (e.g. "100" and "211") in each internal voltage state, which generate the same output voltage level. Conventionally, the classical space vector modulation (SVM) uses all of the vectors during every switching cycle period. Therefore, an increase in the switching loss is expected from the classical SVM, due to the high switching frequency operation. The ASVM technique is implemented in this controller, in order to improve the inverter efficiency. The overall switching loss is decreased by reducing the switching frequency, since one of the vector pairs is utilized in each switching cycle [32, 43]. This can be observed from the current flow based on the vector pair "100" and "211", as demonstrated in Fig. 3.3.

Figure 3.3: Circuit diagram and current path for vectors of one vector pair in ASVM technique.

Even though both vectors generate same output voltage level, they have different effects on the dc-link capacitor voltages. For instance, when the state vector is "100", the dc-link capacitors C_1 and C_2 are in charging and discharging states, respectively, according to the voltage potentials. Hence, the dc-link capacitor voltage balancing is achieved based on the state vector selection principle as described in (3.2) and (3.3). The vector selection principle is applicable for other vector pairs as well.

$$\left. \begin{array}{l} v_{c-u} \leq v_{c-l} \quad \& \quad i_a \geq 0 \\ v_{c-u} > v_{c-l} \quad \& \quad i_a < 0 \end{array} \right\} \Rightarrow (100) \quad (3.2)$$

$$\left. \begin{array}{l} v_{c-u} \geq v_{c-l} \quad \& \quad i_a \geq 0 \\ v_{c-u} < v_{c-l} \quad \& \quad i_a < 0 \end{array} \right\} \Rightarrow (211) \quad (3.3)$$

The ASVM voltage balancing method is independent of the main controller and it can balance the capacitor voltages in all operation conditions, including unbalanced voltage sags. On the other hand, the ASVM technique can directly use the stationary frame reference voltages to generate the switching signals, which results in less computational complexity and higher accuracy of the controller.

It can be seen that this conventional controller can not be implemented fro the operation of the GCPVPP during voltage sags, an it needs some modifications. The following Sections presents the detailed implementation of the proposed controller for the GCPVPP with 3L-NPC inverter and injection of balanced currents during voltage sags.

3.3 Proposed Balanced Current Injection Control Strategy during voltage sags

Two controllers, one for the dc-dc stage and one for the grid-connected 3L-NPC inverter, are required for the operation of the GCPVPP. Each of these controllers require separate control strategies, which are specific for the grid operating condition be it during its normal operation or during network disturbances (voltage sag). Therefore, a fast and precise voltage sag detection strategy is required to determine the operating mode of the controllers. The following Section provides the details of the implemented voltage sag detection algorithm.

The extraction of the grid voltage positive sequence is another issue in the execution of the controller, which will be discussed in the following Sections, followed by detailed explanation of the proposed controller.

3.3.1 Voltage Sag Detection

Fast detection of the voltage sag is important for quick operation of the controller at the beginning of the voltage sag [119,120]. In this study, second order generalized integrator (SOGI) based orthogonal system is applied for the calculation of the amplitude of phase voltages, as illustrated in Fig. 3.4. As output signals, two sine waves ($v_{a-\alpha}$ and $v_{a-\beta}$) with a phase shift of 90° are generated. The component $v_{a-\alpha}$ has the same phase and magnitude as the fundamental of the input signal (v_a). The SOGI block is defined as:

$$GI = \frac{\omega s}{s^2 + \omega^2}, \quad (3.4)$$

where, ω represents the resonance frequency of the SOGI. The closed-loop transfer functions ($H_d = v_{a-\alpha}/v_a$ and $H_q = v_{a-\beta}/v_a$) can be calculated as [121]:

$$H_d(s) = \frac{v_{a-\alpha}}{v_a} = \frac{k\omega s}{s^2 + k\omega s + \omega^2} \quad (3.5)$$

$$H_q(s) = \frac{v_{a-\beta}}{v_a} = \frac{k\omega^2}{s^2 + k\omega s + \omega^2}, \quad (3.6)$$

where, k affects the bandwidth of the closed-loop system. The detailed description of the SOGI block can be found in [121]. The main limitation of the SOGI-based

sag detection algorithm is the delay of half of the voltage period, that is occurred by the SOGI block.

Since the phase voltage amplitudes are required to detect the single- or two-phase voltage sags, the orthogonal voltages ($v_{x-\alpha}$ and $v_{x-\beta}$, where x is referred to phase a , b or c) are calculated by independent SOGI blocks for each phase. In this figure, ω_n denotes the fundamental angular frequency of the grid voltage. The amplitude of the phase voltage ($\hat{V}_x$) is calculated as:

$$\hat{V}_x = \sqrt{v_{x-\alpha}^2 + v_{x-\beta}^2}. \quad (3.7)$$

Subsequently, the minimum phase voltage amplitude ($\hat{V}_{min}$) is determined instantaneously, which is utilized for the detection of the voltage sag and operation mode of the controller.

Figure 3.4: Voltage sag detection algorithm.

3.3.2 Adaptive Phase-Locked-Loop Control

The conventional phase locked loop (PLL) is suitable for calculation of the positive-sequence voltage angle under balanced voltage conditions. However, it is not able to calculate the positive sequence voltage angle under unbalanced conditions [122]. Therefore, an adaptive PLL is applied for extracting the angle of the positive sequence voltage, as shown in Fig. 3.5. During voltage sags, the grid voltage contains both positive and negative sequences. By using the conventional PLL, the voltage of positive sequence cannot be calculated accurately. With the adaptive PLL [122], first

Figure 3.5: Schematic diagram of adaptive phase-locked-loop (PLL) algorithm.

the positive sequence of voltage is extracted using an arbitrary angle that rotates at $2\pi f$ for both the direct and reverse abc - dq transformations. A moving average filter (MAF) is also implemented on the calculated dq voltage, which filters instantaneous oscillations of the dc-link voltages by performing the following operation:

$$\bar{x}(t) = \frac{1}{T_w} \int_{t-T_w}^t x(\tau) d\tau, \quad (3.8)$$

where T_w is the window width of the MAF and $\bar{x}(t)$ is the moving average value of $x(t)$ calculated over T_w . A window width of $T_w = 1/(2f)$, where f is the grid frequency, can remove all the second-order oscillations of the dc-link voltages [122]. Subsequently, the angle of voltage positive sequence is calculated using the conventional PLL.

3.3.3 Proposed Control Strategy for Inverter and dc-dc Converter during Voltage Sags

A comprehensive structure of the proposed controller of the 3L-NPC inverter during voltage sags is presented in Fig. 3.6.

The main contribution of this study is the proposed method for calculation of dq -coordinate current references during various operation modes of the GCPVPP. The proposed method ensures that the full current capacity of the grid-connected inverter of the GCPVPP is utilized for injecting active/reactive power during voltage sags.

The q-axis current reference (I_q^*) can be calculated from the grid code, as per (2.1). During *Normal* condition, the inverter should inject purely active power to the grid and consequently, I_q^* equals to zero. During *Sag I* operation, the amount of the

Figure 3.6: Proposed current controller for multi-string GCPVPP with 3L-NPC inverter during voltage sags.

reference reactive current, depends on the minimum voltage amplitude ($\hat{V}_{min}$), while the inverter should purely inject the reactive current to the grid ($I_q^* = -I_{Ndq}$) during *Sag II* condition,.

The calculation of d-axis current reference (I_d^*) is more challenging because it relates on the injected active power to the grid (p) and extracted power from PV strings. This chapter proposes the following algorithm for calculating I_d^* during various operation conditions in order to utilize the maximum capability of the 3L-NPC inverter in injecting active/reactive power to the grid during voltage sags.

$$I_d^* = \begin{cases} I_{d-m}^*, & \text{Grid : Normal} \\ I_{d-n}^*, & \text{Grid : SagI} \\ I_{d-m}^*, & \text{Grid : SagII} \end{cases} \quad (3.9)$$

where the proposed algorithms for calculating I_{d-m}^* and I_{d-n}^* under three different operation modes are as follows.

Normal During *Normal* operation, the dc-dc converters extract the maximum power from PV strings, while the 3L-NPC inverter controller is used to maintain the dc-link voltage (v_{dc}) by controlling the injected active power into the grid. It is realized by manipulating the active current reference I_{d-m}^* , as shown in Fig. 3.6. Due to the objective of the dc-link voltage controller, the injected active power to the grid is adjusted to the extracted power from PV strings. The PI dc-link voltage

controller with anti-windup is implemented to calculate I_{d-m}^* . The implementation of the anti-windup prevents the saturation of the integrator part of the PI controller. If the output of the PI controller is beyond its operation range, the difference is reduced from the input error of the integrator. This reduces the input error to the integrator and prevents its saturation. The detailed description of anti-windup scheme can be found in [123].

Sag I As mentioned in Section 2.4.2, in this operation mode, I_q^* is a fraction of the inverter nominal current. Therefore, the inverter is also able to inject active power to the grid, simultaneously. Since, the priority should be given to the reactive power, first I_q^* is calculated from grid code and then the amount of d-axis current reference I_{d-n}^* is calculated as per:

$$I_{d-n}^* = \min \left[\sqrt{I_{N_{dq}}^2 - I_q^{*2}}, \frac{P_{Tot}}{|v_{pcc}^+|} \right], \quad (3.10)$$

where, P_{Tot} is the instantaneous total extracted power from all PV strings (P_{Str1} , P_{Str2} , ...), as shown in Fig. 3.6. Also $|v_{pcc}^+|$ is the amplitude of PCC voltage positive-sequence which is calculated dynamically through the controller.

$I_{N_{dq}}$ is related to the inverter nominal current, which usually is chosen based on the nominal maximum power of PV strings. However, during voltage sags, the nominal maximum power of PV strings might not be available. Therefore, by injection of d-axis current of $\sqrt{I_{N_{dq}}^2 - I_q^{*2}}$ to the grid, the injected active power to the grid is larger than the extracted power from PV strings, which results in discharging of dc-link capacitors and decreasing the dc-link voltage lower than the nominal range. In order to avoid this problem, the instantaneous amount of the extracted power from PV strings should be considered in the calculation of I_d^* , as in (3.10). The amount of $P_{Tot}/|v_{pcc}^+|$ refers to the available d-axis current which can be injected to the grid based on the instantaneous extracted power from PV strings.

On the other hand, if the total extracted power from PV strings is higher than the injected active power to the grid, the excessive energy between the extracted power from PV strings and the injected active power to the grid ($P_{Tot} - p$, where p is the instantaneous injected active power to the grid), will be stored in the dc-link capacitors, which may lead to overvoltage. Hence, the extracted power from PV strings should be reduced during *Sag I*. Thus, a power reduction algorithm is

Figure 3.7: Power reduction strategy from PV strings during *Sag I*: (a) Power-voltage curve of the PV string and (b) dc-dc converter controller.

implemented by controlling the dc-link voltage through the dc-dc converters as shown in Fig. 3.7. In order to reduce the extracted power from the PV string, a reduced power (RP) signal is defined. This signal is set to 1 for all PV strings during *Sag I*, while it is set to 0 for all PV strings during *Normal* condition. As illustrated in Fig. 3.7(a), while $RP = 1$ the voltage (ΔV_{st}) is added to V_{mpp} , which results in moving the operation point from A to B.

It should be mentioned that according to Fig. 3.7(a), moving the operation point to points B or C can result in the reduction of the extracted power from the PV string. In this chapter, the operation point of the PV string during *Sag I* is moved to point B (in the right-side of the *MPP*), because:

- The difference between v_B and v_{mpp} ($|v_{mpp} - v_B|$) is smaller than $|v_{mpp} - v_C|$ and therefore moving the operation point from A to point B can be executed faster than to point C, which results in a faster response.

- For small power references, the operation of the PV string in the left-side of *MPP* (point *C*) necessitates the PV string voltage to be close to the short-circuit voltage. This imposes the dc-dc converter duty cycle to be close to one. As a result, controlling the dc-dc converter becomes more difficult and large oscillations may appear in the input/output voltages. This issue is avoided by moving the operation point to the right-side of the *MPP* (*B*), where the PV string voltage becomes closer to its open-circuit voltage resulting in a decrease of the duty cycle.

In order to control the dc-link voltage during *Sag I*, the stored energy of the dc-link ($0.5Cv_{dc}^2$, where C is the equivalent value of all dc-link capacitors) is manipulated. Therefore, ΔV_{st} is calculated with the aim of controlling the dc-link energy. Accordingly, the square of the dc-link voltage reference (v_{dc}^{*2}) is compared with the instantaneous dc-link voltage square (v_{dc}^2) and is multiplied with $0.5C$. This error is fed into the PI controller in order to calculate the required ΔV_{st} . The duration of the voltage sag is short, hence, it is assumed that irradiation and temperature do not change during this condition and V_{mpp} is constant. Accordingly, the MPPT algorithm stops its operation during the voltage sag and the calculated V_{mpp} before the occurrence of the voltage sag is considered during the voltage sag.

As shown in Fig. 3.7(b), various types of MPPT algorithms, like perturb and observe (P&O) or incremental conductance (INC), can be implemented in the proposed controller. Partial shading has been extensively addressed in several research articles and can also be implemented in the MPPT algorithm, however, since the main focus of this chapter is study of the LVRT of the grid-connected GCPVPP, partial shading is not investigated in this study. Accordingly, the well-known P&O algorithm, as introduced in [124], is implemented. As shown in Fig. 3.7(b), the calculated reference voltage, is then compared with the instantaneous voltage of the PV string (v_{st}) and the difference is fed to a PI controller in order to generate the duty cycle of the boost converter.

Sag II Grid codes require GCPVPPs to inject the maximum possible reactive current of the inverter to the grid, during *Sag II*. Therefore, due to the current limitation of the grid-connected inverter, the active power injection is maintained to zero in order to inject maximum possible reactive current to compensate for the voltage sag. Accordingly, PV strings are open-circuited (*O.C.*) in order to reduce

the extracted power from all of the PV strings to zero. The operation point of the PV string is moved to point D in Fig. 3.7(b) which results in zero power extraction from the PV string. During this operation mode, I_d^* is considered to be I_{d-m} , which is calculated from the dc-link voltage controller, as shown in Fig. 3.6. Since, no power is injected to the dc-link from PV strings during *Sag II*, the amount of I_{d-m} is almost zero. However, it can help to keep the dc-link voltage at its reference value, especially during unbalanced voltage sags which result in the oscillation of the dc-link voltage.

As shown in Fig. 3.6, the computed dq -axis current references (I_d^* and I_q^*), from (2.1) and (3.10), are converted to their equivalent reference stationary frame currents (i_α^* and i_β^*) using the inverse park transformation. An adaptive phase locked loop (PLL) is applied for extracting the angle of the voltage positive sequence, as shown in Fig. 3.6. The respective $\alpha\beta$ current errors are then obtained by subtracting the stationary frame current references with the stationary frame currents (i_α and i_β) obtained from the measured three-phase output inverter currents through inverse Clarke transformation. The errors between the calculated current references and instantaneous phase currents are fed into the PR with anti-windup controller, which is implemented in $\alpha\beta$ -coordinate. Although, the implementation of the conventional PI controller for balanced current injection is simple, it requires multiple frame transformation and results in slow performance. The PR controller with anti-windup shows faster dynamic response and zero steady-state error [74]. Finally, an ASVM technique is applied for generating the switching signals of the 3-wire 3L-NPC inverter by considering dc capacitor voltage balancing.

3.4 Simulation Results

The multi-string GCPVPP (Fig. 2.5) is modelled and developed using Matlab/Simulink and PLECS toolbox. Three parallel PV strings are connected to the dc-link of the grid-connected 3L-NPC inverter. Each PV string is constructed with 15 paralleled PV branches with each branch having 14 series connected PV panels. The PV panel is modelled according to the parameters of the SHARP NU-U235FI, which its characteristics are given in Table 3.1.

Consequently, the maximum output power of each PV string is 50 kW and the maximum total power of GCPVPP equals to 150 kW. The detailed parameters of the simulated GCPVPP are presented in Table 3.2. In order to validate the performance

Table 3.1: Sharp NU-U235F1 electrical characteristics [125].

Parameter	Value
Maximum power (P_{max})*	235 W
Tolerance of P_{max}	+10% - - 5%
Type of cell	Monocrystalline silicon
Cell configuration	60 in series
Open-circuit voltage (V_{oc})	37 V
Maximum-power voltage (V_{mpp})	30 V
Short-circuit current (I_{sc})	8.6 A
Maximum-power current (I_{mpp})	7.84 A
Module efficiency (%)	14.4%
Maximum system (dc) voltage	600 V
Series fuse rating	15 A
Nominal operating cell temperature	47.5°C
Temperature coefficient for P_{max}	-0.485%/°C
Temperature coefficient for V_{oc}	-0.351%/°C
Temperature coefficient for I_{sc}	0.053%/°C

*Measured at standard test conditions ($T = 25^\circ\text{C}$ and $I_r = 1 \text{ kW/m}^2$).

Table 3.2: Simulation parameters of the GCPVPP with NPC inverter

Parameter	Symbol	Value
Grid line-line voltage	v_{pcc-ab}	12.47 kV _{rms}
PCC phase-neutral voltage	v_{pcc-an}	230 V _{rms}
dc-link voltage	v_{dc}	700 V _{dc}
dc-link capacitor	C_u/C_l	2.2 mF
Fundamental frequency	f_0	50 Hz
3L-NPC switching frequency	f_s	3.6 kHz
dc-dc converter switching frequency	$f_{s-dc-dc}$	10 kHz
dc-dc converter inductor	L	1 mH

of the proposed controller, under various irradiation and temperature values, different amounts of irradiance and temperature are induced for the PV strings where String I ($Ir = 1 \text{ kW/m}^2$, $T = 25^\circ\text{C}$), String II ($Ir = 0.5 \text{ kW/m}^2$, $T = 25^\circ\text{C}$) and String III ($Ir = 1.1 \text{ kW/m}^2$, $T = 35^\circ\text{C}$).

It is necessary to perform a comprehensive power system test case simulation in order to investigate the performance of the designed GCPVPPs in terms of the control and dynamic performance. Accordingly, a medium voltage grid test case, based on North American Network, depicted in Fig. 3.8, is introduced in [126]. The grid voltage is 12.47 kV and the GCPVPP is connected to Bus 3 (PCC) using a step up transformer (0.4 kV/12.47 kV). The test case system consists of both single-phase and three-phase loads. Single-phase loads are connected to Bus 2 and Bus 5. The X/R ratio of lines equals to 6 and the medium voltage grid is connected to the 115 kV line through a 12.47 kV/115 kV transformer. The total load of Sub-network 1, shown in Fig. 3.8, is 200 kVA, while 150 kVA of this capacity, can be supplied by the only DG unit in this network, which is the GCPVPP connected to Bus 3.

Two different study sets are performed on the modelled grid-connected GCPVPP and results are presented in the following subsections. Firstly, the dynamic performance of the proposed controller is investigated during the different voltage sag conditions. Subsequently, the effect of the proposed active/reactive power injection method in enhancing the PCC voltage during various fault conditions at different buses of the system is evaluated.

3.4.1 Dynamic performance of the proposed controller

In order to validate the applicability of the proposed controller, the operation of GCPVPP is examined under two different voltage sags:

- *Sag I*: It includes a single phase to ground fault at Bus 4 which results in a 27% two-phase voltage sag between $t = 0.15 \text{ s}$ and $t = 0.3 \text{ s}$ in the PCC, as shown in Fig. 3.9(a).
- *Sag II*: It consist of a two-phase fault at Bus 4 which leads to a 64% three-phase voltage sag between $t = 0.45 \text{ s}$ and $t = 0.6 \text{ s}$ in the PCC, as shown in Fig. 3.9(a).

The amounts of injected active and reactive power to the grid are shown in Fig.

Figure 3.8: Schematic diagram of the medium-voltage test-case network [126].

3.9(b). It can be observed that the 3L-NPC inverter injects maximum active power to the grid during *Normal* operation, however, the amount of active power is reduced during *Sag I*, due to the injection of the reactive power in this period. After $t = 0.3$ s, the grid recovers to *Normal* condition and hence the inverter output active power is increased while the injected reactive power becomes zero. The injection of reactive power increases to its maximum possible value at $t = 0.45$ s due to *Sag II*, while the injected active power is zero. It should be mentioned that the oscillation of injected active and reactive power during *Sag I* and *Sag II*, is as a consequence of the injection of balanced currents to the grid during unbalanced grid voltages. The

Figure 3.9: Dynamic performance of the multi-string GCPVPP with three PV strings during various operation modes: (a) PCC voltages, (b) injected active and reactive power to the grid, (c) dc-link and dc capacitors voltages, (d) PV string voltages, (e) PV string currents and (f) extracted power from PV strings.

oscillation of the injected active power results in the oscillation of the dc-link voltages, as illustrated in Fig. 3.9(c). Besides, the proposed control method maintains v_{dc} at its reference value during all of the operation modes. The dc-link capacitor voltages remains balanced due to the implementation of the ASVM with voltage balancing capability.

The dynamic performance of PV strings is presented in Fig. 3.9(d). Since the PV strings are exposed to different amounts of irradiation and temperature, they have different maximum power values, voltages and currents during *Normal* condition. During *Sag I*, the extracted power from PV strings reduces to a certain value which is calculated by the dc-link voltage controller. Accordingly, the voltage of PV strings increases. This moves PV strings operation point to the right-side of *MPP* point. Moreover, the current of PV strings reduces during *Sag I*, as depicted in Fig. 3.9(e). The total extracted PV power is decreased to zero in order to deliver pure reactive power to the grid during *Sag II*. During this condition the current reduces to zero

and PV string voltages increase to their open-circuit value.

The dynamic performance of the current controller of the 3L-NPC inverter at the beginning and end of the voltage sag are depicted in Fig. 3.10. During *Normal* operation, the 3L-NPC inverter delivers only active power to the grid under unity power factor operation and no phase-shift exists between the PCC phase voltages and the injected currents, as shown in Fig. 3.10(b). However, there is a phase-shift (ϕ_1) between the voltage and currents, during *Sag I*, which shows the simultaneous injection of active and reactive powers to the grid. Fig. 3.10(d) shows the injected currents during *Sag II*. A phase-shift of $\phi_2 = \pi/2$ exists between the PCC voltage and injected currents, which implies the pure reactive power injection, during *Sag II*. Moreover, the currents of the inverter recover to *Normal* mode with unity power factor operation quickly, due to the fast performance of the PR current controller. It should be noticed that the amplitude of the inverter current remains at its nominal current amplitude during all sag conditions, which shows the effectiveness of the proposed dq -axis current reference calculation in using the full current capacity of the inverter when injecting active/reactive power to the grid during voltage sags.

3.4.2 Grid voltage support during voltage sags

Since the main objective of this chapter is to utilize the full current capacity of the grid-connected inverter in enhancing the PCC voltage during voltage sags, the obtained voltage enhancements under three different fault conditions are investigated and results are shown in Fig. 3.11.

Fault Case 1 A single-phase to ground fault in Bus 4 results in the 40% voltage sag in PCC. As shown in Fig. 3.11, between $t = 0.15$ s and $t = 0.3$ s, the GCPVPP is disconnected from the grid (*Disconnect*). During this period, $\hat{V}_{min}$ equals to 151 V (0.65 pu). The same fault situation is repeated between $t = 0.45$ s and $t = 0.6$ s at Bus 4, however in this period, the GCPVPP stays connected to the grid and injects both active and reactive power simultaneously to the grid (*PQ-inject*), as depicted in Fig. 3.11(a). It can be observed that due to the injection of the active/reactive powers with GCPVPP, $\hat{V}_{min}$ is increased to 182 V (0.79 pu).

Figure 3.10: Dynamic current controller performance of the grid-connected 3L-NPC inverter: (a) Starting of *Sag I* - PCC voltages, (b) starting of *Sag I* - injected currents, (c) ending of *Sag II* - PCC voltages and (d) ending of *Sag II* - injected currents.

Fault Case 2 A two-phase to ground fault is modeled at Bus 7 in this case study. The operation of the GCPVPP is kept same as before and the amount of $\hat{V}_{min}$ during

Figure 3.11: Voltage enhancement of the proposed active/reactive power injection strategy during different fault cases: (a) *Fault case 1*: Single-phase to ground fault at Bus 4 - injected active and reactive powers, (b) *fault case 1*: Single-phase to ground fault at Bus 4 - PCC rms voltages, (c) *fault case 2*: Two-phase to ground fault at Bus 7 - PCC rms voltages and (d) *Fault case 2*: Three-phase to ground fault at Bus 2 - PCC rms voltages

Table 3.3: PCC voltage enhancement under various fault conditions

Case Study	$\hat{V}_{min}$ during <i>Disconnect</i> mode	$\hat{V}_{min}$ during <i>PQ-inject</i> mode
<i>Fault Case 1</i>	151 V (0.65 pu)	182 V (0.79 pu)
<i>Fault Case 2</i>	122 V (0.53 pu)	152 V (0.66 pu)
<i>Fault Case 3</i>	75 V (0.32 pu)	100 V (0.43 pu)

both *Disconnect* and *PQ-inject* operation modes are simulated and results are shown in Fig. 3.11(c) and quantified in Table 3.3. It can be seen that the PCC voltage is enhanced from 122 V (0.53 pu during *Disconnect* operation of the GCPVPP, to 152 V (0.66 pu during *PQ-inject* operation mode of the GCPVPP, which shows a 13% improvement in the PCC voltage during the voltage sag, due to the implementation of the proposed controller.

Fault Case 3 In this case study, a balanced fault occurs at Bus 2 which results in 68% voltage sag in PCC. As a result, the GCPVPP injects reactive power to the grid (shown in Fig. 3.11(d) between 0.45 s and 0.6 s) as per the grid code requirements of (2.1). The comparison between the case where the GCPVPP disconnects and stays connected to the grid is also shown in Table 2, where an 11% improvement in the PCC voltage is attained.

It can be seen from Table 2 that the injection of the active/reactive power to the grid through the proposed controller enhances the PCC voltage compared to disconnection of the GCPVPP. This shows the effectiveness of the proposed active/reactive power control strategy in enhancing the grid voltage during voltage sags.

3.5 Experimental Evaluation

A three-phase 3L-NPC converter setup (Fig. 3.12) has been utilized in order to experimentally validate the effectiveness of the proposed controller under unbalanced voltage sags. The 3L-NPC setup consists of Semikron SKM145GB176D 1700V IGBT modules. The grid is generated using a TopCon TC.ACS 4-quadrant grid simulator, while the PV side is emulated using an ETS600/8 Terra SAS photovoltaic simulator. A dc-dc boost converter is connected between the PV panel and dc-link, which extracts the maximum power for the PV panel during normal operation mode. The proposed controller and protection functions of the converter are implemented in

Figure 3.12: Experimental setup of the grid-connected 3L-NPC inverter

a dSPACE 1006 platform. The parameters of the experimental setup are given in Table 3.4. The proposed controller has been evaluated under two different cases corresponding to *Sag I* and *Sag II*.

Sag I This case study includes a 36% two-phase voltage sag for a duration of 150 ms. The three-phase grid voltages (v_{pcc}) and injected currents (i_{abc}) are depicted in Fig. 3.13(a). Due to the implementation of the proposed control algorithm, the injected three-phase currents are balanced during such unbalanced voltage sag. Additionally, because the injected currents are equal to the inverter nominal current, maximum current capacity of the inverter is applied for enhancing the grid voltages during the voltage sag. A delay of maximum $T/4$, where T is the grid voltage period, is introduced by the SOGI due to the single-phase quadrature signal generation. It should be noted that this delay also depends on the amplitude of the voltage sag. During voltage sags with smaller amplitude (for instance between 10% and 30%), the sag can be detected faster compared to voltage sags with larger amplitudes (for instance between 70% and 90%).

Table 3.4: Experimental Parameters of the GCPVPP with NPC inverter

Parameter	Symbol	Value
PV panel and dc-dc converter parameters		
PV panel maximum power	p_{mpp}	3.3 kW
PV panel maximum power point voltage	v_{mpp}	480 V
PV panel maximum power point current	i_{mpp}	7 A
PV panel filling factor	FF	0.8
PV panel capacitor	C_{pv}	200 μ F
dc-dc converter switching frequency	f_{sw}	10 kHz
3L-NPC inverter parameters		
Apparent power	S	3.3 kVA
PCC phase-neutral voltage	$v_{pcc-abc}$	320 V _{rms}
dc-link voltage	v_{dc}	560 V _{dc}
dc-link capacitor	C_u / C_l	4.9 mF
Fundamental frequency	f_0	50 Hz
3L-NPC switching frequency	f_s	1.5 kHz
Inductor filter	L_f	4 mH

The dc-link voltage and capacitor voltages are depicted in Fig. 3.13(b). The dc-link voltage during *Normal* operation is 560 V_{dc} and remains constant during *Sag I*. Additionally, dc-link capacitors remain balanced during all operation modes. The PV voltage (v_{st}) is equal to 480 V_{dc} during *Normal* mode, which shows the operation of the PV string at *MPPT*. During *Sag I*, v_{st} increases to 555 V_{dc} with the proposed controller in Fig. 3.7 in order to decrease the extracted power. The extracted power from PV string (p_{st}) and output current of the PV string (i_{st}) are reduced during *Sag I*.

The quantities of the injected active and reactive powers (p and q) during *Sag I* are illustrated in Fig. 3.13(c). During *Normal* operation, the 3L-NPC inverter injects purely active power to the grid equal to 3.1 kW. The average active power is reduced to 1.3 kW for the duration of *Sag I*. As expected, second harmonic oscillation exists in the injected active power, due to the injection of balanced currents during the unbalanced voltage sag. On the other hand, the average of reactive power Q is increased to 2 kVAR. Consequently, the average injected apparent power is equal

Figure 3.13: Experimental results: *Sag I* - 36% two-phase voltage sag: (a) Three-phase voltages and currents, (b) dc-link voltage, PV string voltage, current and power and (c) injected active/reactive power

to 2.4kVA ($S = \sqrt{1.3^2 + 2^2}$), which is 77% of the apparent power during *Normal* operation ($S_N = 3.1 KVA$). The reduction of the injected apparent power is due to the decrease of the grid voltages during the voltage sag, while the injected currents

remain at the nominal value.

Sag II This case study consists of a three-phase voltage sag of 70% as shown in Fig. 3.14(a). Phase a experiences the smallest voltage amplitude at 30% of the nominal value, however due to the implementation of the proposed controller, the injected currents remain balanced and the maximum current capacity of the inverter is utilized during the voltage sag. The dc-link voltage, shown in Fig. 3.14(b), remains at its nominal value during *Sag II*, while v_{st} increases to $165 V_{dc}$, which is equal to the PV panel open-circuit voltage. Accordingly, p_{st} and i_{st} are also reduced to zero in this condition. The injected active and reactive powers are depicted in Fig. 3.14(c). It can be seen that the average active power is reduced to zero. The average reactive power (q) is increased to 1.3 kVAR during the voltage sag, i.e. (45%) of S_N . It should be noted that in this case study the delay of the voltage sag detection algorithm is smaller than *Sag I*, because of the smaller voltage amplitude of the voltage sag.

Figure 3.14: : (a) Three-phase voltages and currents, (b) dc-link voltage, PV string voltage, current and power and (c) Injected active/reactive power

3.6 Summary

This chapter studies the performance of the grid-connected three-level neutral-point-clamped (3L-NPC) inverter of the medium-scale multi-string grid-connected GCPVPPs during voltage sags. A control algorithm for the operation of the GCPVPP during *Normal* operation is implemented using two PR current controllers, implemented in $\alpha\beta$ -frame, and ASVM technique, which balances the capacitor voltages of the 3L-NPC inverter.

A voltage sag detection using SOGI with fast dynamic response has been implemented on the GCPVPP, in order to determine various operation modes, based on the grid PCC voltages. Since, the grid voltage positive-sequence is required in the controller to synchronize the output current of the inverter with grid voltage, an adaptive PLL has been investigated in this Chapter, which utilizes an moving average filter to eliminate the negative-sequence of the voltage. Subsequently, the detailed implementation of the proposed controller for the operation of the GCPVPP with balanced current injection to the grid during voltage sags has been discussed. In the proposed algorithm, a method for calculating the dq -axis current references based on the extracted power from PV strings and grid code requirements is implemented. Based on the grid requirements, the 3L-NPC inverter injects the required active/reactive power to the grid during voltage sags. Furthermore, an algorithm for reduction of the extracted power from PV strings during voltage sags, has been introduced. The proposed control strategy employs the full current capacity of the grid-connected inverter resulting in a better grid voltage enhancement, however, the injected active/reactive powers to the grid experience oscillations, which also affects the dc-link voltage.

Detailed implementation of the proposed control scheme has been presented, and its effectiveness are demonstrated through simulation results on a 150-kVA GCPVPP connected to the 12.47-kV medium-voltage test-case system under various voltage sag conditions. Experimental results on a laboratory 3.3-kVA 3L-NPC setup have been presented showing the effectiveness of the proposed control strategy in injecting active/reactive power to the grid during voltage sags.

The operation of the GCPVPP with balanced current injection during voltage sags has been investigated in this chapter. By using the proposed controller, the GCPVPP complies with grid code requirements and achieve LVRT capability. How-

ever, as mentioned, there is an oscillation in both injected active/reactive powers to the grid. The oscillation affects the dc-link voltage and increases the THD of the injected current. Therefore, the unbalanced current injection, with zero active power oscillation is investigated in the following chapter, to eliminate the limitations of the balanced current injection.

Chapter 4

Unbalanced Current Injection Strategy for Photovoltaic Grid-Connected Inverter during Unbalanced Voltage Sags

The chapter introduces a control algorithm for active/reactive power injection of a photovoltaic grid-connected inverter with peak current limitation and zero active power oscillation during unbalanced voltage sags. The principles of unbalanced active/reactive power theory are discussed in Section 4.2. The detailed implementations of the proposed active/reactive power and current reference calculation algorithm, current controller and dc-dc converter controller during voltage sags are described in Section 4.3. Experimental results of the proposed controller on a 3.3-kVA laboratory three-level neutral-point-clamped (3L-NPC) inverter are illustrated in Section 4.4 and the conclusions of the work are summarized in Section 4.6.

4.1 Introduction

The operation of the GCPVPP with 3L-NPC inverter with unbalanced current injection during unbalanced voltage sags is investigated in this chapter. The schematic of this power plant is explained in Section 2.3.1. The operation of this power plant with balanced current injection to the grid has been investigated in Chapter 3. In this chapter, an unbalanced current injection algorithm is introduced, which results

in zero active power oscillation during unbalanced voltage sags.

Various algorithms has been introduced in the literature for the unbalanced current injection of GCPVPPs in the literature and they are reviewed in Section 2.6.2. These studies have proposed different algorithms for calculating the current references (balanced or unbalanced) according to a certain amount of active/reactive power references, which are empirically determined only based on the rated apparent power of the inverter [9–11, 13, 78–81, 127–129]. However, if the amount of active/reactive power references are set only based on the rated apparent power of the inverter, then the corresponding injected current references during a voltage sag can be higher than the maximum inverter currents. Until now, this problem is solved by setting a fixed apparent power value, which limits the maximum current under certain maximum voltage sag conditions. In that sense, the maximum GCPVPP capabilities may not be used because the current references are set below the inverter rated current. Consequently, there is a necessity to develop a control algorithm, which can achieve zero active power oscillation, while it limits the peak current of the inverter during voltage sags. Furthermore, in all of

This chapter derives an analytical expression for calculating active/reactive power references (P^* and Q^*) which limits the inverter peak current during voltage sags. Unlike the current studies in the literature [7, 82–87], the proposed analytical expression for P^* and Q^* does not depend on the current reference calculation method and, as a general formulation, can be implemented in combination with various such methods. Additionally, an analytical expression is introduced, which calculates the required active power from PV strings during voltage sags. This method ensures that the inverter current remains within its nominal operation range and also keeps the dc-link voltage at its nominal value. The proposed power references are used to define improved current references, which result in zero active power oscillation. In order to obtain a constant dc-link voltage and maintain the active and reactive power injection during voltage sags, a coordinated maximum power point tracking (MPPT) algorithm is also implemented for the dc-dc converters of the multi-string GCPVPP, which reduces the extracted power from PV strings to the amount of active power that can be injected to the grid according to the inverter nominal current and the injected reactive current.

4.2 Unbalanced Active/Reactive Power Theory

According to the instantaneous power theory, the injected active power (p) to the grid for GCPVPP, shown in Fig. 2.5, is:

$$p = v_{pcc} i_{abc} = v_{pcc-a} i_a + v_{pcc-b} i_b + v_{pcc-c} i_c, \quad (4.1)$$

where $v_{pcc} = [v_{pcc-a} \ v_{pcc-b} \ v_{pcc-c}]$ are the phase-neutral voltages of PCC and $i_{abc} = [i_a \ i_b \ i_c]^T$ are the output currents of the grid-connected 3L-NPC inverter, shown in Fig. 2.5.

The instantaneous active power can be calculated using the symmetric sequence transformation as follows:

$$\begin{aligned} p &= (v_{pcc}^+ + v_{pcc}^-) \cdot (i_{abc}^+ + i_{abc}^-) \\ &= \left(\overbrace{v_{pcc}^+ i_{abc}^+}^{P^+} + \overbrace{v_{pcc}^- i_{abc}^-}^{P^-} \right) + \left(\overbrace{v_{pcc}^+ i_{abc}^- + v_{pcc}^- i_{abc}^+}^{\tilde{p}} \right) \\ &= P + \tilde{p}, \end{aligned} \quad (4.2)$$

where:

v_{pcc}^+ : The positive-sequence voltage vector.

v_{pcc}^- : The negative-sequence voltage vector.

i_{abc}^+ : The inverter positive-sequence current vector.

i_{abc}^- : The inverter negative-sequence current vector.

P : The average active power.

$\tilde{p}$: The active power oscillation term.

P^+ : The positive-sequences of the average active power.

P^- : The negative-sequences of the average active power.

A traditional algorithm to compute the current references is to define values k_1 and k_2 as the ratio of the positive-sequence active or reactive power to the total active or reactive power ($k_1 = \frac{P^+}{P}$ and $k_2 = \frac{Q^+}{Q}$), where Q is the average reactive power and Q^+ is its positive-sequence [77]. Hence, the current references can be calculated as follows:

$$\begin{aligned}
i_{abc}^* = & \overbrace{\frac{k_1 P^*}{|v_{pcc}^+|^2} v_{pcc}^+}^{i_{abc-p}^+} + \overbrace{\frac{(1-k_1) P^*}{|v_{pcc}^-|^2} v_{pcc}^-}^{i_{abc-p}^-} \\
& + \overbrace{\frac{k_2 Q^*}{|v_{pcc}^+|^2} v_{pcc\perp}^+}^{i_{abc-q}^+} + \overbrace{\frac{(1-k_2) Q^*}{|v_{pcc}^-|^2} v_{pcc\perp}^-}^{i_{abc-q}^-},
\end{aligned} \tag{4.3}$$

with

$$v_{pcc\perp} = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} v_{pcc},$$

where:

P^* : The average active power reference.

Q^* : The average reactive power reference.

Thus, the positive- and negative-sequences of the current reference can be computed according to (4.3) as:

$$i_{abc}^{+*} = \frac{k_1 P^* - j k_2 Q^*}{|v_{pcc}^+|^2} v_{pcc}^+ \tag{4.4}$$

$$i_{abc}^{-*} = \frac{(1-k_1) P^* + j(1-k_2) Q^*}{|v_{pcc}^-|^2} v_{pcc}^-. \tag{4.5}$$

It is shown that the positive- and negative-sequences of the current reference depend on k_1 and k_2 . Therefore, as will be explained later in detail, these values can be dynamically calculated based on the purpose of the controller during unbalanced voltage sags.

4.3 Proposed Active/Reactive Power Control Strategy during Unbalanced Voltage Sags

Two separate controllers for the grid-connected 3L-NPC inverter and the dc-dc converters are required to operate the GCPVPP system. These controllers along with the proposed algorithms for calculation of the active/reactive power references and current references are presented in detail in the following subsections. Each of these

controllers require separate control strategies, which are specific for a GCPVPP operation mode. Therefore, a fast and precise voltage disturbance detection algorithm is required to determine the operating mode of the GCPVPP. The voltage sag detection algorithm, used in this work, has been presented in Section 3.3.1.

4.3.1 Proposed Active/Reactive Power Reference Calculation

The controller of the 3L-NPC inverter is used to maintain the dc-link voltage (V_{dc}) by controlling the injected active power into the grid. It is realized by manipulating the d-axis current reference (I_d^*) through a PI controller. The q-axis current reference (I_q^*) is calculated from the grid code as in (2.1). In order to achieve unity power factor operation during *Normal* operation mode, I_q^* is set to zero.

According to (4.4) and (4.5), the average active and reactive power references (P^* and Q^*) are required for the calculation of unbalanced current references. On the other hand, the dc-link voltage controller and grid codes provide the d-axis and q-axis current references (I_d^* and I_q^*). Consequently, the instantaneous calculation of P^* and Q^* from I_d^* and I_q^* is necessary for the operation of GCPVPP during various operation modes.

In the dq -frame, the amount of injected active and reactive power can be calculated as:

$$p = v_d i_d + v_q i_q \quad (4.6)$$

$$q = v_q i_d - v_d i_q, \quad (4.7)$$

where:

v_d : The instantaneous d-axis component of PCC voltage.

v_q : The instantaneous q-axis component of PCC voltage.

i_d : The instantaneous d-axis component of the injected current to the grid.

i_q : The instantaneous q-axis component of the injected current to the grid.

Accordingly, the average injected active and reactive powers can be calculated as:

$$P = \frac{1}{T_w} \left| \int_{t-T_w}^t v_d i_d dt + \int_{t-T_w}^t v_q i_q dt \right| \quad (4.8)$$

$$Q = \frac{1}{T_w} \left| \int_{t-T_w}^t v_q i_d dt - \int_{t-T_w}^t v_d i_q dt \right|, \quad (4.9)$$

where T_w is the window width used for the average calculation, typically $T/2$ or T , T being the grid-voltage period ($T = 1/f$, where f is the grid voltage fundamental frequency). i_d and i_q are calculated with the outer control loop and it can be assumed that their values remain constant within one average calculation window width, being equal to I_d and I_q , respectively. It should be noted that the instantaneous values of I_d and I_q is not constant and is determined based on the minimum amplitude of the voltage sag. However, since the bandwidth of the outer loop controller is slower than the inner current controller, in each calculation time-step, their value can be assumed as constant. Consequently, the average active and reactive powers can be written as:

$$P = \frac{1}{T_w} \left| I_d \int_{t-T_w}^t v_d dt + I_q \int_{t-T_w}^t v_q dt \right| \quad (4.10)$$

$$Q = \frac{1}{T_w} \left| I_d \int_{t-T_w}^t v_q dt - I_q \int_{t-T_w}^t v_d dt \right|. \quad (4.11)$$

The voltage vector can be represented in dq -coordinates through the Park transformation using a synchronous reference frame rotating at the fundamental frequency [130]:

$$\begin{aligned} \begin{bmatrix} v_d \\ v_q \end{bmatrix} &= |v_{pcc1}^+| \begin{bmatrix} \cos(\theta_0) \\ \sin(\theta_0) \end{bmatrix} \\ &+ \sum_{\substack{n=-\infty \\ n \neq 1}}^{\infty} |v_{pccn}^+| \begin{bmatrix} \cos[(n-1)\omega t + \theta_0 + \theta_n] \\ \sin[(n-1)\omega t + \theta_0 + \theta_n] \end{bmatrix} \end{aligned} \quad (4.12)$$

where:

θ_0 : The initial position of the d -axis in the dq transformation.

n : The harmonic number.

$|v_{pcc1}^+|$ is the amplitude of positive-sequence fundamental voltage which in this study is referred as $|v_{pcc}^+|$. Assuming that d -axis is aligned with the voltage vector, then $\theta_0 = 0$. Accordingly, the average dq -axis voltages can be calculated, by integrating from (4.12), as below:

$$V_d = \frac{1}{T_w} \int_{t-T_w}^t v_d dt = |v_{pcc}^+| \quad (4.13)$$

$$V_q = \frac{1}{T_w} \int_{t-T_w}^t v_q dt = 0, \quad (4.14)$$

where:

V_d : The average values of v_d during one average calculation window width.

V_q : The average values of v_q during one average calculation window width.

The integral of harmonics in (4.12) over one voltage cycle equals to zero.

By inserting (4.13) and (4.14) in (4.10) and (4.11), the average active and reactive power references are calculated as:

$$P = |I_d| \cdot |v_{pcc}^+| \quad (4.15)$$

$$Q = |I_q| \cdot |v_{pcc}^+|. \quad (4.16)$$

The equations (4.15) and (4.16) are applied in the proposed controller for computing the active and reactive power reference as:

$$P^* = |I_d^*| \cdot |v_{pcc}^+| \quad (4.17)$$

$$Q^* = |I_q^*| \cdot |v_{pcc}^+|, \quad (4.18)$$

where I_d^* and I_q^* are calculated from the dc-link voltage controller and the grid code. $|v_{pcc}^+|$ is instantaneously calculated from PCC phase voltages as depicted in Fig.

4.1. Finally, the active/reactive power references (4.17) and (4.18) are used in (4.4) and (4.5) in order to calculate the current references. In the proposed algorithm, the amount of active/reactive power does not depend on the current reference calculation algorithm, and (4.17) and (4.18) are general equations that can be implemented in combination with various current reference calculation methods, while the peak current of the inverter during voltage sags remains within its nominal value.

4.3.2 Proposed Unbalanced Current Reference Calculation Algorithm with Zero Active Power Oscillation

After calculating the active/reactive power references, the unbalanced current references are calculated in order to obtain zero active power oscillation of GCPVPP during unbalanced voltage sags because:

- According to the standards and grid codes, the reactive power should be injected to the grid. The injection of the reactive power leads to an increase of the phase voltage in the PCC. By injecting balanced reactive currents to the grid during unbalanced voltage sags, the voltage of nonfaulty (healthy) phases can increase beyond its nominal value, which activates the over-voltage protection. In order to avoid this situation, unbalanced current injection is investigated.
- The oscillation of the active power results in second-order harmonic oscillation of the dc-link voltage. Therefore, the injected active power oscillation should be reduced to zero in order to minimize the dc-link voltage oscillation while avoiding unnecessary trips on dc-voltage protections.

The active power oscillation can be calculated by substituting the positive- and negative-sequence currents from (4.4) and (4.5) in (4.2), as follows:

$$\begin{aligned} \tilde{p} = & \left[\left(\frac{1-k_1}{|v_{pcc}^-|^2} + \frac{k_1}{|v_{pcc}^+|^2} \right) P^* \right. \\ & \left. + j \left(\frac{1-k_2}{|v_{pcc}^-|^2} - \frac{k_2}{|v_{pcc}^+|^2} \right) Q^* \right] v_{pcc}^+ \cdot v_{pcc}^- \end{aligned} \quad (4.19)$$

Since the target is to obtain positive and negative sequences of the current references while obtaining zero active power oscillation, k_1 and k_2 are obtained from

(4.19), considering $\tilde{p}$ equal to zero, as per:

$$k_1 = \frac{1}{1 - \frac{|v_{pcc}^-|^2}{|v_{pcc}^+|^2}} \quad (4.20)$$

$$k_2 = \frac{1}{1 + \frac{|v_{pcc}^-|^2}{|v_{pcc}^+|^2}}. \quad (4.21)$$

Then, k_1 and k_2 , which change dynamically based on the instantaneous grid positive- and negative-sequence voltages, are used for the calculation of the current references ((4) and (5)). This ensures zero oscillation of the injected active power of the inverter during all operation modes.

4.3.3 Current Controller during Unbalanced Voltage Sags

A comprehensive schematic of the proposed current controller is illustrated in Fig. 4.1. After calculating I_d^* and I_q^* , the phase current references ($\bar{i}_a^*$, $\bar{i}_b^*$ and $\bar{i}_c^*$) are calculated based on the grid voltages. A detailed implementation of the proposed current reference calculation algorithm is shown in Fig. 4.2. Firstly, the PCC positive- and negative-sequence voltages (v_{pcc}^+ and v_{pcc}^-) are calculated. The calculations are implemented in the s-plane and voltage angle is calculated using the three phase adaptive phase-locked-loop [122]. The positive-sequence voltage is assumed to be aligned with the voltage vector of phase a . As the aim of the controller is to achieve zero active power oscillation during unbalanced voltage sags, k_1 and k_2 are calculated according

Figure 4.1: Proposed current controller for grid-connected 3L-NPC inverter.

Figure 4.2: Proposed current reference calculation algorithm during unbalanced voltage sags.

to (4.20) and (4.21). These values are considered in (4.4) and (4.5) for the enumeration of reference positive and negative-sequence currents.

The calculated active and reactive power references from (4.17) and (4.18) are considered in the proposed controller as shown in Fig. 4.2. The positive- and negative-sequence current references are calculated from (4.4) and (4.5) and then are transformed to abc coordinates.

The calculated current references (i_a^* , i_b^* and i_c^*) of one or two phases may be higher than the inverter nominal current because the controller aims to achieve zero active power oscillation. Thus, the current references should be limited to the inverter nominal current. On the other hand, according to (4.1), the current references of all three phases should be rescaled with the same factor to ensure the constant active power injection. Therefore, a rescaling factor (K_{rs}) is defined based on the maximum rms value of current references as below:

$$K_{rs} = \begin{cases} \frac{I_{rms}}{i_{rms-max}^*}, & \text{if } i_{rms-max}^* > I_{rms} \\ 1, & \text{if } i_{rms-max}^* \leq I_{rms}, \end{cases} \quad (4.22)$$

where I_{rms} is the rms value of the nominal current of the inverter and $i_{rms-max}^*$ is the maximum rms value of the three phase current references (Fig. 4.2). The final current references are calculated as follows:

$$\begin{bmatrix} \bar{i}_a^* \\ \bar{i}_b^* \\ \bar{i}_c^* \end{bmatrix} = K_{rs} \begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix}. \quad (4.23)$$

The errors between the calculated current references and instantaneous phase currents are fed into the proportional resonant (PR) with anti-windup controller which is implemented in the abc -frame. The PR controller is implemented on each phase separately in order to obtain independent unbalanced phase currents. Although, the implementation of the conventional PI controller for balanced current injection is simple, it requires multiple frame transformation and results in slow performance. On the other hand, for injection of proper unbalanced currents under unbalanced voltage sags, the calculation of both positive- and negative-sequence voltages in dq -frame is required which increases the computational complexity [131]. The PR controller with anti-windup shows faster dynamic response and zero steady-state error [74]. Finally, adaptive space vector modulation (SVM) is applied for generating the switching signals of the 3L-NPC inverter, based on [43].

4.3.4 dc-dc Converter Controller during Voltage Sags

During the *Normal* operation, the dc-dc converters of the multi-string GCPVPP (Fig. 2.5) extract the maximum power from PV strings. However, during *Sag I* or *Sag II*, the extracted power from the PV strings should be reduced due to the current limitation of the inverter. Therefore, a modification in the controller of the dc-dc converters is necessary. A comprehensive schematic of the proposed control algorithm for the dc-dc converters is depicted in Fig. 4.3. The proposed control algorithm consists of three operation modes:

Figure 4.3: Proposed PV strings control algorithm.

Normal All of the dc-dc converters extract the maximum power from PV strings, which is referred as *MPPT* in this chapter. The PV string operates at point *A* as shown in Fig. 4.4(a). As illustrated in Fig. 4.4(b), the calculated V_{MPP} from MPPT algorithm is compared with the instantaneous string voltage (V_{st}) and the error is fed into the PI controller. During this operation mode, the reduction power signal (RP), which will be explained later in this chapter, equals zero. Subsequently, the switching signals of the dc-dc boost converter are generated.

Sag I Both active and reactive powers are injected to the grid during this operation state. Priority is given to the reactive power. Firstly, the required reactive current is calculated according to (2.1). Afterwards, the possible injected active current is calculated based on the nominal current of the inverter as follows:

$$I_{d1} = \sqrt{I_{N_{dq}}^2 - I_q^{*2}}. \quad (4.24)$$

Subsequently, the maximum possible active power is calculated by (4.15) based on

Figure 4.4: (a) Power-voltage curve of the PV string and (b) dc-dc boost converter controller during voltage sags.

the maximum possible active current and the amplitude of positive-sequence voltage:

$$P_{sagI}^* = |V_{pcc}^+| I_{d1}. \quad (4.25)$$

In order to ensure that the grid code requirement is fulfilled by prioritizing the injected reactive power, the rescaling factor (K_{rs}), is multiplied by the calculated active power reference from (4.25):

$$\bar{P}_{sagI}^* = K_{rs} P_{sagI}^*. \quad (4.26)$$

As a result, if the calculated current reference of the 3L-NPC inverter is larger than its nominal current, the controller reduces the active power to give the priority to the reactive power requirement.

The active power reference ($\bar{P}_{sagI}^*$) is then compared with extracted power from individual PV strings as depicted in Fig. 4.3. If $\bar{P}_{sagI}^*$ is smaller than the extracted power of String 1 (p_{st1}), then all other PV strings are open-circuited (*O.C.*) and p_{st1}

is reduced to $\bar{P}_{sagI}^*$. This means that the operation point of PV String 1, which is referred as Str1 in Fig. 4.3, should be moved to point B in Fig. 4.4(a).

In order to reduce the extracted power from the PV string, a reduced power (RP) signal is defined. This signal is set to 1 for the PV string which power should be reduced, while it is 0 for PV strings with *MPPT* operation mode. As illustrated in Fig. 4.4(b), while $RP = 1$, the voltage (ΔV_{st}) is added to V_{mpp} which results in the movement of the operation point from point A to point B . The instantaneous extracted power from PV string (p_{st}) is compared with the power reference (p_{st}^*), which is calculated by the central controller (Fig. 4.3) and the error is fed into a PI controller which results in ΔV_{st} .

If $\bar{P}_{SagI}^*$ is larger than p_{st1} and is smaller than $p_{st1} + p_{st2}$, the PV String 1 is set to *MPPT*, String 2 operates at power reduction mode ($RP = 1$) and all other PV strings are open circuited. The power reduction algorithm can be implemented in the same manner for other power references (larger than $p_{st1} + p_{st2}$) as well. It should be noted at each moment, only one of PV strings operates at power reduction mode and other PV strings are operating at *MPPT* or *O.C.*. This algorithm results in fast performance of the controller at the beginning of the voltage sag as well as after the clearance of the voltage sag.

Sag II Based on the grid codes, the injected active power to the grid is zero. Therefore, all PV strings are *O.C.* to reduce the extracted power from all PV strings to zero. The dc-link voltage controller, shown in Fig. 4.1, continues its operation during this operation mode in order to regulate the dc-link voltage to its reference. It should be mentioned that the amount of I_d^* is near zero during *Sag II*, because the extracted power for PV strings is zero. The operation point of the PV string is moved to point C in Fig. 4.4(a), which results in zero power extraction from the PV string.

The performance of the dc-dc control algorithm is illustrated in Fig. 4.5. During *Normal* operation, all PV strings operate in *MPPT* mode. The injected active power is 1 pu and accordingly the extracted power from each one of the three PV strings is 0.33 pu. During *Sag I*, the injected active power is reduced to 0.5 pu. Therefore, String 1 remains at *MPPT*, String 3 is *O.C.* and the extracted power of String 2 is reduced to adjust the required active power ($p_{st2}^* = \bar{P}_{sagI}^* - p_{st1}$). During *Sag II*, the injected active power is zero and, as a result, the extracted powers from all PV strings are zero.

Figure 4.5: Simulation results of multi-string GCPVPP with three PV string during various operation modes: (a) PCC voltages, (b) injected active and reactive power to the grid and (c) extracted power from PV strings.

4.3.5 Discussion on the Proposed PV String Control Algorithms

In Chapter 3, as depicted in Fig. 3.7 (page 66), the dc-link voltage is applied in the reduction of the power from the PV strings. In this case, the calculation of the power reference is not required. The grid-connected inverter reduces the injected active power to the grid during voltage sags based on the grid codes. The excessive power between the extracted power from PV strings and the injected power to the grid is stored in the dc-link capacitors, which increases the dc-link voltage. Therefore, by controlling the dc-link voltage, the amount of the extracted power from PV strings can be regulated to the injected active power to the grid.

In Chapter 4, as shown in Figs. 4.3 and 4.4 (pages 94 and 95), the required power

reference is calculated dynamically through the proposed algorithm. By knowing the required power reference and the instantaneous extracted power from PV strings, a decision on keeping the PV string on their maximum power or zero power can easily be made, as illustrated in this figure. Therefore, it is only required to move the operation point of one PV string to the right-side of *MPP*. The principle for the movement of the operation point to the right-side of *MPP* is also illustrated in Figs. 4.4 (page 95).

A comprehensive comparison between these two algorithms is as follows:

- The calculation of the power reference is required for the algorithm in Chapter 4, however the regulation of the power is performed based on the dc-link voltage in Chapter 3 and the amount of power reference is not required.
- The operation points of all of the PV strings are moved to the right-side of *MPP* in Chapter 3, however only the operation point of one PV string is moved to the right-side of *MPP* and other PV strings are kept either at maximum power production or they are open-circuited.
- The proposed algorithm in Chapter 4 shows a faster dynamic compared to the algorithm in Chapter 3, because:
 - The power reference can be instantaneously calculated based on the algorithm in Chapter 4 and accordingly the extracted power can be adjusted to it. However, the slow dynamic of the dc-link voltage causes a slow dynamic performance in the algorithm in Chapter 3.
 - Since the operation points of some of the PV strings are kept at *MPP* in the algorithm in Chapter 4, after the clearance of the voltage sag, they can easily continue the extraction of maximum power. However, there is a delay for the movement of the operation point of PV strings from *CPG* to *MPP* in the algorithm in Chapter 3.

4.4 Experimental Evaluation

A three-phase 3L-NPC converter setup (Fig. 2.5) has been utilized in order to experimentally validate the effectiveness of the proposed controller under unbalanced voltage sags. The 3L-NPC setup consists of Semikron SKM145GB176D 1700V IGBT

Table 4.1: Experimental parameters for grid-connected 3L-NPC inverter

Parameter	Symbol	Value
PV panel and dc-dc converter parameters		
PV panel maximum power	p_{mpp}	3.3 kW
PV panel maximum power point voltage	v_{mpp}	480 V
PV panel maximum power point current	i_{mpp}	7 A
PV panel filling factor	FF	0.8
PV panel capacitor	C_{pv}	200 μ F
dc-dc converter switching frequency	f_{sw}	10 kHz
3L-NPC inverter parameters		
Apparent power	S	3.3 kVA
PCC phase-neutral voltage	$v_{pcc-abc}$	320 V _{rms}
dc-link voltage	v_{dc}	560 V _{dc}
dc-link capacitor	C_u, C_l	4.9 mF
Fundamental frequency	f_0	50 Hz
3L-NPC switching frequency	f_s	1.5 kHz
Inductor filter	L_f	4 mH

modules. The grid is simulated using TopCon TC.ACS 4-quadrant grid simulator while the PV side is emulated using an ETS600/8 Terra SAS photovoltaic simulator and its characteristics are given in Table 4.1. A dc-dc boost converter is connected between the PV panel and dc-link, which extracts the maximum power for the PV panel during normal operation mode. The proposed controller and protection functions of the converter are implemented in a dSPACE 1006 platform. The parameters of the converter are given in Table 4.1. The proposed controller has been evaluated under two different cases corresponding to *Sag I* and *Sag II* of Section 4.3.

Sag I It includes 36% two-phase voltage sag for a duration of 150 ms. The three phase grid voltages (v_{pcc}) and injected currents (i_{abc}) are depicted in Fig. 4.6(a). The amplitude of positive-sequence voltage ($|v_{pcc}^+|$) during *Normal* operation is 270 V (1 pu), however it is reduced to 205 V (0.77 pu) during *Sag I* mode, as depicted in Fig. 4.6(b). As a result, k_1 and k_2 changed according to (4.20) and (4.21). The value

of k_1 increases to 1.02 during the voltage sag, which means P^+ is larger than P or the amount of negative-sequence active power (P^-) is negative, which results in higher injected current (i_c) into the phase with lower voltage (v_{pcc-c}).

The dc-link voltage and capacitor voltages are depicted in Fig. 4.6(b). The dc-link voltage during *Normal* operation is 560 V_{dc} and is remained constant during *Sag I*. Additionally, dc-link capacitors are remained balanced during all operation modes. The PV voltage (V_{st}) is equal to 480 V_{dc} during *Normal* mode which shows the operation of the PV string at *MPPT*. During *Sag I*, V_{st} is increased to 555 V_{dc} through the proposed controller in Fig. 4.4 in order to decrease the extracted power. The extracted power from PV string (P_{st}) and output current of the PV string (I_{st}) are reduced during *Sag I*.

The quantities of the injected active and reactive powers (p and q) during *Sag I* are illustrated in Fig. 4.6(c). During *Normal* operation, the 3L-NPC inverter injects purely active power to the grid equal to 3.1 kW. The active power is reduced to 1.3 kW for the duration of *Sag I*. As expected from the controller, the active power oscillation is zero during *Sag I*. On the other hand, the average of reactive power Q is increased to 2 kVAR. Consequently, the average injected apparent power ($S = \sqrt{1.3^2 + 2^2}$) is equal to 2.4 kVA which is 77% of the apparent power during *Normal* operation ($S_N = 3.1 \text{ KVA}$). It can be seen that the current of the inverter remains within its nominal current.

Sag II It consists of a three-phase voltage sag of 70% as shown in Fig. 4.7(a). Phase *a* experiences the smallest voltage amplitude of 30% of the nominal one. Due to the implementation of the proposed controller, the current of phase *a* is larger than phases *b* and *c* during the voltage sag. The dc-link voltage, shown in Fig. 4.7(b) is remained at its nominal value during *Sag II* while V_{st} is increased to 165 V_{dc}, which is equal to the open-circuit voltage of the PV panel. Accordingly P_{st} and I_{st} are reduced to zero during this condition. The injected active and reactive powers are depicted in Fig. 4.7(c). It can be seen that p is reduced to zero. The average reactive power (Q) is increased to 1.3 kVAR during the voltage sag that is 45% of S_N . It should be noted that $|v_{pcc}^+|$ is also reduced to approximately 45% of its nominal value. Therefore, under this condition, the injected reactive power is also reduced to 45% of the nominal apparent power according to (4.18), which results in remaining the inverter current within its nominal value.

Figure 4.6: Experimental results: *Sag I*: (a) Three-phase voltage and currents, (b) dc-link voltage, PV string voltage, current and power and (c) positive- and negative-sequence voltages, k_1 , k_2 and injected active/reactive power.

Figure 4.7: Experimental results: *Sag II*: (a) Three-phase voltage and currents, (b) dc-link voltage, PV string voltage, current and power and (c) positive- and negative-sequence voltages, k_1 , k_2 and injected active/reactive power.

4.5 Discussion on the Proposed Balanced and Unbalanced Current Injection Algorithms

The focus of Chapter 3 is to calculate the d- and q-axis current references in the controller of the grid-connected inverter during voltage sags. The balanced currents are injected to the grid under different voltage sag conditions. The injection of the balanced currents to the PCC during unbalanced voltage sags results in the second harmonic oscillation of the injected active and reactive power to the grid. This problem is addressed in Chapter 4 by implementing an algorithm for the injection of proper unbalanced currents to the grid during unbalanced voltage sags. The performances of these two algorithms are investigated on the same simulation and experimental setups and results are presented in Chapters 3 and 4. The following differences can be observed from the experimental results under *Sag I* and *Sag II* conditions with unbalanced current injection in Figs. 4.6 and 4.7 compared to the experimental results with balanced current injection in Figs. 3.13 and 3.14:

- Second order harmonic oscillation of the injected active and reactive power is reduced to zero by using the proposed algorithm in Chapter 4, however large oscillation can be observed by injecting balanced currents to the grid in Fig. 3.13 and 3.14.
- The oscillation of the dc-link voltage is smaller in Figs. 4.6 and 4.7 (with unbalanced current injection), compared to the dc-link voltage oscillation in Figs. 3.13 and 3.14.
- The dynamic response of the dc-link voltage controller is improved in the proposed algorithm in Chapter 4, due to the implemented control algorithm in this chapter. The detailed comparison of the implemented dc-dc converters controllers is provided in the response of question 6 of the examiner.

4.6 Summary

The unbalanced current injection from the GCPVPP during unbalanced voltage sags has been investigated in this chapter. A comprehensive control algorithm to limit the inverter peak current and achieve zero active power oscillation for the grid-connected PV power plant (GCPVPP) during unbalanced voltage sags has been

introduced and investigated. It is shown that the average active and reactive power references (P^* and Q^*) can be calculated by multiplying the amplitude of the voltage positive-sequence ($|v_{pc}^+|$) with the dq current references (I_d^* and I_q^*).

The main contribution of this study is to calculate P^* and Q^* as a general equation that can be implemented in combination with various current reference calculation algorithms, while ensures that the inverter peak current remains within its nominal value. Since, the amplitudes of the phase current references depend the voltage positive- and negative-sequences, a rescaling factor (K_{rs}) has been applied in order to ensure the operation of the inverter within its nominal range.

The extracted power from PV strings has been reduced during voltage sags through the implementation of the control algorithm for dc-dc converters of the multi-string GCPVPP. Therefore, the GCPVPP complies with the reactive current requirements of the grid codes and current limitation of the inverter. A detailed implementation of the proposed control scheme has been presented, and its effectiveness has been proved in a 3.3-kVA three-phase grid-connected 3L-NPC inverter prototype. The experimental results verify the theoretical analysis and demonstrate the satisfactory performance of the proposed control algorithm during various voltage sags.

The proposed algorithm in this chapter is general algorithm, which can be applied in different types of grid-connected inverters. The operation of the 3L-NPC inverter, which has been considered in this chapter, does not require additional controllers for balancing of capacitor voltages, because the voltage balancing has been performed easily through the ASVM technique. However, the operation of other multilevel converters might need additional consideration on voltage balancing of capacitors. Accordingly, the following chapter, investigates the operation of GCPVPP with CHB inverter during voltage sags, which needs voltage balancing of capacitors.

Chapter 5

Operation of Photovoltaic Grid-Connected Cascaded H-Bridge Inverter during Voltage Sags

The operation of photovoltaic grid-connected cascaded H-bridge inverter during voltage sags is investigated in this chapter. An introduction to this subject and summary of the available algorithms in the literature is presented in Section 5.1. Section 5.2 provides an overview of the proposed strategy for grid-connected CHB inverter during voltage sags, including detailed discussions about the proposed feedforward, inter-phase and inter-bridge controllers. The simulation and experimental results are presented in Sections 5.4 and 5.5, respectively, while the conclusions of the work are summarized in Section 5.6.

5.1 Introduction

The operation of the GCPVPP with seven-level cascaded H-bridge (7L-CHB) inverter is explored in this chapter. The structure of the power plant and its characteristics have been presented in Section 2.3.2. Various control algorithms for the operation of the GCPVPP with CHB inverter during partial shading and failure of the switches are introduced in the literature, which have been discussed in details in Section 2.6.3. Based on the presented discussion, there is a need for a flexible control

strategy, which can ensure dc-link voltage balancing, for the GCPVPP with CHB inverter during voltage sags.

This chapter introduces a flexible control strategy for the operation of GCPVPP with CHB inverter during unbalanced voltage sags. The proposed strategy is capable of balancing dc-link voltages while injecting both active and reactive powers with either balanced or unbalanced currents. A zero-sequence voltage injection algorithm is proposed for inter-phase balancing, which allows for energy exchange between various phases. For inter-bridge balancing, the extracted power from different bridges of one phase is changed by modifying bridge voltage references. A feedforward compensation is also applied to decrease the inverter transient current at the beginning of the voltage sag. The performance of the proposed control strategy is investigated on a 10-MVA GCPVPP simulation setup under various voltage sags, while experimental results of a 9-kVA grid-connected seven-level cascaded H-bridge (7L-CHB) inverter setup are also presented, which validate the capability of the proposed algorithm for the operation of the grid-connected 7L-CHB inverter during voltage sags. Unbalanced voltage sags are more common compared to balanced voltage sags and the operation of the grid-connected PV CHB inverter during balanced voltage sags or normal grid condition is also easier to deal with. Therefore, unbalanced voltage sags are taken into consideration in all of the investigated case studies in this chapter, while the proposed control strategy can also be used during grid normal operation or balanced voltage sags.

5.2 Proposed Control Strategy for Grid-Connected PV CHB Inverter

In order to generalize the proposed strategy, an N -level CHB is considered in this section. The structure of the proposed control strategy, divided into five different parts, is depicted in Fig 5.1.

The controller of the CHB inverter is used to maintain the average dc-link voltage ($\overline{V_{dc}}$) by controlling the injected active power into the grid. $\overline{V_{dc}}$ is calculated as follows:

$$\overline{V_{dc}} \triangleq \frac{\sum_{x=a}^c \sum_{j=1}^N v_{dc-xj}}{N \times 3}, \quad (5.1)$$

Figure 5.1: Proposed control strategy for grid-connected CHB inverter during voltage sags.

where $x \in \{a, b, c\}$. The bridge number is denoted by j , while v_{dc-xj} is the dc-link voltage of bridge xj . The error between $\overline{V_{dc}}$ and V_{dc}^* , which is the bridge voltage reference, is fed into a PI controller, that calculates the d -axis current reference (i_d^*). Based on the amplitude of the voltage sag, the q -axis current reference (i_q^*) is calculated from grid codes, as in [5]. In order to show the flexibility of the proposed strategy, two different current reference calculation strategies are demonstrated in this study:

- Balanced currents during balanced/unbalanced voltage sags, which use the full current capacity of the inverter to enhance the point of common coupling (PCC) during voltage sags.
- Unbalanced currents during unbalanced voltage sags in order to achieve zero active power oscillation, as in [129].

The proposed algorithm is flexible to inject both balanced and unbalanced current of the grid during voltage sags, however the injection of the unbalanced currents during unbalanced voltage sags brings the following advantages for the GCPVPP with CHB inverter:

- ✓ The oscillation of the active power results in the oscillation of the dc-link voltages. Additionally, the oscillation of the dc-link voltages increases the harmonic distortion of the injected current to the grid. According to grid codes and standards, the injected harmonic currents to the grid should be limited to some specific amounts. Therefore, the injection of unbalanced currents during unbalanced voltage sags, improves the harmonic distortion of the injected current to the grid.

- ✓ By reducing the dc-link voltage oscillation, due to the injection of the unbalanced currents, smaller dc-link capacitors can be used in the CHB inverter.
- ✓ The oscillation of the dc-link voltage affects the voltage of the PV strings. As a result, the oscillation of the extracted power from PV strings will be increased, which reduces the total amount of extracted power from them.

The errors between the calculated current references and instantaneous phase currents, transformed to the $\alpha\beta$ coordinate (i_α and i_β), are fed into the proportional resonant (PR) with anti-windup controllers. Although, the implementation of the conventional PI controller for balanced current injection is simpler, it requires multiple frame transformations and results in reduced dynamic performance as compared with *abc*-framework-based controllers [131, 132]. Furthermore, for injection of accurate unbalanced currents under unbalanced voltage sags, the calculation of both positive- and negative-sequence voltages in *dq*-frame is required, which increases the computational complexity [131]. Furthermore, the PR controller with anti-windup shows faster dynamic response and zero steady-state error [74]. The voltage references ($v_{\alpha-1}^*$ and $v_{\beta-1}^*$) are calculated through PR controllers. Subsequently, feedforward and voltage balancing controllers are implemented and their detailed descriptions are provided in the following subsections.

5.2.1 Feedforward Compensation

Fast detection of voltage sags is important for quick operation of the controller [120]. In this study, a second order generalized integrator (SOGI) based orthogonal system is applied for the calculation of the amplitude of grid phase voltages, and detection of the voltage sag. The detailed description of the SOGI can be found in Section 3.3.1. A maximum delay of $T/4$, where T is the grid voltage period, is introduced by the SOGI due to the single-phase quadrature signal generation. It should be noted that this delay also depends on the amplitude of the voltage sag.

The delay of the voltage sag detection algorithm, leads to a high transient current at the beginning of voltage sags because the controller continues to inject maximum power to the grid in the period between the occurrence of the voltage sag and its detection. Thus, employing a feedforward compensator is necessary to decrease the transient current in this period. The feedforward compensator is depicted in Fig.

5.1. The instantaneous PCC voltages ($v_{pcc-\alpha}$ and $v_{pcc-\beta}$), which are transformed to $\alpha\beta$ coordinate using the Clark transformation, are added to $v_{\alpha-1}^*$ and $v_{\beta-1}^*$, respectively, as follows:

$$\begin{aligned} v_{\alpha-2}^* &= v_{\alpha-1}^* + v_{pcc-\alpha}, \\ v_{\beta-2}^* &= v_{\beta-1}^* + v_{pcc-\beta}. \end{aligned} \quad (5.2)$$

The vector diagram during the grid normal operation is depicted in Fig. 5.2(a). During such condition, the inverter operates under unity power factor and the output voltage of the inverter has a similar phase and amplitude as v_{pcc} . Accordingly, a large portion of $v_{\alpha-2}^*$ and $v_{\beta-2}^*$ are provided by $v_{pcc-\alpha}$ and $v_{pcc-\beta}$, respectively, while the current controller only regulates the required voltage drop on the filter inductors for the intended current references. Therefore, the amplitudes of $v_{\alpha-1}^*$ and $v_{\beta-1}^*$ are small during the grid normal operation.

At the beginning of the voltage sag, as shown in Fig. 5.2(b), the instantaneous values of $v_{pcc-\alpha}$ and $v_{pcc-\beta}$ are reduced immediately, following the voltage sag amplitude. At the same time, the values of $v_{\alpha-1}^*$ and $v_{\beta-1}^*$ cannot change immediately, because they depend on the voltage sag detection algorithm, current reference calculation method and current controller. Consequently, $v_{\alpha-2}^*$ and $v_{\beta-2}^*$ decrease instantaneously at the beginning of the voltage sag. This reduces the output voltage of the inverter at the beginning of the voltage sag and decreases its transient current. It should be noted that without this feedforward compensator, the voltage references are only regulated through the current controller, which cannot react instantaneously to the voltage sag and hence the transient current becomes large at the beginning of the voltage sag. Finally, a feed-forward voltage controller for reducing the effect of the variation of dc-link voltage is also implemented by multiplying the voltage references

Figure 5.2: Feedforward compensation principle for the grid-connected CHB inverter - voltage references: (a) During the grid normal operation, (b) at the beginning of the voltage sag and (c) during the steady-state period of the voltage sag.

by V_{dc}^*/v_{dc-xj} .

5.2.2 Proposed Inter-Phase Balancing Strategy

An inter-phase balancing strategy is implemented by adding a zero-sequence voltage (v_{zero}) to the voltage references (v_{a-2}^* , v_{c-2}^* and v_{c-2}^*), as shown in Part IV of Fig. 5.1.

The proposed algorithm for the calculation of v_{zero} is presented in Fig. 5.3(a). The error between $\overline{V_{dc}}$ and the average of the bridge voltages of phase a ($\overline{V_{dc-a}} = (v_{dc-a1} + v_{dc-a2} + \dots + v_{dc-aN})/N$) is fed into a moving average filter (MAF), which filters instantaneous oscillations of the dc-link voltages by performing the following operation:

$$\bar{x}(t) = \frac{1}{T_w} \int_{t-T_w}^t x(\tau) d\tau, \quad (5.3)$$

where T_w is the window width of the MAF and $\bar{x}(t)$ is the moving average value of $x(t)$ calculated over T_w . A window width of $T_w = 1/(2f)$, where f is the grid frequency, can remove all the second-order oscillations of the dc-link voltages [122].

The calculated average error from the MAF is then multiplied by $\sin(\omega t + \phi)$, while $i_a = I_m \sin(\omega t + \phi)$. It should be noted that $\omega t + \phi$ is the instantaneous angle of the current and depends on the instantaneous injected current to the grid. Since, the instantaneous value of $\sin(\omega t + \phi)$ is required in the proposed algorithm, instead of using the PLL, the following algorithm is implemented in this study. As shown in Fig. 5.3(a), the instantaneous value of $\sin(\omega t + \phi)$ is approximated as:

$$\sin(\omega t + \phi) \approx \frac{i_a}{RMS(i_a) \times \sqrt{2}}, \quad (5.4)$$

in which

$$RMS(i_a) = \sqrt{\frac{1}{T_w} \int_{t-T_w}^t i_a^2 dt}. \quad (5.5)$$

Subsequently, the calculated zero-sequence voltage from phase a (v_{zero-a}) is added to v_{zero-b} and v_{zero-c} . The total zero voltage (v_{zero}) is adjusted using a proportional controller with a proportional gain of K_1 , which ensures the inter-phase balancing of the grid-connected CHB inverter during unbalanced voltage sags.

The vector diagram of the CHB inverter, during balanced operation, is depicted in Fig. 5.3(b). In this condition, the injected zero-sequence voltage is zero. The

Figure 5.3: Proposed inter-phase balancing algorithm for grid-connected CHB inverter: (a) Proposed zero-sequence generation strategy, (b) vector diagram during balanced operation and (c) vector diagram during zero-sequence voltage injection.

operation of the proposed inter-phase balancing strategy is investigated considering $v_{dc-a} > \overline{V_{dc}}$ and $v_{dc-b}, v_{dc-c} < \overline{V_{dc}}$. The corresponding voltages and currents vector diagram after the injection of the proposed zero-sequence voltage are presented in Fig. 5.3(c). Since $v_{dc-a} - \overline{v_{dc}} < 0$, v_{zero-a} is in the opposite direction of i_a . Similarly, v_{zero-b} and v_{zero-c} are in the same direction of i_b and i_c , respectively. Thus, the neutral point of the CHB inverter is moved from n to n' , by a vector of v_{zero} . The amplitude of the new voltage vector of phase a (v'_a) is larger than phases b and c (v'_b and v'_c). Therefore, the extracted power from phase a ($p'_a = v'_a \cdot i_a$) is larger than p'_b and p'_c , which means that the extracted power from the capacitors of phase a is larger than b and c . As a consequence, v_{dc-a} reduces and dc-link capacitors become balanced. It should be noted that because the proposed method of zero-sequence voltage injection depends on the current direction, it can achieve inter-phase balancing under all different types of current injection including active/reactive power injection with balanced/unbalanced currents.

5.2.3 Inter-Bridge Balancing Strategy

It is important that all of the dc-link voltages of each phase remain equal to achieve high-quality output voltages. Since the current of all of the bridges of one phase are equal, their voltage varies if their power is different. An inter-bridge balancing mechanism, shown in Part V of Fig. 5.1, is implemented in this study as in [51]. The voltage reference of each bridge is calculated by dividing the voltage reference of the phase (v_{a-3}^*) by N and subsequently, is added with Δv_{xj} , which is the required deviation of the voltage reference of each bridge for inter-bridge balancing. The proposed algorithm for the calculation of Δv_{xj} is presented in Fig. 5.4(a). The difference between v_{dc-xj} and $\overline{V_{dc}}$ is fed into the MAF, as defined in (5.3). The filtered voltage difference is then multiplied by $\sin(\omega t + \phi)$ (5.4) and fed into a proportional controller with a proportional gain of K_2 to calculate Δv_{xj} .

The operation of the proposed inter-bridge voltage balancing algorithm is investigated via an example in which $V_{dc-x1} > \overline{V_{dc-x}}$ and $V_{dc-x2}, V_{dc-x3} < \overline{V_{dc-x}}$. The corresponding voltages and currents vector diagram after modifying the voltage reference using the proposed algorithm are presented in Fig. 5.4(a). Since $V_{dc-x1} - \overline{V_{dc-x}} > 0$, ΔV_{x1} is in the same direction of i_a and similarly ΔV_{x2} and ΔV_{x3} are in the opposite direction of i_a . As a result, the new voltage reference for H-bridge $x1$ (v'_{o-x1}) becomes larger, while v'_{o-x2} and v'_{o-x3} become smaller. Consequently, the extracted power from

Figure 5.4: Proposed inter-bridge voltage balancing algorithm: (a) Schematic of the proposed algorithm, (b) voltages vector diagram during unbalanced dc-link voltages in phase a.

the dc-link $x1$ ($p_{x1} = v'_{o-x1} \times i_a \sin(\omega t + \phi)$) is larger than p_{x2} and p_{x3} . Thus V_{dc-x1} reduces and dc-link voltages become balanced. Although the proposed inter-bridge voltage balancing algorithm is simple for implementation, it balances the H-bridges dc-link voltages of each phase during all kinds of power/reactive power injection (balanced or unbalanced current injection), because the direction of ΔV_{xj} depends on the current direction ($\sin(\omega t + \phi)$).

The “moving average filter (MAF)”, which is applied in the proposed inter-phase and inter-bridge voltage balancing algorithms, eliminates the second harmonic oscillation of the measured voltage that is fed to the voltage balancing algorithm. The purpose of the proposed inter-phase and inter-bridge voltage balancing algorithms is to balance the average dc component of these voltages. The bandwidth of the dc-link voltage controller is set to 20 Hz in this study. Consequently, the bandwidth of the proposed inter-phase and inter-bridge voltage balancing algorithms is also chosen as 20 Hz. The MAF block introduces a delay of $1/(2f)$, in which f is the grid frequency, (0.01 s) in the controller. Therefore, the bandwidth of the MAF block (100 Hz) is five times faster compared to the bandwidth of the voltage balancing algorithm. Hence, its delay has a small effect on the performance of the voltage balancing algorithm.

It should be noted that due to the single-phase behavior of each leg of the CHB converter, the second order harmonic exists in the dc-link voltage. The lack of MAF block in the proposed voltage balancing algorithm results in adding large offset values to the voltage references, due to the large instantaneous difference of capacitor voltages as a result of second harmonic oscillation. This can result in instability of the controller. The effectiveness of an MAF block to eliminate the second order harmonic oscillation of the measured voltage that is fed to the controller has been demonstrated in several studies [74,122].

5.3 dc-dc Converter Controller during Voltage Sags

Two different control algorithms are introduced in Chapter 3 and 4 for the control of dc-dc converters of the GCPVPP during voltage sags. However, due to the following issues, the same algorithms cannot be implemented for the control of the dc-dc converters of the GCPVPP with CHB inverter:

- Equal power should be extracted by the dc-dc converters of all of the H-bridges,

because the extraction of unequal powers results to unbalance the capacitor voltages. Therefore, the proposed control algorithm in Chapter 4 (Figs. 4.4 and 4.5), with the extraction of unequal power values from different PV strings cannot be applied in this topology.

- In the proposed control algorithm for the CHB inverter, the dc-link voltage is regulated to its reference through the controller of the CHB inverter during voltage sags. Therefore, the implemented algorithm in Chapter 3 (Fig. 3.7), in which the dc-link voltage control is used to reduce the power from PV strings, cannot be applied in this topology.

Accordingly, the following algorithm is implemented to control the dc-dc converters of the GCPVPP with CHB inverter.

The required active power reference from PV strings is calculated according to (4.26). As equal power should be extracted from PV strings, the calculated power reference from (4.26) is divided by the number of PV strings, which are connected to the CHB inverter, which gives the power reference for each PV string. The calculated power reference for each PV string is used in the proposed controller in Fig. 4.5 to calculate the switching signals of each dc-dc converter. It should be noted that in this topology, despite of the implemented algorithm in Chapter 4, the proposed dc-dc controller is implemented on all of the dc-dc converters of the GCPVPP.

5.4 Simulation Results

The GCPVPP with 7L-CHB inverter (Fig. 2.6) is modeled and developed using Matlab/Simulink and PLECS toolbox. The proposed algorithm is evaluated on two GCPVPPs: A 10-MVA GCPVPP connected to the 6.6kV distribution network to show the validity of the algorithm on a large-scale GCPVPP and a 9-kVA GCPVPP, which has the same parameters to the experimental setup. The main system parameters for both of the systems are listed in Table 5.1.

The main criteria in the selection of the dc-link capacitor of the CHB converter is the limitation of the dc-link voltage to 10% of its nominal value. Two conditions are considered in the calculation of the maximum voltage oscillation of the dc-link:

- The second harmonic oscillation of the dc-link voltage due to the operation of

the CHB converter under unbalanced grid voltages.

- The effect of variation of the extracted power from PV strings on the dc-link voltage, while constant power injection to the grid is intended. In this case, the dynamic response of the storage system should be considered in the selection of the capacitor value.
- The dynamic response of the CHB inverter for the operation during voltage sags. In this condition, the dc-link voltage can be increased at the beginning of the voltage sag, due to the slow dynamic of the controller.

By considering the worst case scenarios in the above-mentioned conditions, the size of the dc-link capacitors can be selected. It should be noted that always the over-voltage protection and crowbars should be implemented to prevent the increase of the dc-link voltage beyond its nominal range.

5.4.1 Simulation Results on the 10-MVA GCPVPP

In this topology, by using three H-bridges with 2.2 kV capacitor voltage in each phase, the converter is able to connect to the 6.6 kV distribution network directly, without a line-frequency power transformer. In practical applications, the capacitor voltage could be lower if more H-bridges are introduced. Since three H-bridges are cascaded in each phase leg, the converter output phase voltages feature seven-level waveforms with an equivalent switching frequency of 3.6 kHz. It should be noted that using low switching frequency for semiconductor switches, reduces the switching losses and increases the overall efficiency of the converter. Additionally, the dynamic response and active/reactive power oscillations mainly depend on the implemented controller, not the switching frequency.

In order to evaluate the flexibility of the proposed strategy, two different voltage sag conditions are investigated: 40% single-phase voltage sag with simultaneous injection of active and reactive powers with balanced currents (*Case I*), and 60% two-phase voltage sag with reactive power injection and unbalanced currents (*Case II*).

Case I This case demonstrates the operation of the CHB inverter during 40% single-phase voltage sag, which requires simultaneous injection of active and reactive

Table 5.1: Simulation and Experimental Parameters of the GCPVPP with CHB inverter

Parameter	Symbol	Simulation	Experiment
PV panel and flyback dc-dc converter parameters			
PV string maximum power	p_{mpp}	1.11 MW	1 kW
PV panel <i>MPP</i> voltage	v_{mpp}	30 V	145 V
PV panel <i>MPP</i> current	i_{mpp}	7.84 A	7 A
Number of series-connected PV panels in the PV string	N_s	35	1
Number of parallel-connected PV panels in the PV string	N_p	135	1
PV panel capacitor	C_{pv}	5 mF	4.5 mF
dc-dc conv. switching frequency	f_{sw}	10 kHz	N/A
dc-dc conv. transformer turn ratio	$n_1 : n_2$	1 : 4	N/A
7L-CHB inverter parameters			
Apparent power	S	10 MVA (1 pu)	9 kVA (1 pu)
PCC voltage	v_{pcc-ll}	6.6 kV _{rms} (1 pu)	430 V _{rms} (1 pu)
Inductor filter	L_f	3 mH (0.17 p.u.)	8 mH (0.15 p.u.)
dc-link voltage	v_{dc}	2.2 kV	145 V
dc-link capacitor	C_{dc-xj}	10 mF	4.5 mF
Carrier frequency	f_{carr}	600 Hz	600 Hz
Apparent switching frequency	f_{sw}	3.6 kHz	3.6 kHz

power, according to grid codes [119]. The balanced current injection method is chosen in this case, which utilizes the full current capacity of the inverter in enhancing the PCC voltage. The voltage sag occurs at phase *c* with duration of 150 ms. The three-phase grid voltages (v_{pcc}) and injected currents (i_{abc}) are depicted in Fig. 5.5(a). Before $t = 0.05$ ms, the grid is at normal condition and the inverter injects active power to the grid with balanced currents (Fig. 5.5(c)), while no phase-displacement exists between the phase currents and voltages. Since the minimum amplitude of the voltage sag in this test study is larger than 0.5 pu, the inverter injects both active and reactive powers to the grid between $t = 0.05$ ms and $t = 0.2$ ms. A second harmonic

Figure 5.5: Simulation results of GCPVPP 7L-CHB inverter with isolated dc-dc converters: *Case I* - 40% single-phase voltage sag with balanced current injection: (a) PCC voltages, (b) inverter output currents, (c) injected active/reactive power to the grid, (d) dc-link individual and average voltages and (e) extracted power from PV strings.

voltage oscillation exists in both active and reactive powers, due to the injection of balanced currents to the PCC with unbalanced voltages.

It can be seen from Fig. 5.5(b) that the transient current of the inverter at the beginning of the voltage sag is reduced through the feedforward compensator. The bridge capacitor voltages (v_{dc-xj}), presented in Fig. 5.5(d), are balanced and their average remains close to 2.2 kV, during this unbalanced voltage sag condition. The extracted powers from PV strings are decreased to 0.4 MW by the dc-dc converters, due to the current limitation of the inverter beside its reactive power injection during the voltage sag. After the clearance of the voltage sag, the output power of the inverter recovers to 10 MW and reactive power reduces to zero, while capacitor voltages stay balanced.

Case II The performance of the proposed control strategy during a deep unbalanced voltage sag with reactive power injection and unbalanced currents is examined in this test, considering a two-phase 60% voltage sag, shown in Fig. 5.6(a). By implementing the unbalanced current injection strategy, the current of the phases a and b (phases with smaller voltage amplitudes) are larger than phase c during the voltage sag, which causes to zero active power oscillation as presented in Fig. 5.6(c). The inverter injects 6 MVAR average reactive power to the grid, while the injected active power decreases to zero. The dc-link voltages remain balanced and their average is close to their voltage reference by reducing the extracted power from PV strings to zero through dc-dc converters. It can be seen that the second-order harmonic oscillation of the injected active power is reduced close to zero, though the implementation of the proposed unbalanced current injection algorithm. However, the second harmonic oscillation exists in the injected reactive power to the grid, because the proposed algorithm is designed to reduce the oscillation of the injected active power to the grid. The presented simulation results verify the flexibility of the proposed strategy under various voltage sags and different power/current injection strategies.

5.4.2 Simulation Results on the 9-kVA GCPVPP

The simulation results of a 9-kVA GCPVPP with 7L-CHB inverter are provided in this section. The parameters of the simulation platform are set same as the parameters of the experimental setup (as Table 5.1). Three case studies, similar to

Figure 5.6: Simulation results of GCPVPP 7L-CHB inverter with isolated dc-dc converters: *Case II* - 60% two-phase unbalanced voltage sag with unbalanced current injection: (a) PCC voltages, (b) inverter output currents, (c) injected active/reactive power to the grid, (d) dc-link individual and average voltages and (e) extracted power from PV strings.

the experimental case studies are performed to verify the experimental results with simulation.

Case I This case examines the performance of the proposed control strategy during a 30% single-phase voltage sag, which requires simultaneous injection of active and reactive power to the grid. Unbalanced current injection is also taken into consideration.

The sag occurs in phase b for a duration of 150 ms. The three-phase grid voltages (v_{pcc}) and injected currents (i_{abc}) are depicted in Fig. 5.7(a). The current of phase b , the phase with the voltage sag, remains equal to the nominal current of the inverter ($11 \text{ A}_{\text{rms}}$), while the currents of nonfaulty phases reduce to $9.2 \text{ A}_{\text{rms}}$. This leads to zero active power oscillation to the grid during such unbalanced voltage sag, as depicted in Fig. 5.7(c). The average active power reduces to 5.3 kW, while the average reactive power increases to 3.1 kVAR. The bridge capacitor voltages are depicted in this figure. Before $t = 0.175 \text{ s}$, which grid is in normal operation mode, the capacitor voltages are balanced and their average voltage is equal to $145 \text{ V}_{\text{dc}}$, which is equal to v_{mpp} of the simulated PV string.

Case II This case study demonstrates a three-phase 70% unbalanced voltage sag (phase a experiences deeper voltage sag compared to phases b and c) in order to verify the performance of the proposed control strategy during reactive power injection with balanced currents, and results are displayed in Fig. 5.8.

It can easily be seen that the transient current of the inverter at the beginning of such deep voltage sag is not large. During the voltage sag, the amplitude of currents remains as its nominal value, while a phase displacement of $\pi/2$ exists between the phase current and voltage. This indicates the injection of reactive power to the grid with an average value of 3.4 kVAR, while the average injected active power is zero. A second harmonic oscillation exists in both active and reactive powers due to the injection of balanced currents to the PCC with unbalanced voltages. The dc-capacitor voltage are balanced during the voltages sag and their average is increased to 177 V (equal to the open-circuit voltage of the PV panel) in order to reduce the extracted power from the PV panels to zero.

Figure 5.7: Simulation results of 9-kVA grid-connected 7L-CHB inverter: Case I - 30% single-phase voltage sag with unbalanced current injection: (a) PCC voltages, (b) inverter output currents, (c) injected active/reactive power to the grid and (d) dc-link voltages.

Case III The performance of the proposed controller in balancing the capacitor voltages under an unbalanced voltage sag with long duration is evaluated in this case study. The simulated voltage sag is similar to *Case II*, although its duration is increased to 1 s. Besides, the unbalanced current injection strategy is taken into consideration in order to verify the flexibility of the proposed strategy and results are depicted in Fig. 5.9. $\overline{V}_{dc}$ is equal to 145 V (v_{mpp}) during the grid normal operation,

Figure 5.8: Simulation results of 9-kVA grid-connected 7L-CHB inverter: Case II - 70% three-phase voltage sag with balanced current injection: (a) PCC voltages, (b) inverter output currents, (c) injected active/reactive power to the grid and (d) dc-link voltages.

while it increases to 177 V during the voltage sag. The dc-link voltages remain balanced during such unbalanced voltage sag with a long duration, which shows the stable operation of CHB inverter during unbalanced voltage sags.

Figure 5.9: Simulation results of 9-kVA grid-connected 7L-CHB inverter: Case III - 70% long-duration three-phase voltage sag with unbalanced current injection: (a) PCC voltages, (b) inverter output currents and (c) dc-link voltages.

5.5 Experimental Evaluation

Fig. 5.10(a) and (b) show the circuit diagram and the hardware setup, respectively, for a 9-kVA three-phase 7L-CHB converter. The parameters of the CHB prototype are listed in Table 5.1. The converter was fed by nine isolated Elgar TerraSAS PV simulators from Ametek, each of which was programmed to simulate the electrical behavior of a PV string, with a solar irradiance of 1000 W/m^2 and a module temperature of 25°C . The control strategy was implemented on a dSPACE DS1006 platform with onboard Xilinx FPGA modules operating at 100 MHz. The grid is simulated using a TopCon TC.ACS 4-quadrant grid simulator with capability of simulating various voltage sag conditions. The dc-dc conversion is not included in the setup and the variation of the maximum power point, owing to irradiance or temperature

Figure 5.10: Experimental verification of the grid-connected CHB inverter: (a) Circuit diagram and (b) experiment setup.

changes, cannot be accurately tracked. However, this does not affect the purpose of this chapter, which lies in the control of the CHB inverter during voltage sags including inter-phase and inter-bridge balancing [38, 47, 50]. The proposed controller has been evaluated under three different voltage sag conditions and power and current injection strategies.

Case I This case experimentally examines the performance of the proposed control strategy during a 30% single-phase voltage sag, which requires simultaneous injection of active and reactive power to the grid. Unbalanced current injection is also taken into consideration. The sag occurs in phase c for a duration of 150 ms. The three-phase grid voltages (v_{pcc}) and injected currents (i_{abc}) are depicted in Fig.

5.11(a). The delay between the beginning of the voltage sag and its detection is also presented in this figure. The transient currents during this time are not large, as a result of the proposed feedforward compensator. The current of phase c , the phase with the voltage sag, remains equal to the nominal current of the inverter ($11 A_{\text{rms}}$), while the currents of nonfaulty phases reduce to $9.2 A_{\text{rms}}$. This leads to zero active power oscillation to the grid during such unbalanced voltage sag, as depicted in Fig. 5.11(c). The average active power reduces to 5.3 kW , while the average reactive power increases to 3.1 kVAR .

The bridge capacitor voltages are depicted in Fig. 5.11(b). Before $t = 0.175 \text{ s}$, which grid is in normal operation mode, the capacitor voltages are balanced and their average voltage is equal to $145 V_{\text{dc}}$, which is equal to v_{mpp} of the simulated PV string. This results in the extraction of maximum power from all of the PV strings, which in total is equal to 9 kW as presented in Fig. 5.11(c). The implementation of the proposed inter-phase and inter-bridge balancing schemes leads to the balanced capacitor voltages during the voltage sag. It should be noted that because the dc-dc converter stage is omitted from the experimental setup, the reduction of the power from PV strings during the voltage sag is performed by increasing the voltage of PV panels to 168 V .

Case II This case study demonstrates a three-phase 70% unbalanced voltage sag (phase a experiences deeper voltage sag compared to phases b and c) in order to verify the performance of the proposed control strategy during reactive power injection with balanced currents, and results are displayed in Fig. 5.12. It can easily be seen that the transient current of the inverter at the beginning of such deep voltage sag is not large. During the voltage sag, the amplitude of currents remain as its nominal value, while a phase displacement of $\pi/2$ exists between the phase current and voltage. This indicates the injection of reactive power to the grid with an average value of 3.4 kVAR , while the average injected active power is zero. A second harmonic oscillation exists in both active and reactive powers due to the injection of balanced currents to the PCC with unbalanced voltages. The dc-capacitor voltage are balanced during the voltage sag and their average is increased to 177 V (equal to the open-circuit voltage of the PV panel) in order to reduce the extracted power from the PV panels to zero.

Figure 5.11: Experimental results of grid-connected 7L-CHB inverter: *Case I* - 30% single-phase voltage sag with unbalanced current injection: (a) PCC voltages and currents, (b) dc-link voltages and (c) injected active/reactive power to the grid.

Case III The performance of the proposed controller in balancing the capacitor voltages under an unbalanced voltage sag with long duration is evaluated in this case study. The simulated voltage sag is similar to *Case II*, although its duration

Figure 5.12: Experimental results of grid-connected 7L-CHB inverter: *Case II* - 70% three-phase voltage sag with balanced current injection: (a) PCC voltages and currents, (b) dc-link voltages and (c) injected active/reactive power to the grid.

is increased to 1 s. Besides, the unbalanced current injection strategy is taken into consideration in order to verify the flexibility of the proposed strategy and results are depicted in Fig. 5.13. The extracted power and current from the PV modules

Figure 5.13: Experimental results of grid-connected 7L-CHB inverter: *Case III* - 70% long-duration three-phase voltage sag with unbalanced current injection: (a) PCC voltages and currents, (b) PV panels voltages, powers and (c) dc-link voltages.

decrease to zero during the voltage sag, as shown in Fig. 5.13(b). The dc-link voltage of all of the nine bridges and its average are depicted in Fig. 5.13(c). $\overline{V_{dc}}$ is equal to 145 V (v_{mpp}) during the grid normal operation, while it increases to 177 V during

the voltage sag. It can be seen, the dc-link voltages remain balanced during such unbalanced voltage sag with a long duration, which shows the stable operation of CHB inverter during unbalanced voltage sags.

By comparing the presented results in Section 5.4.2 for simulation (without considering the resistance) are similar parameters to the experimental results in Section 5.5 (with the existence of the resistance of the inductor), it can be seen that the proposed algorithm performs similar in both cases. However, a small resistance exists in the inductor of the experimental results, while it is not considered in the simulation setup. It can be concluded that the effect of the small resistance of the inductor filter can be neglected.

5.6 Summary

Active/reactive power injection is required for medium- and large- scale GCPVPPs during voltage sags, however, there is lack of a detailed study in the literature for the operation of grid-connected CHB inverters, which are a promising candidate for these types of GCPVPPs. Accordingly, a flexible control strategy for the operation of the photovoltaic grid-connected CHB inverter during unbalanced voltages sags has been introduced in this chapter. A zero-sequence voltage injection has been introduced in order to achieve the inter-phase balancing, while the inter-bridge balancing has been obtained through the modification of bridges voltage references. Transient currents of the inverter, at the beginning of the voltage sag have been greatly reduced by implementing a feedforward compensator.

Detailed implementation of the proposed control strategies has been presented, and its effectiveness has been demonstrated through simulation and experimental results on a 10-MVA photovoltaic connected to the 6.6-kV medium-voltage test-case system and 9-kVA seven-level CHB setup, respectively, during different unbalanced voltage sags. The CHB inverter achieves low-voltage ride-through capability and it is able to inject the required active/reactive power to the grid according to grid codes. Flexibility of the proposed controller has also been verified under two different current injection strategies: a) balanced current injection with the advantage of using the full current capacity of the inverter in enhancing the PCC voltage, and b) unbalanced current injection with zero active power oscillation. The evaluation results verify the applicability of the proposed control strategy for medium- and large-scale GCPVPPs during voltage sags.

Chapter 6

A General Constant Power Generation Algorithm in Grid-Connected Photovoltaic Power Plants during Voltage Sags

A general constant power generation (CPG) algorithm in photovoltaic power plants during voltage sags is proposed in this chapter. An introduction to CPG and summary of available algorithms in the literature are presented in Section 6.1. Principles of the CPG operation for PV strings are analyzed in Section 6.2 and the detailed implementations of the proposed CPG algorithm are described in Section 6.3. The simulation results of the proposed controller on a 50-kW GCPVPP are presented in Section 6.4, while the experimental evaluation on a 1-kW PV panel is illustrated in Section 6.5. The conclusions of the work are drawn in Section 6.7.

6.1 Introduction

The main focus of the previous chapters of this thesis was on the operation of the grid-connected inverter of the GCPVPP during voltage sags. During the grid *Normal* operation, as defined in Section 2.4.2, dc-dc converters of the multi-string GCPVPP extract maximum power from PV strings. However, due to the reactive current injection during voltage sags, the amount of injected active power is reduced, because of the current limitation of the inverter. Therefore, the extracted power from

PV strings should be reduced to a constant value, which is calculated based on the current capacity if the inverter and the injected reactive power during voltage sags. This chapter introduces a general algorithm for the extraction of constant power from PV strings.

An overview of the available algorithms for constant power generation from PV panel has been presented in Section 2.6.4. The single- and two-stage GCPVPPs are most common structures for GCPVPPs as described in Section 2.1. Each of the available algorithms in the literature has several advantages and disadvantages, however, a general algorithm which can be implemented on both single- and two-stage GCPVPPs, illustrated in Fig. 6.1, is not presented in the literature.

Motivated by the above, this chapter proposes a general algorithm for the calculation of the PV panel voltage reference, which leads to generation of a constant power from the PV panel. The proposed algorithm is an adaptation of the P&O algorithm, based on the characteristics of the P-V curve of the PV panel. During the *CPG* operation, the typical MPPT algorithm is replaced with the proposed algorithm to calculate the voltage reference based on the required power reference and as a result no modification is made in the controller of the dc-dc converter. Unlike the presented studies in the literature, the proposed algorithm is flexible to move the operation point of the PV panel to the right- or left-side of the *MPP* and is also applicable in both single- or two-stage GCPVPPs. A hysteresis band controller is pro-

Figure 6.1: Various topologies of photovoltaic power plants: (a) Single-stage power conversion structure and (b) two-stage power conversion structure.

posed to change the frequency of execution for the algorithm (time-step) and voltage increments between consecutive operating points (voltage-step) in order to achieve fast dynamic response and low power oscillation during steady-state operation of the controller. The generality and flexibility of the proposed algorithm is evaluated using simulation and experimental validation on various GCPVPP topologies and different irradiance and power reference curves.

6.2 Power Reduction Principles

In this chapter, the operation of the PV string is divided into two different modes:

1. Maximum power extraction mode, referred as *MPPT*, in which the maximum power (p_{mpp}) is extracted from the PV string (operating at point *MPP* in Fig. 6.2(a)). The conventional P&O algorithm is applied in this operation mode.
2. Constant power generation mode, named as *CPG*, in which the extracted power from the PV string is regulated to a certain power reference (p_{ref}), provided by an external controller, like the central controller of the grid-connected GCPVPP. The principles of the proposed algorithm for the *CPG* operation mode, which is the main contribution of this study, are presented in this section.

According to the P-V curve of the PV string (Fig. 6.2(a)), there are two operation points resulting in the extraction of p_{ref} from the PV string: point *A* in the left-side of *MPP*, shown by red arrow, and point *B* located in the right-side of *MPP*, depicted by green arrow. Each of these operation points have its advantages and disadvantages.

By moving the operation point of the PV panel to point *B* in the right-side of *MPP*:

- The difference between v_b and v_{mpp} ($|v_{mpp} - v_b|$) is smaller than $|v_{mpp} - v_a|$ and therefore moving the operation point from *MPP* to point *B* can be executed faster than to point *A*, which results in a faster dynamic response.
- The output power of the PV panel has higher oscillation at point *B* compared to point *A*, because a small voltage change at this point results in a large power change.

(a)

(b)

(c)

Figure 6.2: Power-voltage curve of the PV string: a) Operation at maximum power point, (b) operation at left-side of *MPP* and (c) operation at right-side of *MPP*.

- The operation point of the PV panel on the right-side of *MPP* may go beyond the open-circuit voltage of the PV panel under fast changes of the irradiance or temperature. This issue should be considered in the design of the *CPG* control algorithm.

With shifting the operation point of the PV panel to point *A* in the left-side of *MPP* during *CPG*:

- For small power references, it necessitates the PV string voltage to be close to the short-circuit voltage. This imposes the dc-dc converter duty cycle to be close to one, which consequences to large oscillation of the dc-dc converter input/output voltages and its inductor current.
- Because of the larger difference between V_a and V_{mpp} , the dynamic performance is slower, however the oscillation of the power at this point is smaller compared to point B .

In two-stage GCPVPPs, the operation point during *CPG* can be moved to either right- or left-side of *MPP*, however there is a limitation in single-stage GCPVPPs for the movement of the operation point to the left-side of *MPP* [112, 113]. Therefore, the operation point is moved to the right-side of *MPP* for single-stage GCPVPPs. By operating the single-stage GCPVPP in the left-side of *MPP* during *CPG*, if the dc-link voltage becomes smaller than a certain value, the grid-connected inverter is not able to produce the desired voltage for grid-connection and consequently the GCPVPP should be disconnected from the grid. The proposed method in this chapter is flexible for moving the operation point to the right- or left-side of *MPP* and it can be used for both types of GCPVPPs. The operation principles of these two methods are presented in this study and each one of them can be implemented on the desired GCPVPP.

In order to ensure the operation of the PV string in the left- or right-side of *MPP* during *CPG* mode, the P-V curve characteristics are analyzed. Δv is defined as $\Delta v = v_{new} - v_{old}$, where v_{new} is the PV string voltage in the current time-step and v_{old} is the PV string voltage in the previous time-step. Similarly, $\Delta p = p_{new} - p_{old}$, in which p_{new} and p_{old} are the output powers of the PV string in the current- and previous execution time-steps, respectively. Assuming the operation at point A in the current execution time-step (Fig. 6.2(b)), the operation point of the next time-step can be A_1 or A_2 , which result in:

$$\begin{cases} \frac{\Delta p}{\Delta v} = \frac{p_{a1} - p_a}{v_{a1} - v_a} > 0 \\ \frac{\Delta p}{\Delta v} = \frac{p_{a2} - p_a}{v_{a2} - v_a} > 0 \end{cases} \quad (6.1)$$

Consequently, $\Delta p/\Delta v$ is always positive in left-side of *MPP*. Similarly, as presented in Fig. 6.2(c), moving the operation point from point B to point B_1 or B_2 in the

right-side of *MPP* results in:

$$\begin{cases} \frac{\Delta p}{\Delta v} = \frac{p_{b1} - p_b}{v_{b1} - v_b} < 0 \\ \frac{\Delta p}{\Delta v} = \frac{p_{b2} - p_b}{v_{b2} - v_b} < 0 \end{cases} \quad (6.2)$$

Therefore, $\Delta p/\Delta v$ is always negative in the right-side of *MPP*. This attribute of the P-V curve is considered in the proposed voltage reference calculation algorithm in order to ensure the operation of the PV string in the right-side of *MPP* during *CPG*.

6.3 Proposed Voltage Reference Calculation Algorithm

A comprehensive schematic of the proposed algorithm for the operation of GCPVPP during both *MPPT* or *CPG* mode is depicted in Fig. 6.3. The operation mode of the dc-dc converter is imposed by an external controller. If the operation mode of the GCPVPP is *MPPT*, the controller calculates $V_{ref} = v_{mpp}$ using an MPPT algorithm. For calculating V_{ref} during *CPG* operation, three variables including Δv , Δp and Δp^* , which is defined as $\Delta p^* = p_{new} - p_{ref}$ are calculated.

During *MPPT* mode, the voltage calculation execution time step (T_{step}) is considered to be relatively large (e.g. $T_{step-mppt} = 0.2s$) in order to reduce the output power

Figure 6.3: Proposed voltage reference calculation strategy.

oscillation during the steady-state operation. Furthermore, the voltage-step between different operating points (V_{step}) is set to be a relatively small value ($V_{step-mppt}$) in order to reduce the power oscillation during *MPPT*. However, fast performance of the controller in regulating p_{pv} to a specified power reference (p_{ref}) is necessary during *CPG*. Therefore, T_{step} and V_{step} are calculated based on the proposed method based on the hysteresis band controller. Afterwards, by applying the chosen V_{step} and T_{step} , the voltage reference is calculated. The detailed implementation of the proposed time- and voltage-step calculation algorithm and voltage reference calculation strategy are presented in the following subsections.

6.3.1 Proposed Time- and Voltage-Step Calculation Algorithm

It is important for the *CPG* controller to perform fast dynamic response and low power oscillation in the steady-state. Fast dynamic response is desired during fast changes of irradiance, temperature or power reference. Furthermore, during grid faults in which the active power of the GCPVPP should be limited to a certain value, the fast dynamic response is required for the *CPG* controller. This goal is achieved by applying different values of V_{step} and T_{step} during steady-state or transient operation modes, based on the hysteresis band controller.

The operation principle of the hysteresis band controller is depicted in Fig. 6.4(a) and (b). The operation is divided into two conditions based on the sign of Δp , be positive or negative. Δp_{th} is the critical (threshold) value of Δp that is used to differentiate between the steady-state and transient operation. The vertical axis, named as *Status*, refers to the operation mode of the controller. If *Status* = 1, the proper time- and voltage-step for steady-state operation are chosen, which means $T_{step} = T_{step-cpg-st}$ and $V_{step} = V_{step-cpg-st}$. Accordingly, when *Status* = 0, T_{step} and V_{step} are set as $T_{step-cpg-tr}$ and $V_{step-cpg-tr}$, respectively, which are the chosen time- and voltage-step during the transient period.

As depicted in Fig. 6.4(a), if $\Delta p > \Delta p_{th}$ (operation at point *A*), the controller operates at transient operation and *Status* = 0. By continuing the operation of the controller, Δp decreases and it becomes smaller than Δp_{th} (point *B*). In the case that, *Status* changes to 1, immediately after Δp passes Δp_{th} , the operation of the controller becomes slow and it takes long time for the controller to reach steady-state

Figure 6.4: Proposed voltage- and time-step calculation strategy: (a) Hysteresis controller with positive power deviation, (b) hysteresis controller with negative power deviation and (c) proposed voltage- and time-step calculation scheme.

with $\Delta p \simeq 0$. Therefore, in the proposed algorithm, the $Status$ remains 0 until Δp crosses zero. At $\Delta p \simeq 0$, the output power of the PV panel is close to p_{ref} and consequently, the controller should keep the operation point at this point. This is achieved by changing $Status$ value to 1 at this moment which moves the operation point to C . Afterwards, $Status$ remains 1 and operation point moves between points C and D . Similar procedure is implemented for negative values of Δp , as depicted in Fig. 6.4(b).

The detailed scheme of the proposed time- and voltage-step calculation algorithm is depicted Fig. 6.4(c). During grid fault condition, the controller sets T_{step} and V_{step} to $T_{step-cpg-tr}$ and $V_{step-cpg-tr}$, respectively, in order to achieve fast dynamic performance. If the grid is under normal condition and CPG operation is desired for the GCPVPP, time- and voltage-steps are calculated according to presented algorithm

in this figure. If $|\Delta p| > \Delta p_{th}$, which shows the transient operation mode with $Status = 0$, as depicted in Fig. 6.4(a) and (b), $T_{step-cpg-tr}$ and $V_{step-cpg-tr}$ are chosen as time- and voltage-step. If $|\Delta p| < \Delta p_{th}$, $Status$ can be either 0 or 1, based on the sign of Δp in the current and previous calculation-step, referred as Δp_{old} . For instance, in Fig. 6.4(a), if the operation point is shifted from point A to B in the current calculation-step, $\Delta p/\Delta p_{old} > 0$ and $Status$ is equal to 0, which sets $T_{step-cpg-tr}$ and $V_{step-cpg-tr}$ as time- and voltage-step. After the moment that Δp crosses 0, $\Delta p/\Delta p_{old} < 0$ and consequently $Status$ is changed to 1 and $T_{step-cpg-st}$ and $V_{step-cpg-st}$ are selected. A similar concept can also be applied in Fig. 6.4(b) for negative values of Δp . The selected time- and voltage-step in this stage are considered in the proposed algorithm for calculation of the voltage reference during *CPG*.

6.3.2 Proposed Voltage Reference Calculation Algorithm

The schematic of the proposed algorithm for the calculation of the voltage reference during *CPG* operation, with the movement to left- or right-side of *MPP* is presented in Fig. 6.5. It should be noted that at any time only one of these methods are applied during the *CPG* operation. The detailed implementation of these methods are presented in this section.

Proposed voltage reference calculation algorithm in right-side of *MPP*

At the start of *CPG*, the current operation point of the PV string is determined by calculating $\Delta p/\Delta v$. If the current operating point is in the left-side of *MPP*, the voltage reference in the next execution step is increased as $V_{ref} = V_{ref-old} + V_{step-cpg}$. The relatively large amount of $V_{step-rp-tr}$, which is assigned by the controller, consequences in the fast movement of the operation point to the right-side of *MPP*. After ensuring that the operation point of PV string is in the right-side of *MPP*, the proposed algorithm determines the voltage reference, related to p_{ref} by calculating Δp^* . Positive Δp^* shows that the output power is larger than p_{ref} , hence V_{ref} should be increased in the next time step, to reduce the output power (Fig. 6.2(c)). Similarly, for negative Δp^* , the voltage reference of the next execution step should be decreased ($V_{ref} = V_{ref-old} - V_{step-cpg}$) in order to increase the output power.

Proposed voltage reference calculation algorithm in left-side of *MPP* Similar to the mentioned algorithm, after determining the current operation point of the

Figure 6.5: Proposed voltage reference calculation strategy: (a) voltage reference calculation at right-side of *MPP* and (b) voltage reference calculation at left-side of *MPP*.

PV string by calculating $\Delta p/\Delta v$, if the operation point is in the right-side of *MPP*, it is moved to the left-side of *MPP* by decreasing the voltage reference in the next calculation step. subsequently, the voltage reference is calculated by comparing the output power of the PV panel and p_{ref} and if Δp^* is positive/negative, the voltage reference is decreased/increased, as depicted in Fig. 6.5(b).

The selection of Δp_{th} mainly depends on the nominal power of the PV string. Δp_{th} is the threshold power, which is used to differentiate between the steady-state and transient operation of the PV string during *CPG*. By selecting a relatively large value for Δp_{th} , the proposed algorithm remains in the steady-state operation mode for larger deviations of the extracted power and reference power. In this case, the steady-state error of the system becomes larger. The choice of a relatively small value for Δp_{th} results into the fast transient response of the proposed controller, however it increases the output power oscillation of the PV string. Therefore, the selection of a reasonable value for Δp_{th} is necessary to achieve desirable performance from the proposed algorithm. In this study, a value of between 5% and 15% of the nominal power of the PV string is used for Δp_{th} .

It should be noted that the proposed algorithm is based on the perturb & observe (P&O) MPPT algorithm. The selection of voltage- and time-step in the P&O algorithm is also a common challenge in this area, in which several research studies are available in the literature [133–136]. The aim of these studies is to achieve an optimized operation for the P&O algorithm. Similar criteria can also be applied for the selection of Δp_{th} , $T_{step-cpg-tr}$ and $V_{step-cpg-tr}$ in the proposed algorithm to achieve an optimized operation for the proposed *CPG* algorithm.

In the proposed voltage reference calculation algorithm, the main concerns regarding the operation of PV string during *CPG* are addressed as follows:

Remark 1 In order to achieve fast response, $V_{step-cpg}$ which is the voltage reference increment in each execution step, should be relatively large during the transient period. This is set to $V_{step-cpg-tr}$ during the transient period of *CPG*, which results in the fast movement of v_{ref} from v_{mpp} to v_a or v_b (Fig. 6.2(a)). The transient period of *CPG* is determined by using the hysteresis band controller as shown in Fig. 6.4(c). This transient period occurs at the start of *CPG* or fast changes of irradiance, temperature or power reference, however it also can take place during grid faults. These step changes result in quick deviation of p_{pv} and hence $T_{step-cpg} = T_{step-cpg-tr}$ and $V_{step-cpg} = V_{step-cpg-tr}$. The parameters P_{th} , $T_{step-cpg-tr}$ and $V_{step-cpg-tr}$ can be set based on the nominal voltage and power of the PV string.

Remark 2 By operating at point *A* or *B* during *CPG*, a small modification of the voltage reference produces a relatively large change of p_{pv} . In this study, the oscillation of p_{pv} during the steady-state of *CPG*, determined by the proposed hysteresis band controller, is reduced by imposing a relatively small value for $V_{step-cpg}$, equal to $V_{step-cpd-st}$.

Remark 3 If the required power reference is greater than the maximum available power from the PV string during *CPG*, the proposed algorithm is able to calculate the voltage of maximum power point. Assuming that the movement of operation point to right- side of *MPP* is chosen as the *CPG* control method, at the start of *CPG*, the proposed algorithm moves the operation point to the right-side of *MPP* by increasing V_{ref} . After moving the operation point to the right-side of *MPP*, the proposed algorithm calculates Δp^* and since it is negative, v_{ref} is reduced for the

Figure 6.6: Control diagram of the single- and two-stage PVPP topologies.

next execution time step which as a result it brings the operation point to the left-side of MPP again. This operation will be repeated in this condition and hence the operation point oscillates around MPP resulting in the extraction of the maximum available power from the PV string. It should be noted that since the parameters of the proposed algorithm are mainly designed for the CPG operation of the PV string, a performance similar to conventional MPPT algorithms can not be achieved.

Remark 4 One of the reasons that available algorithms in the literature, move the operation point only to the left-side of MPP is that by moving the operation point to right-side of MPP , it may go beyond the open-circuit voltage on the PV string as a result to a sudden change of irradiance or temperature. However, the proposed algorithm for moving the operation point to right-side of MPP in this chapter, can regulate the power under such condition. As depicted in Fig. 6.5(a), if the operation point is in right-side of MPP and the power becomes smaller than p_{ref} as a result of the sudden change of irradiance or temperature, V_{ref} reduces in the subsequent steps, which moves the operation point lower than the open-circuit voltage of the PV panel.

6.4 Simulation Results

Both single- and two-stage GCPVPP topologies (Fig. 6.1) are modeled and developed using Matlab/Simulink and the PLECS toolbox. The PV panels are modeled using the SHARP NU-U235F1 model, which its parameters are given in Table 3.1. The main system parameters are listed in Table 6.1.

The schematic of the control algorithm, which can be implemented in both single- and two-stage PVPPs is illustrated in Fig. 6.6. The operation mode and power refer-

ence are set by an external controller, like the central controller of the grid-connected PVPP. Furthermore, the operation region of the PV panel (operation in the right- or left-side of MPP) is also predetermined in the central controller. The operation mode is set based on the implemented fault detection and protection algorithm in the central controller. The PV string voltage reference is calculated through the proposed voltage reference calculation algorithm. Subsequently, V_{ref} is fed into the power converter controller, being the dc-dc converter in the two-stage PVPP or the grid-connected inverter in the single-stage PVPP. It should be noted that since the calculated V_{ref} using the proposed voltage reference calculation algorithm results in the regulation of the extracted power to P_{ref} , no additional controller or modifications of the dc-dc converter controller are required for the operation during CPG and

Table 6.1: Simulation parameters of the grid-connected inverter with CPG capability

Parameter	Symbol	Two-stage case study value	Single-stage case study value
PV maximum power	p_{mpp}	235 W	235 W
PV maximum power point voltage	v_{mpp}	30 V	30 V
PV maximum power point current	i_{mpp}	7.84 A	7.84 A
Number of parallel-connected PV panels in the PV string	N_p	15	9
Number of series-connected PV panels in the PV string	N_s	15	25
PV panel filling factor	FF	0.72	0.72
dc-bus voltage	v_{dc}	770 V	770 V (= v_{pv})
Grid voltage	v_{pcc}	430 V _{rms}	430 V _{rms}
PV panel capacitor	C_{pv}	5 mF	5 mF
$MPPT$ mode time-step	$T_{step-mppt}$	0.1 s	0.1 s
Steady-state CPG mode time-step	$T_{step-cpg-st}$	0.1 s	0.15 s
Transient CPG mode time-step	$T_{step-cpg-tr}$	0.002 s	0.05 s
$MPPT$ mode voltage-step	$V_{step-mppt}$	5 V	5 V
Steady-state CPG mode voltage-step	$V_{step-cpg-st}$	Right-side: 1 V Left-side: 6 V	Right-side: 1 V Left-side: 6 V
Transient CPG mode voltage-step	$V_{step-cpg-tr}$	Right-side: 3 V Left-side: 8 V	Right-side: 3 V Left-side: 8 V
Threshold power	ΔP_{th}	8 kW	8 kW

the same controller as *MPPT* can be applied.

Remark 5 It can be observed from the presented control strategies for single- and two-stage GCPVPPs, that since the calculated V_{ref} using the proposed voltage reference calculation algorithm can result in the regulation of the extracted power to p_{ref} , no additional controller or modification of the dc-dc converter controller is required for the operation during *CPG* and the same controller as *MPPT* can be applied.

In order to evaluate the generality of the proposed *CPG* algorithm, three different cases are investigated:

- 1) Two-stage GCPVPP with the movement of the operation point to the right-side of *MPP*.
- 2) Two-stage GCPVPP with the movement of operation point to the left-side of *MPP*.
- 3) Single-stage GCPVPP with the movement of operation point to the right-side of *MPP*.

Furthermore, two test scenarios are implemented in each of these three cases. In the first test scenario, the performance of the proposed *CPG* algorithm under changes

Figure 6.7: Simulation results: (a) Implemented irradiance profile and (b) available power from the PV module at *MPP*.

of irradiance is investigated. The implemented irradiance profile is presented in Fig. 6.7(a). Different types of irradiance changes, including step increase/decrease and linear increase/decrease are considered. Accordingly, the maximum available power from the PV panel under *MPPT* operation is illustrated in Fig. 6.7(b). As expected, the available power when $Irr = 1 \text{ kW/m}^2$ equals to 50 kW, while it is smaller for lower irradiance amounts and is larger for higher amounts of irradiance. The required power reference in this test scenario is 40 kW, and as depicted in Fig. 6.7(b), there are several instances that the available power from the PV panel is smaller than the required power reference.

Case I This case demonstrates the performance of the proposed *CPG* algorithm on the two-stage GCPVPP with the movement of the operation point to the left-side of *MPP* and results are presented in Fig. 6.8. Before $t = 3 \text{ s}$, $Irr = 1 \text{ kW/m}^2$ and the voltage reference is regulated at 310 V through the proposed algorithm, which keeps the operation point of the PV panel at point *A*, as depicted in Fig. 6.8(c). During this period, the time-step is equal to 0.1 s and voltage-step is set to 6 V; consequently, the output power of the PV panel experiences small power oscillation, as shown in Fig. 6.8(b). The irradiance decreases linearly between $t = 3 \text{ s}$ and $t = 6 \text{ s}$, as illustrated in Fig. 6.7(a), however, before $t = 4 \text{ s}$, the available power is larger than p_{ref} and therefore, p_{pv} is regulated at 40 kW by increasing v_{pv} . It can be seen that during this transient period, small time-step and large voltage-step is used which results in the fast dynamic performance of the proposed *CPG* algorithm.

Between $t = 6 \text{ s}$ and $t = 9 \text{ s}$, the PV string operates at point *B*, which is its maximum power point at $Irr = 0.5 \text{ kW/m}^2$, because the available power is smaller than the required power. There is a step increase of irradiance at $t = 9 \text{ s}$ to $Irr = 1.2 \text{ kW/m}^2$, which as a result the operation point is quickly moved to point *C* in Fig. 6.8(c) with decrease of the voltage to $v_{pv} = 250 \text{ V}$. Similarly, a step decrease in the irradiance occurs at $t = 12 \text{ s}$ to $Irr = 0.75 \text{ kW/m}^2$ that moves the operation point to *D*. At this point, p_{pv} is approximately equal to 38 kW, that is the maximum available power of the PV string under such irradiance. Finally, as a result of the linear increase of the irradiance, the operation point of the PV panel moves to point *E*, which is the same operation point as *A*.

Figure 6.8: Simulation results - *Case I*: Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the left-side of *MPP*: (a) Voltage reference (v_{ref}), (b) PV voltage (v_{pv}), (c) extracted power from the PV module (p_{pv}) and (d) operation point of the PV module.

Case II This case study examines the performance of the proposed *CPG* algorithm for the movement of the operation point to the right-side of *MPP* in the two-stage

Figure 6.9: Simulation results - *Case II*: Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the right-side of *MPP*: (a) Voltage reference (v_{ref}), (b) PV voltage (v_{pv}), (c) extracted power from the PV module (p_{pv}) and (d) operation point of the PV module.

GCPVPP and results are depicted in Fig. 6.9. The same irradiance profile as Fig.

6.7(a) is considered in this study with $p_{ref} = 40$ kW. Before $t = 3$ s, the PV strings operates at point A in Fig. 6.7(c) with $v_{pv} = 470$ V. Due to the decrease of irradiance after this moment, the operation point is moved to point B that is the maximum power point of the PV string at $Irr = 0.5$ kW/m². The similar process as *Case I* is performed in this case study as well. It can be seen that the output power of the PV string is kept at 40 kW during all times, even during a sudden step change of the irradiance. Furthermore, at instances that the maximum available power is smaller than p_{ref} , the PV panel operates at *MPP*.

Case III The operation of the proposed *CPG* algorithm with the movement of the operation point to right-side of *MPP* is examined under the irradiance profile shown in Fig. 6.7(a), for a single-stage GCPVPP with grid-connected inverter and results are depicted in Fig. 6.10. In this case study, the number of series-connected PV panels in the PV string is increased in order to achieve the required dc-link voltage for grid-connection. Under $Irr = 1$ kW/m² (before $t = 3$ s) the proposed algorithm regulates the dc-link voltage to 850 V (point A in Fig. 6.10(c)). Subsequently, the operation point is moved to point B , which is maximum power point of the PV panel $Irr = 0.5$ kW/m² and power of approximately 25 kW. The test scenario continues similar to *Case II* and the presented results demonstrate the capability of the proposed *CPG* algorithm in regulating the output power of the single-stage GCPVPP to the required power reference.

Cases IV, V and IV The performance of the proposed algorithm under three severe operation conditions is demonstrated in these case studies: 1) Change of the operation mode from *MPPT* to *CPG*, 2) step change of the power reference and 3) step decrease of the irradiation which moves the operation point beyond the open-circuit voltage of the PV string. These test scenarios are performed on the presented GCPVPP topologies and results are illustrated in Fig. 6.12, 6.11 and 6.13. Prior to $t = 3$ s, the GCPVPP operates at *MPPT* and the maximum available power of the PV string (50 kW) is extracted in all the three cases. At $t = 3$ s, the operation mode is change to *CPG* from the GCPVPP central controller with $p_{ref} = 35$ kW and therefore, the proposed *CPG* algorithm quickly regulates the PV string power to the required power reference at point B in all of the three cases. The power reference is decreased to $p_{ref} = 25$ kW at $t = 6$ s. Consequently, the proposed algorithm increases/decreases the voltage reference in the right-/left-side of *MPP* to point C

Figure 6.10: Simulation results - *Case III*: Constant power generation of the PV module in the single-stage topology with the movement of the voltage reference to the right-side of *MPP*: (a) Voltage reference (v_{ref}), (b) PV voltage (v_{pv}), (c) extracted power from the PV module (p_{pv}) and (d) operation point of the PV module.

to adjust the PV panel power with its reference value.

Figure 6.11: Simulation results - *Case V*: Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the right-side of *MPP*: (a) Irradiance, (b) PV voltage (v_{pv}), (c) extracted power from the PV module (p_{pv}) and (d) operation point of the PV module.

One of the interesting features of the proposed algorithm is its robustness for the operation in the right-side of *MPP*, when its operation point goes beyond the open-circuit voltage of the PV panel. At $t = 9 \text{ s}$, a sudden decrease of the irradiance

Figure 6.12: Simulation results - Case IV: Constant power generation of the PV module in the two-stage topology with the movement of the voltage reference to the left-side of *MPP*: (a) Irradiance, (b) PV voltage (v_{pv}), (c) extracted power from the PV module (p_{pv}) and (d) operation point of the PV module.

from $Irr = 1 \text{ kW/m}^2$ to $Irr = 0.3 \text{ kW/m}^2$ is simulated. It can be seen from Fig. 6.11(c) and 6.13(c) that the PV panel voltage is equal to 495 V and 883 V before this moment, for the two- and single-stage GCPVPP respectively. Due to the step

Figure 6.13: Simulation results - *Case VI*: Constant power generation of the PV module connected in the single-stage topology with the movement of the voltage reference to the right-side of *MPP*: (a) PV voltage (v_{pv}), (b) PV power (p_{pv}) and (c) operation point of the PV module.

reduction of the irradiance, these voltages are beyond the open-circuit voltage of the PV panel under such irradiance, which are 486 V and 868 V, respectively.

The proposed algorithm decreases the voltage reference under such condition and

consequently brings the operation point inside the P-V curve range of the PV panel. Because the maximum available power of the PV string under this condition is smaller than p_{ref} , the algorithm adjusts v_{pv} , to v_{mpp} during this period.

Simulation results demonstrate the generality of the proposed *CPG* algorithm for different types of GCPVPPs with the flexibility to move the operation point of the PV panel to the right- or left-side of *MPP*. Furthermore the robustness of the proposed algorithm in regulating the PV panel power under step change of irradiance and power reference is demonstrated under various operation conditions.

6.5 Experimental Evaluation

The operation and performance of the proposed algorithm is demonstrated experimentally using a dc-dc boost converter setup (Fig. 6.14) based on the CREE C2M0080120D SiC Power MOSFET. The complete parameters of the experimental setup are given in Table 6.2 and the circuit diagram of the experimental setup is shown in Fig. 6.14(b). The PV side is emulated using an ETS600/8 Terra SAS photovoltaic simulator and the V-I characteristics given in Table 6.2. The dc-side voltage is regulated with a Sorensen SGI 400-38 dc power supply in parallel with a resistor (R_l) as in practical applications it would be controlled by the inverter-side dc-voltage control. The schematic of the implemented controller is same as the presented control strategy for simulation evaluation, shown in Fig. 6.6(a). The proposed controller and protection functions of the converter are implemented in a dSPACE 1006 platform.

Two different cases are experimentally tested in order to verify the operation of the controller under different situations.

Case I This case demonstrates the performance of the proposed algorithm under direct changes in the power reference (p_{ref}) with regards to other control objectives. The irradiance and temperature are assumed to remain constant for the duration of the event and the results are shown in Fig. 6.15. Under steady-state, the converter operates in *MPPT* mode extracting the maximum power (1 kW under 1000 W/m²) from the PV panels. The PV voltage is regulated to 138 V while the inverter dc-side voltage is equal to $v_{dc} = 250$ V, with a duty cycle of approximately 0.45 and the PV panel operates at point *A* of Fig. 6.15(c).

At $t = 1$ s, the external controller sends a direct power reference of 0.35 kW. The calculated voltage reference by the proposed algorithm is 162 V as shown in Fig. 6.15(b) and accordingly the operation point moves to point M in Fig. 6.15(c). The average value of the extracted power remains 0.35 kW during this *CPG1* operation mode. At $t = 2.5$ s, the power reference changes again to 0.75 kW. During this transient, $V_{step-cpg}$ is set to $V_{step-spg-tr}$ due to the implementation of the proposed hysteresis-band-based controller. Thus, the controllers reaches the new voltage reference quickly and the output power of the converter increases to 0.75 kW in less than 0.1 s. It can be seen that the proposed controller can quickly regulate the PV panel power to the required power reference, even under a sudden step change of the power reference.

Figure 6.14: Experimental verification: (a) Schematic diagram of the dc-dc converter test system and (b) setup of the experiment.

Table 6.2: Parameters of the experimental setup of dc-dc converter

Parameter	Symbol	Value
PV panel maximum power	p_{mpp}	1 kW
PV panel maximum power point voltage	v_{mpp}	137 V
PV panel maximum power point current	i_{mpp}	7.5 A
PV panel filling factor	FF	0.77
dc-bus voltage	v_{dc}	250 V
PV panel capacitor	C_{pv}	200 μ F
dc/dc converter switching frequency	f_{sw}	50 kHz
<i>MPPT</i> mode calculation time-step	$T_{step-mppt}$	0.2 s
<i>CPG</i> mode calculation time-step	$T_{step-cpg}$	0.02 s
<i>MPPT</i> mode voltage-step	$V_{step-mppt}$	0.5 V
Steady-state <i>CPG</i> mode voltage-step	$V_{step-cpg-st}$	0.35 V
Transient <i>CPG</i> mode voltage-step	$V_{step-cpg-tr}$	3.5 V
Threshold power	ΔP_{th}	80 W

Case II The second case demonstrates the impact of irradiance to the performance of the proposed algorithm. The irradiance is reduced linearly from 1000 W/m² to 400 W/m² between $t = 1.95$ s and $t = 6.8$ s, while the power reference is kept constant at $P_{ref} = 0.65$ kW. The *CPG* command is received at $t = 1$ s and the controller operates similarly to Case I, at point *B* in Fig. 6.16(c). Between $t = 1$ s and $t = 1.95$ s, the irradiance is constant 1000 W/m², and the PV power is also kept constant. However, after $t = 1.95$ s due to the reduction of the irradiance, V_{ref} changes in order to regulate the power to the requested reference. This happens until $t = 5.9$ s. At this moment, the maximum available power from the PV panel is equal to 0.65 kW and the operating point corresponds to the *MPP*. Further reduction in the irradiance below 595 W/m² means that the reference power cannot be satisfied, at which point the algorithm tracks the *MPP*. After $t = 6.9$ s, when the irradiance stays constant to 400 W/m², the proposed *CPG* algorithm, regulates the reference voltage at 132 V which is equal to v_{mpp} , as shown in Fig. 6.16(c) with the PV panel operating at point *C*. The robustness of the the proposed *CPG* control algorithm is

Figure 6.15: Experimental results: *Case I* - Behavior of the proposed power reduction method under change of the power reference: (a) PV panel voltage, current, power and dc-link voltage, (b) voltage reference and dc-dc converter duty cycle and (c) PV panel operation point.

Figure 6.16: Experimental results: *Case II* - Behavior of the proposed power reduction method under change of the irradiance: (a) PV panel voltage, current, power and dc-link voltage, (b) voltage reference and dc-dc converter duty cycle and (c) operation point of the PV panel.

show in this case study and it is shown that it is able to regulate the PV panel power to the required power reference under the change of irradiance.

The cases that are presented and experimentally verified, demonstrate that the proposed algorithm combined with the change in the time- and voltage-step is capable of either controlling the extracted PV power to the required power reference or tracking the maximum power point when the power requirements cannot be satisfied.

6.6 Discussion on the Stability of the Proposed CPG Algorithm

The stability of the PV string system with dc-dc converter can be divided to two parts:

Stability of the voltage controller of the dc-dc converter The stability of the controller of the dc-dc converter depends on the tuning of the parameters of the controller and design of the dc-dc converter. Practically, the voltage controller of the dc-dc converter should be able to regulate the PV voltage to the required voltage reference, which is within its range of operation. The movement of the operation point to the left-side of *MPP* for small power reference values requires large gain for the dc-dc converter and reduces the voltage of the PV string close zero. In this condition, the dc-dc converter might become unstable. Therefore, for very small power references it would be better to move the operation point to the right-side of *MPP*.

Stability of the voltage reference calculation algorithm Regarding the stability of the proposed algorithm, two severe cases can be considered, which may result into the instability of the proposed algorithm:

1. Partial shading: The partial shading can effect the operation of the PV string in two different conditions, which are analyzed as follows:
 - (a) The maximum available power from the PV string becomes smaller than the required power reference ($P_{ref} > P_{mpp}$) during the partial shading. One of the interesting characteristics of the proposed algorithm is that

it is able to extract the maximum available power from the PV string, under such partial shading condition. Furthermore, the performance of the proposed algorithm under partial shading is investigated under various operation conditions and results are illustrated in Chapter 6. It can be observed that the proposed algorithm regulates the PV string voltage to the voltage of maximum power point under all of the conditions and is able to extract the maximum available power from the PV string.

- (b) The existence of several local maximum power points is another effect of the partial shading in the PV string. The extraction of maximum power from the PV string under such condition is still a challenging area and several algorithms are introduced in the literature to enhance the performance of maximum power point techniques in extracting the maximum power under such conditions [137–141].

2. The movement of the operation point beyond the open-circuit voltage of the PV panel: This condition can occur under the step reduction of the irradiance, while the operation point of the PV panel is also located in the right-side of *MPP*. This instability is one of the drawbacks of available research studies in the literature. One of the key features of the proposed algorithm is its ability to regulate the PV string voltage under such condition. The detailed explanation has been provided in Remark 4 of this chapter. The performance of the proposed algorithm under such severe condition is evaluated under various test scenarios and results have been presented in Figs. 6.12 and 6.13. The evaluation results prove the stable operation of the GCPVPP under this operation condition.

It can be observed that the proposed algorithm provides a stable operation during various severe operation conditions, which shows the stability of the proposed algorithm.

The stability of the P&O algorithm has been investigated and proved in several research studies [142–144]. Because the proposed algorithm is also based on the conventional P&O MPPT algorithm, its stability can be concluded based on the same conclusions of these studies.

6.7 Summary

A general algorithm for calculating the voltage reference of a PV panel which regulates its output power to a certain power reference has been introduced and investigated in this chapter. The proposed algorithm is based on the P-V curve characteristics of the PV panel. Unlike the presented studies in the literature, the proposed algorithm is flexible in moving the operation point to the right- or left-side of maximum power point and can be applied for single- or two-stage GCPVPP topologies. Because, the time- and voltage-step of the voltage reference calculation algorithm are calculated based on a hysteresis band controller, fast dynamic performance during transients and slow power oscillation during steady-state are obtained.

Detailed implementation of the proposed *CPG* algorithm has been presented and its flexibility and effectiveness has been demonstrated on 50-kVA single- and two-stage GCPVPP simulation setups and a 1-kVA experimental setup, under various irradiance and power reference profiles. The GCPVPP obtains *CPG* capability under all of the presented severe operating conditions. Also, it is shown that if the target power reference is larger than the maximum available power of the GCPVPP, the proposed algorithm operates at maximum power point. Furthermore, the robustness of the proposed algorithm for regulating the GCPVPP power while its operation point goes beyond the open-circuit voltage of the PV panel due to sudden decrease of irradiance, is demonstrated with results for both GCPVPP topologies. The results demonstrate flexibility and generality of the proposed algorithm as an additional function for existing *MPPT* algorithms in grid-connected GCPVPPs.

Chapter 7

Conclusion and Future Work

This chapter summarizes the work have been done in this thesis with the focus on the main conclusions and contributions accomplished from this research. However some of the issues of the operation of GCPVPPs during voltage sags are addressed in this thesis, but there are still many more issues which can be discussed on this subject. Some of these issues are discussed in this chapter.

7.1 Conclusions

Global warming concerns, fossil fuel cost increase and the need of sustainable energy for the future lead to the development of renewable energy sources. Among various types of renewable energy sources, PV energy has several advantages, like higher potential of energy production, availability in almost all parts of the world, ease of installation, low operation and maintenance cost. Moreover, the production cost of PV panels has been going down drastically in the recent years. These advantages result in increasing the installation of photovoltaic power plants. Accordingly, the number of installed medium- and large-scale GCPVPPs is also growing drastically. On the other hand, high penetration of installed medium- and large-scale GCPVPPs results in new challenges for PSOs on the power quality and reliability of the power system. In order to maintain the power quality and reliability of the power system, PSOs and grid codes regulate new requirements for GCPVPPs. According to these new grid codes, medium- and large-scale GCPVPPs should stay connected to the grid during voltage sags and inject reactive power to the grid, in order to enhance the voltage of the grid during such conditions. These reasons have motivated the

research in this thesis, with the focus on the operation of GCPVPPs with multilevel inverters during voltage sags.

Several configurations are introduced in the literature for GCPVPPs. Module inverter configuration is suitable for domestic applications with small amount of generated power. Central inverter topology can be applied for large-scale GCPVPPs, however, its power conversion efficiency is reduced drastically in the occurrence of the partial shading of PV modules. In the multi-string topology, a dc-dc converter is considered to each PV string, which extracts the maximum power. Due to its advantages, it is the state-of-the-art for large-scale GCPVPPs. Due to the high-power rating of the grid-connected inverter in these types of power plants, multilevel inverters are utilized in their structure. This also results in better output voltage quality and higher efficiency due to lower switching frequency, compared to two-level inverters. Two types of multilevel inverters including three-level neutral-point-clamped (3L-NPC) and seven-level cascaded H-bridge (7L-CHB) inverters are considered in this thesis, for the evaluation of the proposed control algorithms.

Voltage-oriented-control (VOC) structure has been found a suitable strategy for the control of GCPVPPs during voltage sags, due to its current control stage, which enables the injection of unbalanced currents to the grid during unbalanced voltage sags. The implementation of the current controller in stationary-frame by using proportional-resonant (PR) controllers results in fast dynamic response and zero steady-state error. Therefore, VPC structure with PR controllers have been applied in this study.

The focus of Chapter 3 is the balanced current injection of the GCPVPP to the grid during voltage sags. An algorithm for the calculation of current references, based on the grid-code requirements and extracted power from PV strings has been introduced in this chapter. Furthermore, an algorithm for reduction of the extracted power from PV strings during voltage sags, has been introduced. The proposed control strategy employs the full current capacity of the grid-connected inverter resulting in a better grid voltage enhancement, however, the injected active/reactive powers to the grid experience oscillations, which also affects the dc-link voltage. Simulation and experimental results on the multi-string GCPVPP with 3L-NPC inverter has been illustrated to verify the performance of the proposed controller for the balanced current injection during voltage sags.

The operation of the GCPVPP with unbalanced current injection to the grid dur-

ing unbalanced voltage sags has been investigated in Chapter 4. A control algorithm has introduced, which limits the inverter peak current and achieves zero active power oscillation for the GCPVPP during unbalanced voltage sags. The average active and reactive power references (P^* and Q^*) are calculated by multiplying the amplitude of the voltage positive-sequence ($|v_{pcc}^+|$) with the dq current references (I_d^* and I_q^*). This general equation can be implemented in combination with various current reference calculation algorithms, while ensures that the inverter peak current remains within its nominal value. The generality of this algorithm is the main contribution of this study. The extracted power from PV strings has been reduced during voltage sags through the implementation of the control algorithm for dc-dc converters of the multi-string GCPVPP. Therefore, the GCPVPP complies with the reactive current requirements of the grid codes and current limitation of the inverter. The effectiveness of the proposed controller has been proved in a 3.3-kVA three-phase grid-connected 3L-NPC inverter prototype and results have been demonstrated.

The proposed algorithms in Chapters 3 and 4 are general control structures, that can be applied in GCPVPPs with various types of inverters. The 3L-NPC inverter has been considered in these chapters for the evaluation of the controllers. This inverter does not require additional controllers for balancing of capacitor voltages, because the voltage balancing has been performed easily through the adaptive space vector modulation technique. Although, other types of multilevel converters, like cascaded H-bridge inverter (CHB), require deep consideration about the voltage balancing of capacitors. This reason has been the motivation for Chapter 5, which is the operation of GCPVPP with CHB inverter during voltage sags.

A flexible control strategy for the operation of the photovoltaic grid-connected CHB inverter during unbalanced voltages sags has been introduced Chapter 5. A zero-sequence voltage injection has been introduced in order to achieve the inter-phase balancing, while the inter-bridge balancing has been obtained through the modification of bridges voltage references. Transient currents of the inverter, at the beginning of the voltage sag have been greatly reduced by implementing a feedforward voltage controller. The performance of the proposed controller is evaluated on simulation and experimental results.

Chapters 3, 4 and 5 focused on the operation of the grid-connected inverter during unbalanced voltage sags. As mentioned, due to the injection of reactive power and current limitation of the inverter, the extracted power from PV strings should be

reduced during voltage sags. In these three chapters, a coordinated maximum power point tracking (MPPT) algorithm has been implemented for the dc-dc converters of the multi-string GCPVPP to reduce the extracted power from PV strings to the amount of active power that can be injected to the grid. However, the evaluation results demonstrate its applicability for GCPVPPs, a general algorithm is required to be used in both single- and two-stage GCPVPPs. This has become the motivation for Chapter 6.

Chapter 6 proposes an algorithm for the calculation of the voltage reference, which extracts a certain amount of power from PV string. The proposed algorithm can be applied for both single- and two-stage GCPVPPs. Furthermore, it can be applied during the *Normal* operation of the GCPVPP in order to inject constant power to the grid, while it can also be applied during voltage sags to reduce the extracted power from PV strings to the amount of active power that can be injected to the grid. Unlike the presented studies in the literature, the proposed algorithm is flexible in moving the operation point to the right- or left-side of maximum power point. The time- and voltage-step of the voltage reference calculation algorithm are also calculated based on a hysteresis band controller, which results in faster dynamic performance during transients and slower power oscillation during steady-state. The simulation and experimental results demonstrate flexibility and generality of the proposed algorithm as an additional function for existing *MPPT* algorithms in grid-connected GCPVPPs. It is also shown that if the target power reference is larger than the maximum available power of the GCPVPP, the proposed algorithm operates at maximum power point. Furthermore, the robustness of the proposed algorithm for regulating the GCPVPP power while its operation point goes beyond the open-circuit voltage of the PV panel due to sudden decrease of irradiance, is demonstrated with results for both GCPVPP topologies.

The proposed control strategies in this thesis result in the low-voltage ride-through (LVRT) capability for GCPVPPs, while they comply with grid codes and standards. The generality and flexibility of the proposed algorithms in the operation of GCPVPPs during voltage sags, as well as grid *Normal* operation, makes them interesting for medium- and large-scale GCPVPPs.

7.2 Recommendations for Future Research

Notwithstanding the above encouraging results, further works are needed in the design of the control system, PV modules, power converters, associated hardware system and the energy storage system of the GCPVPPs to improve their performance.

- The applicability of proposed controller is evaluated under various operation modes, however, the stability analysis is still required to prove its feasibility under all operation modes. The accurate model of the GCPVPP can be extracted and accordingly, the stability of the proposed controller examined under various operation modes.
- This study has examined the performance of the proportional-resonant controller for the GCPVPP inverter, however other current controllers like dead-beat current controller can also be applied in the inner current control loop. The performance of different current controllers can also be compared under various grid normal and fault
- The grid-connected CHB inverter comprises several advantages, however, it also suffers from two issues:
 - It requires large dc-link capacitors due to the existence of the double fundamental frequency voltage ripple, which is generated because of the operation of each phase of the converter as a single-phase converter.
 - Interphase and interbridge voltage imbalances can exist, because unequal amounts of power can be generated from PV strings, connected to each individual H-bridge. As a result, the injected three-phase currents to the grid, during normal grid condition, become unbalanced. Several studies have been reported on the power balancing with zero-sequence voltage injection to the phases [38,50,145], however, this method requires overrating of semiconductor devices.

A potential solution to the above issues is the full-row connected cascaded H-bridge topology, as shown in Fig. 7.1, is studied in [49]. The operation of this converter during voltage sags can be another future direction for this thesis.

- The most common configuration presented in the literature is the star connection. Recently, several publications consider the CHB inverter with delta

Figure 7.1: Circuit configuration for the grid-connected PV power plant with full-row connected H-Bridge converter and isolated dc/dc converters.

configuration [146, 147]. The operation of delta-connected CHB inverter during voltage sags with unbalanced current injection requires deep attention to voltage balancing of capacitors and current reference calculation algorithm. It is not investigated in the literature and can be considered as a future research direction of this thesis.

- In order to eliminate the earth leakage current, the proposed structure considers the high-frequency isolation transformer within the dc-dc converter. However in a large-scale PV power plant the number of PV strings and accordingly required number of isolated dc-dc transformers are high. On the hand, the use of low-frequency isolation transformer results in reduced efficiency and power density. In the four-leg neutral-point-clamped (4-leg NPC) inverter topology, shown in Fig. 7.2, the neutral leg can be controlled to eliminate the earth-leakage current in the four-wire grid system. The study can focus in the design of the controller for this converter to improve the voltage balancing performance and steady state operation of the GCPVPP. Moreover, achieving higher power quality and lower current harmonic distortion is another goal of this study, which can also be investigated on the 4-leg NPC inverter. The earth leakage current is the result of the existence of common mode voltage in the converter. The common mode voltage and leakage current in the 4L-NPC inverter can be

Figure 7.2: Circuit configuration for the grid-connected PV power plant with 4-leg NPC inverter.

Figure 7.3: High diurnal PV power variability in a typical day for Australia, January 2013 [153].

reduced by the injection of zero-sequence voltage to the output voltage of the converter. In this case, the modulation of the fourth leg helps to inject the zero-sequence voltage. The effectiveness of the four-leg grid-connected inverter is investigated in the following references. Usually, Z_n is selected to be equal to the phase line filters (i.e. Z_{ga}). In this case the design on the current controller for different legs of the converter is similar. The effectiveness of the four-leg inverter in reducing the earth leakage current is investigated in [148–152]

- Fig. 7.3 depicts the output power of a typical GCPVPP in a sunny day in

Australia [153]. It can be seen that even the power is measured on a sunny day, there are a lot of fluctuations in the output power of the GCPVPP. This probabilistic characteristic of the PV energy plant should be considered in the design of electrical components. Furthermore, the voltage fluctuations of the grid have some probabilistic characteristics. Therefore, a statistical study should be implemented in order to achieve an optimized size of the electrical components like dc-link capacitors and energy storage system. One part of future works of this study can be allocated to the probabilistic study PV power plant in combination with grid faults and voltage fluctuations.

- Constant voltage- and time-steps have been used in the implementation of the proposed CPG algorithm in this thesis. The performance of the proposed algorithm can be further improved by optimizing the parameters of the proposed algorithm by using meta heuristic techniques (i.e. Particle swarm optimization). The implementation of these algorithms can be considered as a future work.
- The effect of partial shading is not investigated in the design of the proposed constant power generation algorithm in this thesis. One of the areas which can be explored as a future direction of this thesis, is to design and implement a flexible constant power generation algorithm with capability of controlling the output power of the GCPVPP during partial shading. Additionally, the dynamic performance of the proposed CPG algorithm can be further improved by applying adaptive voltage steps in the proposed voltage reference calculation algorithm.
- The power reserve control is becoming a challenging issue in GCPVPPs, due to their high-penetration in the power system and fluctuation of the output power of GCPVPPs. An algorithm is introduced in [114], which controls the power reserve of the two-stage GCPVPPs. This algorithm is not a general algorithm and experiences some issues in single-stage GCPVPPs. The proposed algorithm in Chapter 6, can be extended to a general algorithm for the achievement of power reserve control in GCPVPPs.

List of Publications

- [1] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, J. Pou and F. Blaabjerg, “A general constant power generation algorithm in photovoltaic power plants,” *IEEE Transaction of Power Electronics*, 2017.
- [2] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, Christopher D. Townsend, Pablo Acuna and J. Pou, “Operation of photovoltaic cascaded H-bridge converters during voltage sags,” *IEEE Transactions on Industrial Electronics*, 2017.
- [3] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, J. Pou, K. Kandasamy, Z. Lim and G. H. P. Ooi, “Study on the low-voltage ride-through capability of photovoltaic grid-connected neutral-point-clamped inverters with active/reactive power injection,” *IET Gener. Transm. Distrib.*, vol. 11, no. 8, pp. 1182–1190, Jul. 2017.
- [4] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, J. Pou and P. Acuna, “Active/reactive power control of photovoltaic grid-tied inverters with peak current limitation and zero active power oscillation during unbalanced voltage sags,” *IET Power Electronics*, 2017.

Conferences:

- [5] **H. Dehghani T.**, A. I. Maswood, J. Pou, G. Konstantinou and V. G. Agelidis, “An algorithm for reduction of extracted power from photovoltaic strings in grid-tied photovoltaic power plants during voltage sags,” in *proc. IEEE Industrial Electronics Conference (IECON)*, Oct. 2016, pp. 3018-3023.
- [6] **H. Dehghani T.**, Ali I. Maswood, G. Konstantinou, J. Pou, K. Kandasamy, Z. Lim and G. Ooi H. P., “Unbalanced current injection of the PV grid-tied three-leg four-wire NPC Inverter Using 3-D Space Vector Modulation in abc Frame,” in

- proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2016, pp. 1-6.
- [7] **H. Dehghani T.**, Ali I. Maswood, G. Konstantinou and J. Pou, “Low-voltage ride-through capability of cascaded H-bridge multilevel converters for large-scale photovoltaic power plants,” in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Nov. 2016, pp. 52 - 57.
- [8] **H. Dehghani T.**, Ali I. Maswood, G. Konstantinou, C. D. Townsend and J. Pou, “Low-voltage ride-through capability of full-row connected cascaded H-bridge converters,” in *proc. IEEE Region 10 Conference TENCN*, Nov. 2016, pp. 984-987.
- [9] **H. Dehghani T.**, A. I. Maswood, Z. Lim, G. H. P. Ooi and P. H. Raj, “A review of active/reactive power control strategies for PV power plants under unbalanced grid faults,” in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-6.
- [10] **H. Dehghani T.**, A. I. Maswood, Z. Lim, G. H. P. Ooi and P. H. Raj, “NPC photovoltaic grid-connected inverter with ride-through capability under grid faults,” in *proc. IEEE 11th International Conference on Power Electronics and Drive Systems*, Jun. 2015, pp. 518-523.
- [11] **H. Dehghani T.**, A. I. Maswood, A. Ukil, O. H. P. Gabriel and L. Ziyou, “NPC photovoltaic grid-connected inverter using proportional-resonant controller,” in *proc. IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Dec. 2014, pp. 1-6.

***Other publications, which are not included in the thesis;
but have been co-authored during the Ph.D. candidature:***

- [12] M. Roomi, A. I. Maswood, **H. Dehghani T.**, P. H. Raj, “A novel modulation method for non-ideal dual z-source neutral point clamped inverter,” *IET Power Electronics*, vol. 10, no. 2, pp. 222-231, 2016.
- [13] **H. Dehghani T.**, A. I. Maswood and M. M. Roomi, “Active/reactive power control of PV grid-tied NPC inverter using 3-D space vector modulation in abc coordinate,” in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-6.

-
- [14] **H. Dehghani T.**, A. I. Maswood, Z. Lim, G. H. P. Ooi and P. H. Raj, "Proportional-resonant controlled NPC converter for more-electric-aircraft starter-generator," in *proc. IEEE 11th International Conference on Power Electronics and Drive Systems*, Jun. 2015, pp. 41-46.
- [15] M. S. U. Khan, A. I. Maswood, **H. Dehaghani T.**, M. M. Roomi and M. Tariq, "Control of bidirectional DC/DC converter for back to back NPC-based wind turbine system under grid faults," in *proc. IEEE 4th International Conference on the Development in the in Renewable Energy Technology (ICDRET)*, Jan. 2016, pp. 1-6.
- [16] P. H. Raj, A. I. Maswood, G. H. P. Ooi and **H. Dehghani T.**, "Five-level multiple-pole multilevel diode-clamped inverter scheme for reactive power compensation," in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-6.
- [17] M. M. Roomi, A. I. Maswood and **H. Dehghani T.**, "Performance evaluation of boost and Z-source converters for fuel cell application," in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-7.
- [18] P. H. Raj, A. I. Maswood, G. H. P. Ooi and **H. Dehghani T.**, "Multiple-pole multilevel diode clamped inverter for permanent magnet synchronous motor drive," in *proc. IEEE 11th International Conference on Power Electronics and Drive Systems*, Jun. 2015, pp. 862-866.

References

- [1] Tracking clean energy progress (2016). [Online]. Available: <http://www.iea.org/>
- [2] Solar price and installation history. [Online]. Available: <https://cleantechnica.com>
- [3] Renewable 2016 global status report. [Online]. Available: <http://www.ren21.net/status-of-renewables/global-status-report/>
- [4] List of photovoltaic power stations. [Online]. Available: https://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations
- [5] Y. Yang, P. Enjeti, F. Blaabjerg, and H. Wang, "Wide-scale adoption of photovoltaic energy: Grid code modifications are explored in the distribution grid," *IEEE Ind. Appl. Mag.*, vol. 21, no. 5, pp. 21–31, Sep. 2015.
- [6] F. Yang, L. Yang, and X. Ma, "An advanced control strategy of PV system for low-voltage ride-through capability enhancement," *Solar Energy*, vol. 109, pp. 24 – 35, 2014.
- [7] A. Camacho, M. Castilla, J. Miret, A. Borrell, and L. G. de Vicua, "Active and reactive power strategies with peak current limitation for distributed generation inverters during unbalanced grid faults," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1515–1525, Mar. 2015.
- [8] B. I. Craciun, T. Kerekes, D. Sera, and R. Teodorescu, "Frequency support functions in large PV power plants with active power reserves," *IEEE J. of Emerging and Selected Topics in Power Electron.*, vol. 2, no. 4, pp. 849–858, Dec. 2014.
- [9] A. Calle-Prado, S. Alepuz, J. Bordonau, J. Nicolas-Apruzzese, P. Corts, and J. Rodriguez, "Model predictive current control of grid-connected neutral-point-clamped converters to meet low-voltage ride-through requirements," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1503–1514, Mar. 2015.
- [10] M. Mirhosseini, J. Pou, and V. G. Agelidis, "Single- and two-stage inverter-based grid-connected photovoltaic power plants with ride-through capability under grid faults," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1150–1159, Jul. 2015.

- [11] A. Camacho, M. Castilla, J. Miret, J. C. Vasquez, and E. Alarcon-Gallo, "Flexible voltage support control for three-phase distributed generation inverters under grid fault," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1429–1441, Apr. 2013.
- [12] J. Miret, A. Camacho, M. Castilla, L. G. de Vicuna, and J. Matas, "Control scheme with voltage support capability for distributed generation inverters under voltage sags," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 5252–5262, Nov. 2013.
- [13] M. Mirhosseini, J. Pou, and V. G. Agelidis, "Individual phase current control with the capability to avoid overvoltage in grid-connected photovoltaic power plants under unbalanced voltage sags," *IEEE Trans. Power Electron.*, vol. 30, no. 10, pp. 5346–5351, Oct. 2015.
- [14] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1292–1306, Sep. 2005.
- [15] E. Romero-Cadaval, G. Spagnuolo, L. G. Franquelo, C. A. Ramos-Paja, T. Suntio, and W. M. Xiao, "Grid-connected photovoltaic generation plants: Components and operation," *IEEE Ind. Electron. Mag.*, vol. 7, no. 3, pp. 6–20, Sep. 2013.
- [16] E. Romero-Cadaval, M. I. Milanés-Montero, E. Gonzalez-Romera, and F. Barrero-Gonzalez, "Power injection system for grid-connected photovoltaic generation systems based on two collaborative voltage source inverters," *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4389–4398, Nov. 2009.
- [17] P. P. Dash and M. Kazerani, "Dynamic modeling and performance analysis of a grid-connected current-source inverter-based photovoltaic system," *IEEE Trans. Sustainable Energy*, vol. 2, no. 4, pp. 443–450, Oct. 2011.
- [18] S. Busquets-Monge, J. Rocabert, P. Rodriguez, S. Alepuz, and J. Bordonau, "Multilevel diode-clamped converter for photovoltaic generators with independent voltage control of each solar array," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2713–2723, Jul. 2008.
- [19] E. Ozdemir, S. Ozdemir, and L. M. Tolbert, "Fundamental-frequency-modulated six-level diode-clamped multilevel inverter for three-phase stand-alone photovoltaic system," *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4407–4415, Nov. 2009.
- [20] P. Somani and D. J. Vaghela, "Design of HERIC configuration based grid connected single phase transformer less photovoltaic inverter," in *Proc. Intern. Conf. on Electrical, Electron., and Optimization Techniques (ICEEOT)*, Mar. 2016, pp. 892–896.
- [21] F. Bradaschia, M. C. Cavalcanti, P. E. P. Ferraz, F. A. S. Neves, E. C. dos Santos, and J. H. G. M. da Silva, "Modulation for three-phase transformerless Z-source inverter to reduce leakage currents in photovoltaic systems," *IEEE Trans. Ind. Electron.*, vol. 58, no. 12, pp. 5385–5395, Dec. 2011.

- [22] Y. Fang, X. Ma, and Y. Xing, "Study on PV micro-inverter with coupled inductors and double boost topology," in *Proc. IEEE Conf. on Ind. Electron. and Appl. (ICIEA)*, Jul. 2012, pp. 2054–2058.
- [23] T. Shimizu, K. Wada, and N. Nakamura, "A flyback-type single phase utility interactive inverter with low-frequency ripple current reduction on the dc input for an ac photovoltaic module system," in *Proc. IEEE 33rd Annual Power Electron. Specialists Conf.*, vol. 3, Jul. 2002, pp. 1483–1488.
- [24] S. Rivera, S. Kouro, B. Wu, J. I. Leon, J. Rodriguez, and L. G. Franquelo, "Cascaded H-bridge multilevel converter multistring topology for large scale photovoltaic systems," in *Proc. IEEE Intern. Symposium Ind. Electron.*, Jun. 2011, pp. 1837–1844.
- [25] S. Kouro, K. Asfaw, R. Goldman, R. Snow, B. Wu, and J. Rodriguez, "NPC multilevel multistring topology for large scale grid connected photovoltaic systems," in *Proc. 2nd Intern. Symposium on Power Electron. for Distributed Generation Systems*, Jun. 2010, pp. 400–405.
- [26] B. Yang, W. Li, Y. Zhao, and X. He, "Design and analysis of a grid-connected photovoltaic power system," *IEEE Trans. Power Electron.*, vol. 25, no. 4, pp. 992–1000, Apr. 2010.
- [27] N. A. Rahim, K. Chaniago, and J. Selvaraj, "Single-phase seven-level grid-connected inverter for photovoltaic system," *IEEE Trans. Ind. Electron.*, vol. 58, no. 6, pp. 2435–2443, Jun. 2011.
- [28] N. A. Rahim and J. Selvaraj, "Multistring five-level inverter with novel PWM control scheme for PV application," *IEEE Trans. Ind. Electron.*, vol. 57, no. 6, pp. 2111–2123, Jun. 2010.
- [29] G. Grandi, C. Rossi, D. Ostojic, and D. Casadei, "A new multilevel conversion structure for grid-connected PV applications," *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4416–4426, Nov. 2009.
- [30] C. Rodriguez and G. A. J. Amaratunga, "Long-lifetime power inverter for photovoltaic AC modules," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2593–2601, Jul. 2008.
- [31] M. Kasper, D. Bortis, and J. W. Kolar, "Classification and comparative evaluation of PV panel-integrated dc-dc converter concepts," *IEEE Trans. Power Electron.*, vol. 29, no. 5, pp. 2511–2526, May. 2014.
- [32] T. Orlowska-Kowalska, F. Blaabjerg, and J. Rodriguez, *Advanced and Intelligent Control in Power Electronics and Drives*. Springer, 2014.
- [33] L. Hassaine, E. Olias, J. Quintero, and V. Salas, "Overview of power inverter topologies and control structures for grid connected photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 796 – 807, 2014.
- [34] SMA, Sunny central- high tech solution for solar power stations. products category, brochure. [Online]. Available: <http://www.sma-america.com>

-
- [35] Y. Xue, L. Chang, S. B. Kjaer, J. Bordonau, and T. Shimizu, "Topologies of single-phase inverters for small distributed power generators: an overview," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1305–1314, Sep. 2004.
 - [36] W. Xiao, M. S. E. Moursi, O. Khan, and D. Infield, "Review of grid-tied converter topologies used in photovoltaic systems," *IET Renewable Power Generation*, vol. 10, pp. 1543–1551, Nov. 2016.
 - [37] H. M. Hasanien, "An adaptive control strategy for low voltage ride through capability enhancement of grid-connected photovoltaic power plants," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 3230–3237, Jul. 2016.
 - [38] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, "Power balance optimization of cascaded H-bridge multilevel converters for large-scale photovoltaic integration," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1108–1120, Feb. 2016.
 - [39] O. Khan, W. Xiao, and H. H. Zeineldin, "Gallium-nitride-based submodule integrated converters for high-efficiency distributed maximum power point tracking PV applications," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 966–975, Feb. 2016.
 - [40] S. Kouro, J. I. Leon, D. Vinnikov, and L. G. Franquelo, "Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology," *IEEE Ind. Electron. Mag.*, vol. 9, no. 1, pp. 47–61, Mar. 2015.
 - [41] B. Xiao, L. Hang, J. Mei, C. Riley, L. M. Tolbert, and B. Ozpineci, "Modular cascaded H-bridge multilevel PV inverter with distributed MPPT for grid-connected applications," *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1722–1731, Mar. 2015.
 - [42] A. D. Grasso, S. Pennisi, M. Ragusa, G. M. Tina, and C. Ventura, "Performance evaluation of a multistring photovoltaic module with distributed dc-dc converters," *IET Renewable Power Generation*, vol. 9, no. 8, pp. 935–942, Nov. 2015.
 - [43] H. R. Pinkymol, A. I. Maswood, O. H. P. Gabriel, and L. Ziyoun, "Analysis of 3-level inverter scheme with DC-link voltage balancing using LS-PWM and SVM techniques," in *Proc. IEEE Intern. Conf. Renewable Energy Research and Appl. (ICRERA)*, Oct. 2013, pp. 1036–1041.
 - [44] "IEEE recommended practice for interconnecting distributed resources with electric power systems," *IEEE Std 1547.6*.
 - [45] "IEEE recommended practice for utility interface of photovoltaic (PV) systems," *IEEE Std. 929*, 2000.
 - [46] C. D. Fuentes, C. A. Rojas, H. Renaudineau, S. Kouro, M. A. Perez, and M. Thierry, "Experimental validation of a single dc bus cascaded H-bridge multilevel inverter for multistring photovoltaic systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 2, pp. 930–934, Oct. 2016.

- [47] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, "Operation of cascaded H-bridge multilevel converters for large-scale photovoltaic power plants under bridge failures," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7228–7236, Nov. 2015.
- [48] P. Sochor and H. Akagi, "Theoretical comparison in energy-balancing capability between star- and delta-configured modular multilevel cascade inverters for utility-scale photovoltaic systems," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 1980–1992, Mar. 2016.
- [49] C. D. Townsend, Y. Yu, G. Konstantinou, and V. G. Agelidis, "Cascaded H-bridge multilevel PV topology for alleviation of per-phase power imbalances and reduction of second harmonic voltage ripple," *IEEE Trans. Power Electron.*, vol. 31, no. 8, pp. 5574–5586, Aug. 2016.
- [50] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, "Power balance of cascaded H-bridge multilevel converters for large-scale photovoltaic integration," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 292–303, Jan. 2016.
- [51] H. Akagi, S. Inoue, and T. Yoshii, "Control and performance of a transformerless cascade PWM STATCOM with star configuration," *IEEE Trans. Ind. Appl.*, vol. 43, no. 4, pp. 1041–1049, Jul. 2007.
- [52] W. Zhao, H. Choi, G. Konstantinou, M. Ciobotaru, and V. G. Agelidis, "Cascaded H-bridge multilevel converter for large-scale PV grid-integration with isolated DC-DC stage," in *Proc. 3rd IEEE Intern. Symposium Power Electron. for Distributed Generation Systems (PEDG)*, Jun. 2012, pp. 849–856.
- [53] B. Tamyurek and B. Krimmer, "An interleaved high-power flyback inverter for photovoltaic applications," *IEEE Trans. Power Electron.*, vol. 30, no. 6, pp. 3228–3241, Jun. 2015.
- [54] Z. Zhang, X. F. He, and Y. F. Liu, "An optimal control method for photovoltaic grid-tied-interleaved flyback microinverters to achieve high efficiency in wide load range," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 5074–5087, Nov. 2013.
- [55] G. Ortiz, M. G. Leibl, J. E. Huber, and J. W. Kolar, "Design and experimental testing of a resonant dc-dc converter for solid-state transformers," *IEEE Trans. Power Electron.*, vol. 32, no. 10, pp. 7534–7542, Oct. 2017.
- [56] R. Bosshard, U. Iruretagoyena, and J. W. Kolar, "Comprehensive evaluation of rectangular and double-d coil geometry for 50 kw/85 khz ipt system," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 4, pp. 1406–1415, Dec. 2016.
- [57] N. H. Baars, J. Everts, H. Huisman, J. L. Duarte, and E. A. Lomonova, "A 80-kw isolated dc-dc converter for railway applications," *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 6639–6647, Dec. 2015.
- [58] H. Cha, R. Ding, Q. Tang, and F. Z. Peng, "Design and development of high-power dc-dc converter for metro vehicle system," *IEEE Transactions on Industry Applications*, vol. 44, no. 6, pp. 1795–1804, Nov. 2008.

-
- [59] “Characteristics of the utility interface for photovoltaic (PV) systems,” *IEC Std. 61727*, 2002.
- [60] “Voltage characteristics of public distribution systems,” *EN Std. 50160*, 1999.
- [61] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*. John Wiley & Sons Ltd, 2011.
- [62] Y. Yang, F. Blaabjerg, and Z. Zou, “Benchmarking of grid fault modes in single-phase grid-connected photovoltaic systems,” *IEEE Trans. Ind. App.*, vol. 49, no. 5, pp. 2167–2176, Sep. 2013.
- [63] H. Kobayashi, “Fault ride through requirements and measures of distributed PV systems in Japan,” in *Proc. IEEE Power and Energy Society General Meeting*, Jul. 2012, pp. 1–6.
- [64] J. Selvaraj and N. A. Rahim, “Multilevel inverter for grid-connected PV system employing digital PI controller,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 1, pp. 149–158, Jan. 2009.
- [65] V. D. N. V. E. N. GmbH, “Transmission code 2007. network and system rules of the german transmission system operators,” 2007.
- [66] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” *IEEE Trans. on Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.
- [67] S. K. Chung, “Phase-locked loop for grid-connected three-phase power conversion systems,” *Proc. IEEE Electric Power App.*, vol. 147, no. 3, pp. 213–219, May. 2000.
- [68] D. Dong, B. Wen, D. Boroyevich, P. Mattavelli, and Y. Xue, “Analysis of phase-locked loop low-frequency stability in three-phase grid-connected power converters considering impedance interactions,” *IEEE Trans Ind. Electron.*, vol. 62, no. 1, pp. 310–321, Jan. 2015.
- [69] M. Malinowski, M. P. Kazmierkowski, and A. M. Trzynadlowski, “A comparative study of control techniques for PWM rectifiers in AC adjustable speed drives,” *IEEE Trans. Power Electron.*, vol. 18, no. 6, pp. 1390–1396, Nov. 2003.
- [70] S. Rivera, S. Kouro, B. Wu, S. Alepuz, M. Malinowski, P. Cortes, and J. Rodriguez, “Multilevel direct power control - a generalized approach for grid-tied multilevel converter applications,” *IEEE Trans. on Power Electron.*, vol. 29, no. 10, pp. 5592–5604, Oct. 2014.
- [71] E. Twining and D. G. Holmes, “Grid current regulation of a three-phase voltage source inverter with an LCL input filter,” *IEEE Trans. Power Electron.*, vol. 18, no. 3, pp. 888–895, May. 2003.
- [72] R. Teodorescu, F. Iov, and F. Blaabjerg, “Flexible development and test system for 11 kW wind turbine,” in *Proc. IEEE 34th Annual Power Electron. Specialist Conf.*, vol. 1, Jun. 2003, pp. 67–72.

- [73] R. Teodorescu, F. Blaabjerg, M. Liserre, and P. C. Loh, "Proportional-resonant controllers and filters for grid-connected voltage-source converters," *Proc. IEEE Electric Power App.*, vol. 153, no. 5, pp. 750–762, Sep. 2006.
- [74] M. Mirhosseini, J. Pou, B. Karanayil, and V. G. Agelidis, "Resonant versus conventional controllers in grid-connected photovoltaic power plants under unbalanced grid voltages," *IEEE Trans. Sustainable Energy*, vol. 7, no. 3, pp. 1124–1132, Mar. 2016.
- [75] C. Jain and B. Singh, "An adjustable DC link voltage based control of multifunctional grid interfaced solar PV system," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, no. 99, pp. 1–1, Nov. 2016.
- [76] F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Design and analysis of active power control strategies for distributed generation inverters under unbalanced grid faults," *IET Gener. Transm. Distrib.*, vol. 4, no. 8, pp. 905–916, Aug. 2010.
- [77] F. Nejabatkhah, Y. W. Li, and B. Wu, "Control strategies of three-phase distributed generation inverters for grid unbalanced voltage compensation," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 5228–5241, Jul. 2016.
- [78] F. Wang, J. L. Duarte, M. A. M. Hendrix, F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Design and analysis of active power control strategies for distributed generation inverters under unbalanced grid faults," *IET Gener. Transm. Distrib.*, vol. 4, no. 8, pp. 905–916, Aug. 2010.
- [79] P. Rodriguez, A. V. Timbus, R. Teodorescu, M. Liserre, and F. Blaabjerg, "Flexible active power control of distributed power generation systems during grid faults," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2583–2592, Oct. 2007.
- [80] F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Active and reactive power control for grid-interactive converters under unbalanced voltage dips," *IEEE Trans. Power Electron.*, vol. 26, no. 5, pp. 1511–1521, Mar. 2011.
- [81] J. L. Sosa, M. Castilla, J. Miret, J. Matas, and Y. A. Al-Turki, "Control strategy to maximize the power capability of pv three-phase inverters during voltage sags," *IEEE Trans. Power Electron.*, vol. 31, no. 4, pp. 3314–3323, Apr. 2016.
- [82] J. Miret, M. Castilla, A. Camacho, L. G. d. Vicuna, and J. Matas, "Control scheme for photovoltaic three-phase inverters to minimize peak currents during unbalanced grid-voltage sags," *IEEE Trans. Power Electron.*, vol. 27, no. 10, pp. 4262–4271, Oct. 2012.
- [83] A. Anurag, Y. Yang, and F. Blaabjerg, "Thermal performance and reliability analysis of single-phase pv inverters with reactive power injection outside feed-in operating hours," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 4, pp. 870–880, Dec. 2015.
- [84] R. Kabiri, D. G. Holmes, B. P. McGrath, and L. G. Meegahapola, "LV grid voltage regulation using transformer electronic tap changing, with PV inverter

- reactive power injection,” *IEEE J. of Emerging and Selected Topics in Power Electron.*, vol. 3, no. 4, pp. 1182–1192, Dec. 2015.
- [85] M. Castilla, J. Miret, A. Camacho, J. Matas, and L. G. de Vicuna, “Voltage support control strategies for static synchronous compensators under unbalanced voltage sags,” *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 808–820, Feb. 2014.
- [86] J. A. Suul, A. Luna, P. Rodriguez, and T. Undeland, “Virtual-flux-based voltage-sensor-less power control for unbalanced grid conditions,” *IEEE Trans. Power Electron.*, vol. 27, no. 9, pp. 4071–4087, Sep. 2012.
- [87] C. T. Lee, C. W. Hsu, and P. T. Cheng, “A low-voltage ride-through technique for grid-connected converters of distributed energy resources,” *IEEE Trans. Ind. Appl.*, vol. 47, no. 4, pp. 1821–1832, Jul. 2011.
- [88] J. I. Y. Ota, Y. Shibano, and H. Akagi, “Low-voltage-ride-through (LVRT) capability of a phase-shifted-PWM STATCOM using the modular multilevel cascade converter based on single-star bridge-cells (MMCC-SSBC),” in *Proc. IEEE Energy Conversion Congress and Exposition*, Sep. 2013, pp. 3062–3069.
- [89] J. I. Y. Ota, Y. Shibano, and H. Akagi, “A phase-shifted PWM D-STATCOM using a modular multilevel cascade converter (SSBC)-part II: Zero-voltage-ride-through capability,” *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 289–296, Jan. 2015.
- [90] Q. Song and W. Liu, “Control of a cascade STATCOM with star configuration under unbalanced conditions,” *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 45–58, Jan. 2009.
- [91] H. C. Chen, P. H. Wu, C. T. Lee, C. W. Wang, C. H. Yang, and P. T. Cheng, “Zero-sequence voltage injection for DC capacitor voltage balancing control of the star-connected cascaded H-bridge PWM converter under unbalanced grid,” *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4584–4594, Nov. 2015.
- [92] E. Behrouzian and M. Bongiorno, “Investigation of negative-sequence injection capability of cascaded H-bridge converters in star and delta configuration,” *IEEE Trans. Power Electron.*, vol. 32, no. 2, pp. 1675–1683, Feb. 2017.
- [93] S. Sajadian and R. Ahmadi, “Model predictive-based maximum power point tracking for grid-tied photovoltaic applications using a Z-source inverter,” *IEEE Trans. Power Electron.*, vol. 31, no. 11, pp. 7611–7620, Nov. 2016.
- [94] Y. T. Jeon, H. Lee, K. A. Kim, and J. H. Park, “Least power point tracking method for photovoltaic differential power processing systems,” *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 1941–1951, Mar. 2017.
- [95] S. M. R. Tousi, M. H. Moradi, N. S. Basir, and M. Nemati, “A function-based maximum power point tracking method for photovoltaic systems,” *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2120–2128, Mar. 2016.

-
- [96] J. H. Teng, W. H. Huang, T. A. Hsu, and C. Y. Wang, "Novel and fast maximum power point tracking for photovoltaic generation," *IEEE Trans. Power Electron.*, no. 99, Apr. 2016.
- [97] M. A. Ghasemi, H. M. Forushani, and M. Parniani, "Partial shading detection and smooth maximum power point tracking of PV arrays under PSC," *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6281–6292, Sep. 2016.
- [98] H. Renaudineau, F. Donatantonio, J. Fontchastagner, G. Petrone, G. Spagnuolo, J. P. Martin, and S. Pierfederici, "A PSO-based global MPPT technique for distributed PV power generation," *IEEE Trans. Power Electron.*, vol. 62, no. 2, pp. 1047–1058, Feb. 2015.
- [99] M. Ricco, P. Manganiello, E. Monmasson, G. Petrone, and G. Spagnuolo, "FPGA-based implementation of dual kalman filter for PV MPPT applications," *IEEE Trans. Ind. Informat.*, vol. PP, no. 99, pp. 1–1, Jul. 2015.
- [100] P. Manganiello, M. Ricco, E. Monmasson, G. Petrone, and G. Spagnuolo, "On-line optimization of the P&O MPPT method by means of the system identification," in *Proc. IEEE Industrial Electronics Conference (IECON)*, Nov. 2013, pp. 1786–1791.
- [101] M. Ricco, P. Manganiello, G. Petrone, E. Monmasson, and G. Spagnuolo, "FPGA-based implementation of an adaptive P&O MPPT controller for PV applications," in *Proc. IEEE 23rd Int. Symposium on Industrial Electronics (ISIE)*, Jun. 2014, pp. 1876–1881.
- [102] K. S. Tey and S. Mekhilef, "Modified incremental conductance algorithm for photovoltaic system under partial shading conditions and load variation," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5384–5392, Oct. 2014.
- [103] A. Reinhardt, D. Egarter, G. Konstantinou, and D. Christin, "Worried about privacy? let your PV converter cover your electricity consumption fingerprints," in *Proc. IEEE Inter. Conf. on Smart Grid Communications (Smart-GridComm)*, Nov. 2015, pp. 25–30.
- [104] D. Sera, L. Mathe, T. Kerekes, S. V. Spataru, and R. Teodorescu, "On the perturb-and-observe and incremental conductance MPPT methods for PV systems," *IEEE J. Photovolt.*, vol. 3, no. 3, pp. 1070–1078, Jul. 2013.
- [105] Y. Yang, H. Wang, F. Blaabjerg, and T. Kerekes, "A hybrid power control concept for PV inverters with reduced thermal loading," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6271–6275, Dec. 2014.
- [106] Y. Yang, F. Blaabjerg, and H. Wang, "Constant power generation of photovoltaic systems considering the distributed grid capacity," in *Proc. IEEE Applied Power Electronics Conf. and Exposition (APEC)*, Mar. 2014, pp. 379–385.
- [107] A. Urtasun, P. Sanchis, and L. Marroyo, "Limiting the power generated by a photovoltaic system," in *10th Int. Multi-Conferences on Systems, Signals Devices (SSD13)*, Mar. 2013, pp. 1–6.

- [108] C. Rosa, D. Vinikov, E. Romero-Cadaval, V. Pires, and J. Martins, "Low-power home PV systems with MPPT and PC control modes," in *Proc. Int. Conf.-Workshop Compatibility And Power Electronics*, Jun. 2013, pp. 58–62.
- [109] A. Hoke and D. Maksimovic, "Active power control of photovoltaic power systems," in *Proc. IEEE 1st Conf. on Technologies for Sustainability (SusTech)*, Aug. 2013, pp. 70–77.
- [110] R. G. Wandhare and V. Agarwal, "Precise active and reactive power control of the PV-DGS integrated with weak grid to increase PV penetration," in *Proc. IEEE 40th Photovoltaic Specialist Conf. (PVSC)*, Jun. 2014, pp. 3150–3155.
- [111] C. Y. Tang, Y. T. Chen, and Y. M. Chen, "PV power system with multi-mode operation and low-voltage ride-through capability," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7524–7533, Dec. 2015.
- [112] A. Sangwongwanich, Y. Yang, F. Blaabjerg, and H. Wang, "Benchmarking of constant power generation strategies for single-phase grid-connected photovoltaic systems," in *Proc. IEEE Applied Power Electronics Conf. and Exposition (APEC)*, Mar. 2016, pp. 370–377.
- [113] A. Sangwongwanich, Y. Yang, and F. Blaabjerg, "High-performance constant power generation in grid-connected pv systems," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 1822–1825, Mar. 2016.
- [114] A. Sangwongwanich, Y. Yang, and F. Blaabjerg, "A sensorless power reserve control strategy for two-stage grid-connected PV systems," *IEEE Trans. Power Electron.*, no. 99, pp. 1–1, Jan. 2017.
- [115] J. Gao, X. Wu, S. Huang, W. Zhang, and L. Xiao, "Torque ripple minimisation of permanent magnet synchronous motor using a new proportional resonant controller," *IET Power Electronics*, vol. 10, no. 2, pp. 208–214, 2017.
- [116] R. Teodorescu, F. Blaabjerg, M. Liserre, and P. C. Loh, "Proportional-resonant controllers and filters for grid-connected voltage-source converters," *Proc. IEEE Electric Power Applications*, vol. 153, no. 5, pp. 750–762, Sep. 2006.
- [117] A. Kuperman, "Proportional-resonant current controllers design based on desired transient performance," *IEEE Trans. Power Electron.*, vol. 30, no. 10, pp. 5341–5345, Oct. 2015.
- [118] T. Ye, N. Dai, C. S. Lam, M. C. Wong, and J. M. Guerrero, "Analysis, design, and implementation of a quasi-proportional-resonant controller for a multi-functional capacitive-coupling grid-connected inverter," *IEEE Trans. Industry Appl.*, vol. 52, no. 5, pp. 4269–4280, Sep. 2016.
- [119] Y. Yang and F. Blaabjerg, "Low-voltage ride-through capability of a single-stage single-phase photovoltaic system connected to the low voltage grid," *Inter. Journal of Photoenergy*, pp. 1–9, Dec. 2013.
- [120] H. D. Tafti, B. Vahidi, R. Naghizadeh, and S. Hosseini, "Power quality disturbance classification using a statistical and wavelet-based hidden markov model

- with dempster-shafer algorithm,” *Inter. Journal of Electrical Power and Energy Systems*, no. 47, pp. 368–377, Dec. 2013.
- [121] M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, “A new single-phase PLL structure based on second order generalized integrator,” in *Proc. IEEE 37th Power Electron. Specialists Conf.*, Jun. 2006, pp. 1–6.
- [122] M. Mirhosseini, J. Pou, V. G. Agelidis, E. Robles, and S. Ceballos, “A three-phase frequency-adaptive phase-locked loop for independent single-phase operation,” *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6255–6259, Dec. 2014.
- [123] E. Tomaszewski and J. Jiangy, “An anti-windup scheme for proportional resonant controllers with tuneable phase-shift in voltage source converters,” in *Proc. IEEE Power and Energy Society General Meeting (PESGM)*, Jul. 2016, pp. 1–5.
- [124] D. Sera, L. Mathe, T. Kerekes, S. V. Spataru, and R. Teodorescu, “On the perturb-and-observe and incremental conductance MPPT methods for PV systems,” *IEEE J. Photovolt.*, vol. 3, no. 3, pp. 1070–1078, Jul. 2013.
- [125] Solar panel Sharp NU-U235F1 datasheet. [Online]. Available: <http://www.sharp-solar.com/>
- [126] A. Yazdani, A. R. D. Fazio, H. Ghoddami, M. Russo, M. Kazerani, J. Jatskevich, K. Strunz, S. Leva, and J. A. Martinez, “Modeling guidelines and a benchmark for power system simulation studies of three-phase single-stage photovoltaic systems,” *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 1247–1264, Apr. 2011.
- [127] S. Alepuz, S. Busquets-Monge, J. Bordonau, J. A. Martinez-Velasco, C. A. Silva, J. Pontt, and J. Rodriguez, “Control strategies based on symmetrical components for grid-connected converters under voltage dips,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 6, pp. 2162–2173, Jun. 2009.
- [128] M. Castilla, J. Miret, A. Camacho, L. G. de Vicuna, and J. Matas, “Modeling and design of voltage support control schemes for three-phase inverters operating under unbalanced grid conditions,” *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 6139–6150, Nov. 2014.
- [129] F. Nejabatkhah, Y. W. Li, and B. Wu, “Control strategies of three-phase distributed generation inverters for grid unbalanced voltage compensation,” *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 5228–5241, Jul. 2016.
- [130] E. Robles, S. Ceballos, J. Pou, J. L. Martin, J. Zaragoza, and P. Ibanez, “Variable-frequency grid-sequence detector based on a quasi-ideal low-pass filter stage and a phase-locked loop,” *IEEE Trans. Power Electron.*, vol. 25, no. 10, pp. 2552–2563, Oct. 2010.
- [131] R. Kabiri, D. G. Holmes, and B. P. McGrath, “Control of active and reactive power ripple to mitigate unbalanced grid voltages,” *IEEE Trans. Ind. Appl.*, vol. 52, no. 2, pp. 1660–1668, Mar. 2016.

-
- [132] R. P. Aguilera, P. Acuna, Y. Yu, G. Konstantinou, C. D. Townsend, B. Wu, and V. G. Agelidis, "Predictive control of cascaded H-bridge converters under unbalanced power generation," *IEEE Trans. Power Electron.*, vol. 64, no. 1, pp. 4–13, Jan. 2017.
- [133] J. H. Teng, W. H. Huang, T. A. Hsu, and C. Y. Wang, "Novel and fast maximum power point tracking for photovoltaic generation," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 4955–4966, Aug. 2016.
- [134] P. Manganiello, M. Ricco, G. Petrone, E. Monmasson, and G. Spagnuolo, "Optimization of perturbative PV MPPT methods through online system identification," *IEEE Trans. Ind. Electron.*, vol. 61, no. 12, pp. 6812–6821, Dec. 2014.
- [135] Y. Jiang, J. A. A. Qahouq, and T. A. Haskew, "Adaptive step size with adaptive-perturbation-frequency digital MPPT controller for a single-sensor photovoltaic solar system," *IEEE Trans. Power Electron.*, vol. 28, no. 7, pp. 3195–3205, Jul. 2013.
- [136] C. C. Hua, W. T. Chen, and Y. H. Fang, "A hybrid MPPT with adaptive step-size based on single sensor for photovoltaic systems," in *Proc. Intern. Conf. Information Science, Electron. and Electrical Engineering*, vol. 1, Apr. 2014, pp. 441–445.
- [137] A. Ramyar, H. Iman-Eini, and S. Farhangi, "Global maximum power point tracking method for photovoltaic arrays under partial shading conditions," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 2855–2864, Apr. 2017.
- [138] J. P. Ram and N. Rajasekar, "A novel flower pollination based global maximum power point method for solar maximum power point tracking," *IEEE Trans. Power Electron.*, vol. 32, no. 11, pp. 8486–8499, Nov. 2017.
- [139] C. Manickam, G. R. Raman, G. P. Raman, S. I. Ganesan, and C. Nagamani, "A hybrid algorithm for tracking of gmpp based on p o and pso with reduced power oscillation in string inverters," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6097–6106, Oct. 2016.
- [140] S. Lyden and M. E. Haque, "A simulated annealing global maximum power point tracking approach for pv modules under partial shading conditions," *IEEE Trans. Power Electron.*, vol. 31, no. 6, pp. 4171–4181, Jun. 2016.
- [141] S. Rajendran and H. Srinivasan, "Simplified accelerated particle swarm optimisation algorithm for efficient maximum power point tracking in partially shaded photovoltaic systems," *IET Renewable Power Generation*, vol. 10, no. 9, pp. 1340–1347, Nov. 2016.
- [142] B. Subudhi and R. Pradhan, "A comparative study on maximum power point tracking techniques for photovoltaic power systems," *IEEE Trans. Sustainable Energy*, vol. 4, no. 1, pp. 89–98, Jan. 2013.
- [143] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of perturb and observe mppt algorithm implementation techniques for pv pumping applications," *IEEE Trans. Sustainable Energy*, vol. 3, no. 1, pp. 21–33, Jan. 2012.

- [144] N. Femia, G. Lisi, G. Petrone, G. Spagnuolo, and M. Vitelli, "Distributed maximum power point tracking of photovoltaic arrays: Novel approach and system analysis," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2610–2621, Jul. 2008.
- [145] C. D. Townsend, T. J. Summers, and R. E. Betz, "Control and modulation scheme for a cascaded h-bridge multi-level converter in large scale photovoltaic systems," in *Proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2012, pp. 3707–3714.
- [146] Y. Yu, G. Konstantinou, C. D. Townsend, R. P. Aguilera, and V. G. Agelidis, "Delta-connected cascaded H-bridge multilevel converters for large-scale PV grid integration," *IEEE Trans. Ind. Electron.*, 2016.
- [147] Y. Yu, G. Konstantinou, C. D. Townsend, R. P. Aguilera, B. Hredzak, and V. G. Agelidis, "Delta-connected cascaded H-bridge multilevel photovoltaic converters," in *Proc. 41st Annual Conf. of the IEEE Ind. Electron. Society (IECON)*, Nov. 2015, pp. 2229–2234.
- [148] X. Li, Z. Deng, Z. Chen, and Q. Fei, "Analysis and simplification of three-dimensional space vector PWM for three-phase four-leg inverters," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 450–464, Feb. 2011.
- [149] L. G. Franquelo, M. A. M. Prats, R. C. Portillo, J. I. L. Galvan, M. A. Perales, J. M. Carrasco, E. G. Diez, and J. L. M. Jimenez, "Three-dimensional space-vector modulation algorithm for four-leg multilevel converters using abc coordinates," *IEEE Trans. Ind. Electron.*, vol. 53, no. 2, pp. 458–466, Apr. 2006.
- [150] O. Lopez, J. Alvarez, F. D. Freijedo, A. G. Yepes, J. Malvar, P. Fernandez-Comesana, J. Doval-Gandoy, A. Nogueiras, A. Lago, and C. M. Penalver, "Multilevel multiphase space vector PWM algorithm with switching state redundancy applied to three-phase four-leg converters," in *Proc. IEEE 36th Annual Conf. on IEEE Ind. Electron. Society*, Nov. 2010, pp. 568–575.
- [151] H. Lei, L. Fei, J. Xiong, X. Lin, and Y. Kang, "Research on paralleled three-phase four-leg voltage source inverters based on dual-loop control in alpha beta coordinate," in *Proc. 8th Intern. Conf. on Power Electron. ECCE Asia*, May. 2011, pp. 2912–2919.
- [152] J. I. Leon, G. Guidi, L. G. Franquelo, T. Undeland, and S. Vazquez, "Simple control algorithm to balance the dc-link voltage in multilevel four-leg four-wire diode clamped converters," in *Proc. Intern. Power Electron. and Motion Control Conf.*, Aug. 2006, pp. 228–233.
- [153] E. T. Flagship, *Solar intermittency: Australia's clean energy challenge*. Global CCS Institute, 2013.

END