

**Z-SOURCE INVERTER (ZSI) BASED
RECONFIGURABLE ARCHITECTURE FOR SOLAR
PHOTO-VOLTAIC (PV) MICROGRID**

Karavita Arachchige Himali Lakshika

178077T

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

April 2021

**Z-SOURCE INVERTER (ZSI) BASED
RECONFIGURABLE ARCHITECTURE FOR SOLAR
PHOTO-VOLTAIC (PV) MICROGRID**

Karavita Arachchige Himali Lakshika

178077T

Thesis submitted in fulfilment of the requirements for the degree of Master
of Science by Research

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

April 2021

DECLARATION

I declare that this is my work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or part in print, electronic or another medium. I retain the right to use this content in whole or part in future works (such as articles or books).

UOM Verified Signature

Signature:

Date: 2021.04.06

The above candidate has carried out research for the Master's thesis under my supervision.

Signature of the supervisor:

Date

ABSTRACT

The principal aim of this research is to identify and use the advantages of Z-source inverter and to develop a reconfigurable architecture for residential microgrid. The researcher has described the summary of the studies on Z-source inverter and reconfigurable systems. The distinctive feature of the proposed, reconfigurable, residential microgrid is the capability to reconfigure microgrid components to operate as a current source (current controlling mode) and a voltage source (voltage-frequency controlling mode) and a static synchronous compensator (STATCOM) (reactive power controlling mode) while replacing the traditional solar inverter from latest Z-source inverter. Where grid-connected, solar photovoltaic customers get uninterrupted power supply from their solar system even at a grid fault, and utility grids can use the same assets to improve the power quality and use their distribution network when it is idle at night. Then, it improves the utilization factor of solar photovoltaic system, power quality at the point of common coupling, and reliable power supply to the loads while increasing controllability of residential microgrid and taking part grid operations with utility grid request. Both the customer and the grid owner could get benefits. The proposed architecture is developed in MATLAB/Simulink platform and results are discussed to prove the proposed architecture.

Index Terms—*Reconfigurable architecture; Solar photovoltaic; Microgrids; Z-source inverter, STATCOM, Power quality, Battery storage system*

ACKNOWLEDGMENTS

Foremost, I am deeply indebted to my supervisor Professor K.T.M.U. Hemapala and co-supervisor Dr. W.D. Prasad of the Department of Electrical Engineering, University of Moratuwa for their constant guidance, encouragement and support from the beginning to the end. It is my pleasure to acknowledge all the other academic staff members of the Department of Electrical Engineering of the University of Moratuwa for their valuable suggestions, comments and assistance which were beneficial to achieve the project objectives. I am grateful to the Department of Science and Technology (DST), Government of India and Ministry of Science, Technology and Research (MSTR), Government of Sri Lanka for the financial grants under Indo-Sri Lanka Joint Research program Grant (MSTR/TR/AGR/3/02/13) scheme and the Faculty of Graduate Studies for the given administrative support to conduct the research. I specially thank to our research team in university of Moratuwa Eng. Gayashan, Eng. Ranaweera, Eng. Lemasha, Eng. Bhagya, Eng. Sisitha, Eng. Malith, Eng. Kaushali, Eng. Yomal and all motivating and helping me to complete this successfully. I thank to the technical officers and other support staff for the assistance they have given to perform laboratory experiments. Moreover, I would like to extend my gratitude to my family for their encouragement, understanding and patience throughout my academic pursuit. Finally, I am grateful to my colleagues and friends for showing interest in my work and giving constructive ideas towards the success of the research.

TABLE OF CONTENTS

DECLARATION.....	i
ABSTRACT	ii
ACKNOWLEDGMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF TABLES	x
LIST OF ABBREVIATIONS	xi
LIST OF APPENDICES	xiii
1 INTRODUCTION.....	1
1.1 Problem identification	1
1.1.1 Reverse power flow	2
1.1.2 Power quality problems.....	3
1.1.3 Power availability and reliability	5
1.1.4 System capacity.....	5
1.1.5 Power losses	6
1.2 Objectives and specific contribution	9
1.3 Methodology.....	10
1.4 Thesis outline.....	10
2 LITERATURE REVIEW.....	12
2.1 Reconfigurable architecture.....	12
2.2 SPV systems	12
2.3 SPV generator.....	14
2.4 Power conditioning unit.....	16
2.4.1 Types of solar inverters	17
2.5 Energy storage systems.....	22
2.6 PV microgrid	23
2.6.1 PV microgrid architecture	24
2.7 Reconfigurable SPV based power systems (RSPVS).....	27
2.7.1 The reconfigurable operation for SPV array	29
2.7.2 The reconfigurable operation for power conditioning unit for a SPVS	31
2.7.3 Reconfigurable inductor	38
2.7.4 Reconfigurable microgrids	38
2.7.5 Reconfigurable control architecture	40

2.7.6	Reconfigurable distribution networks	41
2.7.7	Summary of available reconfigurable solar PV systems.....	43
2.8	MPPT control.....	49
2.9	ZSI controller.....	49
2.10	Importance of reactive power controlling capability	51
2.10.1	STATCOM.....	52
2.10.2	Working Principle of STATCOM:.....	53
2.11	Islanding detection	54
2.12	Islanded mode control methods	56
2.12.1	Master-slave control	56
2.12.2	Hierarchical control.....	57
2.12.3	Multi-agent system control.....	57
3	PROPOSED ARCHITECTURE	58
3.1	Introduction.....	58
3.2	Functions.....	59
3.3	Benefits from this architecture.....	65
4	DESIGN AND MODELLING OF PROPOSED ZSI BASED RECONFIGURABLE, PV MG	66
4.1	Solar panels.....	66
4.1.1	I-V characteristics.....	67
4.1.2	P-V characteristics.....	68
4.2	Z source inverter	71
4.2.1	Z-network component design.....	74
4.2.2	ZSI as STATCOM.....	76
4.3	Battery storage system.....	78
4.4	DC-DC converter.....	79
4.5	Three phase line filter	81
4.6	Residential microgrid loads	82
5	CONTROLLER DEVELOPMENT	83
5.1	Home MG controller.....	83
5.1.1	Islanding detection and synchronization	84
5.2	Battery controller	85
5.3	ZSI controller.....	86
5.3.1	Current controlling mode	86
5.3.2	Closed loop feedback controller.....	89

5.4	Reactive power control mode	92
5.5	V-F control mode.....	94
6	SIMULATION RESULTS AND DISCUSSION.....	96
6.1	Reconfiguration algorithm.....	96
6.2	Current controlling mode.....	98
6.3	Reactive power controlling mode.....	100
6.4	V-F controlling mode	102
6.5	Future work.....	104
7	CONCLUSION	105
7.1	Limitations of this architecture	107
	REFERENCES	108
	Appendix A: MATLAB/Simulink Code for Reconfiguration Algorithm.....	115

LIST OF TABLES

Figure 1.1 Concept of prosumer.....	1
Figure 1.2 Problems with grid connected SPV systems.....	2
Figure 2.1 Definition of reconfiguration	12
Figure 2.2 SPV system architectures (a) Solar farm (b) Rooftop SPV	13
Figure 2.3 Structure of (a) conventional utility grid (b) with the connection of different types of SPV	14
Figure 2.4 Electrical equivalent 5 parameter model based on one diode theory (Ahmed Saidi, 2017)	15
Figure 2.5 I-V Characteristics of solar panel for different solar irradiation..	15
Figure 2.6 SPV architectures (a) Central inverter (b) String inverter (c) Micro/Modular inverter (d) Multi-string inverter	16
Figure 2.7 Structure of voltage source inverter	17
Figure 2.8 Structure of current source inverter	18
Figure 2.9 Structure of Z source inverter	18
Figure 2.10 Relationship of PV microgrid with other SPV	24
Figure 2.11 Different PV microgrid structures according to (Energy, 2015)	25
Figure 2.12 PV microgrid structures according to AC/DC systems (a) AC microgrid (b) DC microgrid (c) Hybrid microgrid.....	26
Figure 2.13 Different microgrid control architectures (Sushil S. Thale, 2015)	27
Figure 2.14 Summary of the function of reconfigurable SPV systems.....	28
Figure 2.15 Summary of the application of reconfigurable SPV systems	29
Figure 2.16 Reconfigurable array basic structures (Damiano La Manna, 2014) (a) Series (b) Parallel (c)Series-Parallel (d) Honeycomb (e) Total-cross-tied (f) Bridge-linked	30
Figure 2.17 Reconfigurable array basic structure (Abdalla, 2013)	30
Figure 2.18 Modes of operation of RSC (Hongrae Kim, 2013).....	32
Figure 2.19 Structure of RSC (Hongrae Kim, 2013)	32
Figure 2.20 Modes of operation of RSC (R. Rizzo, 2015).....	35
Figure 2.21 Structure of single-phase reconfigurable SPV system (Ming-tang Chen, 2016)	35
Figure 2.22 Structure of qZSSRC (Andrii Chub, 2017).....	37

Figure 2.23 Characteristics of qZSSRC (Andrii Chub, 2017)	37
Figure 2.24 Structure of boost converter with reconfigurable inductor (Chapman., 2007).....	38
Figure 2.25 Structure of reconfigurable microgrid (Singh, 2017)	39
Figure 2.26 Proposed reconfigurable control architecture (Sushil S. Thale, 2015).....	41
Figure 2.27 Reconfigurable microgrids (Phillip Oliver Kriett, 2012).....	42
Figure 2.28 Direct DC link control structure of ZSI.	50
Figure 2.29 Indirect DC link control method of ZSI.....	50
Figure 2.30: Active power curtailment (Eiríksson, 2017).....	51
Figure 2.31: Operation of Cos ϕ (P) control (Eiríksson, 2017).	52
Figure 2.32: Operation of Cos ϕ (U) control (Eiríksson, 2017).....	52
Figure 2.33: Operation of Q (U) control (Eiríksson, 2017).....	52
Figure 2.34 Basic structure of MG and utility grid to understand STATCOM working- principle	53
Figure 2.35 Voltage current characteristics of STATCOM	54
Figure 3.1 Proposed microgrid power architecture.	58
Figure 3.2 Control architecture of proposed residential microgrid	59
Figure 3.3 States of controlling of SPV system.	59
Figure 3.4 Algorithm for reconfiguration.....	60
Figure 3.5 Configuration and power flow at the mode of V-F control mode	61
Figure 3.6 Configuration and power flow at the mode of reactive power control mode.....	62
Figure 3.7 Configuration and power flow at the mode of current control mode	63
Figure 3.8 Voltage limits of reconfiguration.....	63
Figure 3.9 Frequency limits of reconfiguration.....	64
Figure 4.1 Five parameter model of SPV cell	66
Figure 4.2 PV array represent in 5 parameter model	67
Figure 4.3 MATLAB/Simulink model of PV array	69
Figure 4.4 MATLAB/Simulink model to generate I_{pv} considering PV array temperature and irradiance	69
Figure 4.5 I-V Characteristics of PV array.....	70

Figure 4.6 P-V Characteristics of PV array.....	70
Figure 4.7 Z Source inverter circuit (a) during non-shoot through period, (b) non shoot through period.....	71
Figure 4.8 Capability of operating in STATCOM mode through equivalent circuits of solar conventional VSC and ZSI.....	76
Figure 4.9 The proposed battery backup arrangement	78
Figure 4.10 Half bridge buck-boost converter	80
Figure 5.1 Inter connection in between PV MG and utility grid.....	83
Figure 5.2 Controller of buck-boost DC-DC converter	85
Figure 5.3 Z source inverter controller and battery controller for current control mode.....	86
Figure 5.4 IV PV characteristics of solar array near MPP	87
Figure 5.5 INC MPPT algorithm.....	88
Figure 5.6 MATLAB/Simulation control block to generate $V_{abc\text{ref}}$	91
Figure 5.7 Z source inverter controller for voltage/reactive power control mode	92
Figure 5.8 Z source inverter controller and battery controller for V-F control mode	95
Figure 6.1 Simulation results of reconfiguration algorithm	97
Figure 6.2 MATLAB/Simulink model for current controlling mode	98
Figure 6.3 Simulation results of current control mode.....	99
Figure 6.4 MATLAB/Simulink model for Reactive power/ voltage controlling mode.....	100
Figure 6.5 Simulation results of reactive power / voltage control mode	101
Figure 6.6 Simulation results of reactive power / voltage control mode - PCC voltage	101
Figure 6.7 MATLAB/Simulink model of V-F control mode.....	102
Figure 6.8 Simulation results of V-F control mode.....	103

LIST OF TABLES

Table 1.1 Parameters considered for validation.	10
Table 2.1 Comparison of inverters (Central inverter, String inverter, Multi-MPPT inverter Module-integrated inverter).....	17
Table 2.2 Limitations and advantages of VSI, CSI, and ZSI	19
Table 2.3 Control methods for DER units based on different operating conditions	20
Table 2.4 Features of SPV microgrid over a solar home system	24
Table 2.5 Summary of available reconfigurable solar PV systems.....	45
Table 2.6 Summary of objectives applied reconfigurability in SPV based power system.....	48
Table 3.1 IEEE standard 1547: Operational limits.....	63
Table 3.2 The state of MG components in each mode of operation	64
Table 5.1 SLS 1547:2016 (IEC 61727:2004): Response to abnormal voltages	84
Table 6.1 Reconfiguration algorithm input data and outcomes	96
Table 6.2 Variations of microgrid components and relevant outcomes – current control mode	98
Table 6.3 Variations of microgrid components and relevant outcomes – V-F control mode.....	102
Table 7.1 Evaluation of research according to research objectives and outcomes.....	106

LIST OF ABBREVIATIONS

Abbreviation	Description
AR	Array Reconfiguration
BESS	Battery Energy Storage System
BL	Bridge-Linked
CSI	Current Source Inverters
DG	Distributed Generations
DN	Distribution Network
DOD	Depth of Discharge
DSO	Distribution System Operators
EV	Electrical Vehicle
FACTS	Flexible AC Transmission System
GWO	Grey Wolf Optimization
HC	Hill Climbing
INC	Incremental Conductance
LTC	Load Tap Changers
LV	Low Voltage
LVR	Line Voltage Regulators
MAS	Multi-agent system
MCBC	Maximum constant boost control
MG	Microgrid
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
MSVMBC	Modified space vector modulation boost
MV	Medium Voltage
P&O	Perturb and Observe
PCC	Point of Common Coupling
PSO	Partial Swarm Optimization
PWM	Pulse Width Modulation
qZSSRC	Quasi-Z-Source Series Resonant DC/DC Converter
RMS	Root Mean Square
RSC	Reconfigurable Solar Converter
SPV	Solar Photovoltaic

Abbreviation	Description
SB	State Based
SBC	Simple boost control
SCC	Short Circuit Current
SIDO	Single-Input Dual-Output
SPWM	Sine PWM
SP	Series-Parallel
ST	Shoot-Through
STATCOM	Static Synchronous Compensator
STC	Standard Test Condition
SVPWM	Space-vector PWM
TCT	Total Cross-Tied
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
TSI	Two-Stage Inverter
UC	Ultra-Capacitor
UOF	Under/Over Frequency
UOV	Under/Over Voltage
VDR	Voltage-Doubler Rectifier
VFOC	Virtual Flux-Oriented Control
VOC	Voltage-Oriented Control
VSI	Voltage Source Inverter
ZSI	Z-Source Inverter
MBC	Maximum boost control

LIST OF APPENDICES

Appendix	Description	Page
Appendix - A	MATLAB/Simulink Code for Reconfiguration Algorithm	114