

**DESIGN AND DEVELOPMENT OF VOLTAGE AND FREQUENCY
CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN
ISOLATED SMALL HYDRO POWER GENERATION**

by

V. RAJAGOPAL
Department of Electrical Engineering

Submitted

In fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
MAY 2011**

CERTIFICATE

This is to certify that the thesis entitled, “Design and Development of Voltage and Frequency Controllers for Asynchronous Generators in Isolated Small Hydro Power Generation”, being submitted by Mr. V. Rajagopal for the award of the degree of Doctor of Philosophy is a record of bonafide research work carried out by him in the Department of Electrical Engineering of the Indian Institute of Technology, Delhi.

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

Dated:

(Prof. Bhim Singh)

Electrical Engineering Department
Indian Institute of Technology, Delhi
Hauz Khas, New Delhi- 110 016, India
Email:-bhimsinghr@gmail.com
bhimsinghiitd@gmail.com

ACKNOWLEDGEMENTS

I do express my deepest gratitude and indebtedness to Prof. Bhim Singh for providing me a life-time opportunity to do the Ph.D work under his supervision. Working with him has opened a new horizon of state-of-the-art knowledge on voltage and frequency controllers for off-grid asynchronous generators. Deep insight of Prof. Singh about the subject, ample research ideas, vast resourcefulness in electrical engineering and versatile exposure in international forum and his strong perception has immensely helped me to do the research work. His continuous monitoring, valuable guidance and input, has been always a source of inspiration and courage which are the driving forces to complete my work. It is a life time experience which I am to cherish always.

My heartfelt thanks and deep gratitude to Prof. T. S. Bhatti, Prof. G. Bhuvaneswari and Dr. B. K. Panigrahi, all SRC members who have equally given me valuable guidance and advice to improve quality of my work. I am overwhelmed with their immeasurable valuable input received during my research work. I do convey my sincere gratitude and respect to Prof. B. P. Singh and Prof. M. Veerachary who have taught me all the relevant course works in IITD and helped a great deal to enrich my knowledge.

I am grateful to the staffs of PG section, Central library, Electrical Engineering Department Library for their valuable co-operation. I am extremely grateful particular to Shri Gurcharan Singh, Shri. Srichand, Shri. Puran Singh and other staffs of Electrical Engineering's Drive and Simulation Lab., IIT Delhi for providing me immense facilities and assistance to carry out my research work. I am also thankful to Mr. Mohit Mahajan of FITT for processing my patents in time with valuable suggestions.

I would like to earnestly extend my sincere thanks to Sh. D. Madhan Mohan, Dr. Gaurav Kasal, Dr. P. Jayaprakash, Dr. Sanjeev Singh, Sh. Ashish Srivastava and Sh. Sunil Kumar who have provided me initial start up in my area of research. I am really to appreciate the

towering efforts, relentless supports and utmost sincerity provided by Sh. Shailendra Sharma, research scholar in the journey to complete my hardware implementation work. It is an exemplary and I am to always cherish his valuable contribution.

Sh. Ram Nivas, Sh. Sabharaj Arya, Sh. M. Rajesh, Sh. M. Sandeep, Sh. N. K. Swami Naidu, Sh. Arun Kumar Verma, Sh. Jeevanand for their valuable assistances and co-operation. I am also grateful to those who have directly or indirectly helped me to complete my thesis work.

My deepest love, appreciation and indebtedness goes to my wife Smt. Rama Devi, Srivarsha (daughter) and Rohan (son) for their wholehearted support, encouragement and valuable time sharing. If I get any success today for the research work, the entire credit and honour should go to my family. It will remain unacknowledged if I don't mention the blessings of my father Late. Sarangapani, my mother Rajeshwari, my in-laws who have always provided the moral supports and enthusiasm in conducting this research work.

I am beholden to almighty and to my SAI BABA, BALAJI and SHIV SHANKAR for their blessing to help me raise my academic level to this stage. I pray for their benediction in my future endeavors.

Date

V. Rajagopal

Place

(2008EEZ8030)

ABSTRACT

The depletion of conventional energy sources has given rise to an increased emphasis on renewable energy sources such as wind, mini/micro hydro, biogas, biodiesel, biomass etc. Therefore for rural electrification as well as electrifying remotely located community such energy sources employing an asynchronous generator becomes a prominent option. In renewable energy applications of low and medium power (up to 100 kW) the induction generator offers several advantages. In low power rating applications, uncontrolled turbines are preferred, as the generator output power to be held constant while varying consumer loads. An auxiliary load in shunt with the consumer loads is necessary to keep the electrical load constant at the generator terminals thus, the Isolated Asynchronous Generators (IAGs) can operate with constant input power.

Due to an increase in greenhouse gas emissions, reasonable attention is given to renewable energy sources. The hydro is one of the prominent renewable energy sources to supply electric power in remote and isolated areas, where grid supply is not accessible. An asynchronous generator for supplying electricity in such areas by harnessing available renewable energy sources such as hydro, wind and biomass becomes the most appropriate option compared to other electric generators like the reluctance generator, a permanent magnet (PM) generator, and a synchronous generator.

In hilly and isolated areas plenty of hydro potential is available. These hydro potentials can be used to drive hydro turbine to generate the electricity. However, asynchronous machine can be used as a generator provided its reactive power requirement is fulfilled by capacitor banks, is called Isolated Asynchronous Generators (IAGs).

The main problem of mini hydro/micro hydro is the prime mover input is constant to the isolated asynchronous generator but the loads are changing. Due to this the frequency and voltage of the generator is changing and wind driven generators the prime mover input as well as the loads connected are changing, the challenge lies in keeping the frequency and voltage constant under the varying input from the prime mover as well as varying loads and keeping the power quality into view. These harmonics in voltage and current increase the power losses, create unequal heating and cause pulsations on the shaft of the IAG and distort voltage to the consumer loads. If such harmonics are present in three-phase four-wire systems the neutral conductor dissipates more power losses and heating. In view of above, an effective and efficient controller is investigated for three-phase three-wire and three-phase four-wire IAG system to control the voltage and frequency, suppress the harmonics and neutral current compensation.

This research work is mainly focused on three-phase three-wire and three-phase four-wire applications for IAG driven by constant power hydro prime movers with no governor control. The advantages of using an asynchronous generator instead of a synchronous generator are well known. Some of them are reduced unit cost and size, ruggedness, brushless (in squirrel cage construction), absence of separate dc source, ease of maintenance, self-protection against severe overloads and short circuits, etc. For such isolated applications the simple control strategy is hold a single point operation by ensuring the input power and output power constant. The output power is maintained constant by having a voltage and frequency controller (VFC) in case of integrated controller and electronic load controller in case of decoupled controller, which ensures the sum of powers consumed by consumer load and controller auxiliary load constant. As consumer load reduces, the VFC diverts the excess active power into the auxiliary load.

The investigation covers design, simulation and development of various topologies of VFCs, which can make the system adaptable to feed various types of three-phase three-wire and three-phase four-wire consumer loads. In view of such requirement, various topologies of VFC may be explored especially for three-phase four-wire systems with various transformer configurations such as star/delta, zigzag/star, T-T connected, star/hexagon and star/polygon connections for neutral current compensation.

The various topologies of VFCs include the three-phase three-wire/four-wire integrated and decoupled voltage and frequency controllers. These controllers to control the voltage and frequency and improve power quality require generation of reference currents. The reference currents are extracted using some existing algorithms like IRPT (instantaneous reactive power theory), SRF (synchronous reference frame), ISCT (instantaneous symmetrical component theory), PI (proportional integral) , Adaline (**AD**Aptive **LI**Near **E**lement), PBT (power balance theory), CSD (current synchronous detection), Icos Φ single-phase p-q theory and a new conductance based control algorithm with indirect current control. The VFCs with the generating system is modeled and simulated in MATLAB environment using Simulink and simpower system (SPS) toolboxes. The simulated results are validated with test results on a developed prototype to demonstrate the effectiveness of the VFC for the control of IAG feeding three-phase three-wire/four-wire consumer loads with the neutral current compensation.

TABLE OF CONTENTS

Certificate	i
Acknowledgements	ii
Abstract	iv
Table of Contents	vii
Table of Figures	xix
List of Tables	xl
List of Symbols	xlii
CHAPTER – I INTRODUCTION	
1.1 General	1
1.2 State of Art	2
1.3 Scope of Work	4
1.3.1 Investigations on Three-Phase Three-Wire Integrated Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	4
1.3.2 Investigations on Three-Phase Three-Wire Decoupled Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	5
1.3.3 Investigations on Three-Phase Four-Wire Integrated Voltage and Frequency Controllers with Transformer for IAGs in Small Hydro Power Generation	5
1.3.4 Investigations on Three-Phase Four-Wire Decoupled Voltage and Frequency Controllers with Transformer for IAGs in Small Hydro Power Generation	6
1.4 Outline of the Chapters	6
CHAPTER – II LITERATURE REVIEW	
2.1 General	11
2.2 Significant Developments in IAGs and Isolated Small Hydro Power Generation	12
2.3 Literature Review on Voltage and Frequency Controllers for Isolated Asynchronous Generators	14
2.3.1 Asynchronous Generators Operating in Isolated Mode	15
2.3.2 Voltage and Frequency Controllers for IAG	16
2.3.3 Control Algorithms for VFC	20
2.3.4 Transformer Configurations for Isolation of VSC of VFC	21
2.3.5 Transformer Configurations for Neutral Current Compensation	21
2.4 Identified Research Areas	22
2.5 Conclusions	23
CHAPTER–III CONFIGURATIONS OF VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION	
3.1 General	24

3.2	Classifications of Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	24
3.2.1	Circuits Based Classification of Voltage and Frequency Controllers for IAGs	28
3.2.2	Topologies Based Classification of Voltage and Frequency Controllers for IAGs	28
3.2.3	Numbers of Wire Based Classification of Voltage and Frequency Controllers for IAGs	29
3.2.4	Numbers of VSC Legs Based Classification of Voltage and Frequency Controllers for IAGs	29
3.2.5	Transformers Based Classification of Voltage and Frequency Controllers for IAGs	39
3.3	Configurations of VSC Based Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	30
3.3.1	Three-Phase Three-Wire Integrated Voltage and Frequency Controllers	30
3.3.1.1	Three-Leg voltage source converter based integrated voltage and frequency controllers	30
3.3.1.2	Two-Leg voltage source converter based integrated voltage and frequency controllers	31
3.3.2	Three-Phase Three-Wire Decoupled Voltage and Frequency Controllers	31
3.3.2.1	Three-Leg voltage source converter based decoupled voltage and frequency controllers	32
3.3.2.2	Two-Leg voltage source converter based decoupled voltage and frequency controllers	32
3.3.3	Three-Phase Four-Wire Integrated Voltage and Frequency Controllers	33
3.3.3.1	Four-leg VSC based integrated voltage and frequency controllers	33
3.3.3.2	Three-leg voltage source converter with mid-point capacitor based integrated voltage and frequency controllers	34
3.3.3.3	Three-single phase VSC based integrated voltage and frequency controllers with isolated transformer	35
3.3.3.4	Three-leg voltage source converter based integrated voltage and frequency controllers with non-isolated transformer	36
3.3.3.5	Three-leg voltage source converter based integrated voltage and frequency controllers with isolated transformer	39
3.3.3.6	Two-leg voltage source converter based integrated voltage and frequency controllers with non-isolated transformer	40
3.3.3.7	Two-leg voltage source converter based integrated voltage and frequency controllers with isolated transformer	42
3.3.4	Three-Phase Four-Wire Decoupled Voltage and Frequency Controllers	44
3.3.4.1	Four-leg VSC based decoupled voltage and frequency controllers	45
3.3.3.2	Three-leg voltage source converter with mid-point capacitor	45

	based decoupled voltage and frequency controllers	
3.3.4.3	Three-single phase VSC based decoupled voltage and frequency controllers with isolated transformer	46
3.3.4.4	Three-leg voltage source converter based decoupled voltage and frequency controllers with non-isolated transformer	48
3.3.4.5	Three-leg voltage source converter based decoupled voltage and frequency controllers with isolated transformer	51
3.3.4.6	Two-leg voltage source converter based decoupled voltage and frequency controllers with non-isolated transformer	54
3.3.4.7	Two-leg voltage source converter based decoupled voltage and frequency controllers with isolated transformer	57
3.4	Control Algorithms of Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	59
3.5	Comparative Features of Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	60
3.6	Rating Considerations of Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	61
3.7	Conclusions	61
CHAPTER – IV DESIGN OF VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
4.1	General	62
4.2	Proposed Configurations and Operating Principle of Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	62
4.3	Design of Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	64
4.3.1	Design of Three-Leg 3-Wire Integrated Voltage and Frequency Controllers	64
4.3.1.1	Design of Electrical System	64
4.3.1.2	DC Bus Capacitor Voltage	64
4.3.1.3	Design of Filtering Inductance	65
4.3.1.4	Design of DC Bus Capacitor	65
4.3.1.5	Design of Three-phase Three-wire IVFC	65
4.3.2	Design of Three-Leg 3-Wire Decoupled Voltage and Frequency Controllers	67
4.3.2.1	Design of Electrical System	67
4.3.2.2	DC Bus Capacitor Voltage of STATCOM	67
4.3.2.3	Design of Filtering Inductance	67
4.3.2.4	Design of DC Bus Capacitor	67

4.3.2.5	Design of STATCOM	68
4.3.2.6	Design of ELC	68
4.3.3	Design of Three-Leg 4-Wire Integrated Voltage and Frequency Controllers	69
4.3.3.1	Design of Electrical System	71
4.3.3.2	DC Bus Capacitor Voltage	71
4.3.3.3	Design of Filtering Inductance	71
4.3.3.4	Design of DC Bus Capacitor	72
4.3.3.5	Design of Three-phase Four-wire IVFC	72
4.3.4	Design of Three-Leg 4-Wire Decoupled Voltage and Frequency Controllers	73
4.3.4.1	Design of Electrical System	74
4.3.4.2	DC Bus Capacitor Voltage	75
4.3.4.3	Design of Filtering Inductance	76
4.3.4.4	Design of DC Bus Capacitor	76
4.3.4.5	Design of STATCOM	77
4.3.4.6	Design of ELC	77
4.3.5	Design of Various Integrated Voltage and Frequency Controllers	78
4.3.6	Design of Various Decoupled Voltage and Frequency Controllers	87
4.3.7	Design of Star/Delta Transformer	99
4.3.8	Design of Zigzag/Star Connected Transformer	100
4.3.9	Design of T-connected Transformer	102
4.3.10	Design of Star/Hexagon Transformer	103
4.3.11	Design of the Star/Polygon Transformer	105
4.4	Results and Discussion	106
4.5	Conclusions	107
CHAPTER – V CONTROL ALGORITHMS FOR VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
5.1	General	108
5.2	Configuration and Operating Principle	109
5.3	PI Controller Based Algorithm	109
5.3.1	In-phase Reference Source Currents	109
5.3.2	Quadrature Reference Source Currents	112
5.3.3	Reference Source Currents	113
5.3.4	Chopper PWM Controller	113

5.4	Synchronous Reference Frame (SRF) Theory Based Algorithm	114
5.4.1	In-phase Reference Source Currents	115
5.4.2	Quadrature Reference Source Currents	115
5.4.3	Reference Source Currents	116
5.4.4	Chopper PWM Controller	117
5.5	Instantaneous Sequence Component Theory (ISCT) Based Algorithm	117
5.5.1	In-phase Reference Source Currents	117
5.5.2	Quadrature Reference Source Currents	119
5.5.3	Reference Source Currents	119
5.5.4	Chopper PWM Controller	120
5.6	Instantaneous Reactive Power Theory (IRPT) Based Algorithm	120
5.6.1	In-phase Reference Source Currents	120
5.6.2	Quadrature Reference Source Currents	122
5.6.3	Reference Source Currents	123
5.6.4	Chopper PWM Controller	124
5.7	Power Balance Theory (PBT) Based Algorithm	124
5.7.1	In-phase Reference Source Currents	124
5.7.2	Quadrature Reference Source Currents	125
5.7.3	Reference Source Currents	126
5.7.4	Chopper PWM Controller	126
5.8	Synchronous Detection Based Control Algorithm	127
5.8.1	In-phase Reference Source Currents	128
5.8.2	Quadrature Reference Source Currents	129
5.8.3	Reference Source Currents	130
5.8.4	Chopper PWM Controller	131
5.9	Icos Φ Algorithm	131
5.9.1	In-phase Reference Source Currents	132
5.9.2	Quadrature Reference Source Currents	133
5.9.3	Reference Source Currents	135
5.9.4	Chopper PWM Controller	135
5.10	Conductance Based Algorithm	135
5.10.1	In-phase Reference Source Currents	136
5.10.2	Quadrature Reference Source Currents	138
5.10.3	Reference Source Currents	139
5.10.4	Chopper PWM Controller	140
5.11	Single-Phase p-q Theory Based Algorithm	140
5.11.1	In-phase Reference Source Currents	140
5.11.2	Quadrature Reference Source Currents	142

5.11.3	Reference Source Currents	143
5.11.4	Chopper PWM Controller	144
5.12	Adaline (ANN) Based Algorithm	144
5.12.1	In-phase Reference Source Currents	144
5.12.2	Quadrature Reference Source Currents	145
5.12.3	Reference Source Currents	147
5.12.4	Chopper PWM Controller	148
5.13	Matlab Based Models of Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	148
5.14	Results and Discussion	156
5.14.1	Performance of VFC for IAG Using PI Controller Based Algorithm	157
5.14.2	Performance of VFC for IAG Using SRF Theory Based Algorithm	160
5.14.3	Performance of VFC for IAG Using ISCT Based Algorithm	163
5.14.4	Performance of VFC for IAG Using IRPT Based Algorithm	166
5.14.5	Performance of VFC for IAG Using PBT Based Algorithm	169
5.14.6	Performance of VFC for IAG Using CSD Based Algorithm	172
5.14.7	Performance of VFC for IAG Using Icos Φ Algorithm	175
5.14.8	Performance of VFC for IAG Using Conductance Based Algorithm	178
5.14.9	Performance of VFC for IAG Using Single-Phase p-q Theory Based Algorithm	180
5.14.10	Performance of VFC for IAG Using Adaline Based Algorithm	185
5.15	Conclusions	188
 CHAPTER –VI MODELING OF THREE-PHASE THREE-WIRE INTEGRATED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
6.1	General	190
6.2	Configurations, Operating Principle and Control Algorithm of Three-Phase Three-Wire Integrated VFCs for IAGs in Small Hydro Power Generation	190
6.2.1	Three-Leg VSC Based Integrated Voltage and Frequency Controllers	190
6.2.2	Two-Leg VSC Based Integrated Voltage and Frequency Controllers	191
6.3	Control Algorithm	192
6.4	MATLAB Based Models of IAG with Three-Phase Three-Wire IVFCs	192
6.4.1	Three-Leg VSC Based Integrated Voltage and Frequency Controllers	193
6.4.2	Two-Leg VSC Based Integrated Voltage and Frequency Controllers	195
6.5	Results and Discussion	196
6.5.1	Performance of Three-Leg VSC based Integrated VFC for IAGs in Small Hydro Power Generation	196
6.5.1.1	Performance of VFC with Balanced/Unbalanced Linear Loads	196
6.5.1.2	Performance of VFC with Balanced/Unbalanced Non-linear	197

Loads	
6.5.1.3 Power Quality Performance of IAG.	197
6.5.2 Performance of Two-leg VSC based Integrated VFC for IAGs in Small Hydro Power Generation	201
6.5.2.1 Performance of VFC with IAG under Linear Loads	201
6.5.2.2 Performance of VFC with IAG under Non-linear Loads	202
6.5.2.3 Power Quality Performance of VFC for IAG	202
6.6 Conclusions	205

CHAPTER –VII DEVELOPMENT OF THREE-PHASE THREE-WIRE INTEGRATED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION

7.1 General	207
7.2 Configuration and Operating Principle	207
7.3 Control Algorithm	208
7.4 Hardware Implementation	210
7.4.1 Hardware Configuration	212
7.4.2 Voltage Source Converter	213
7.4.3 Current Sensor Circuit	214
7.4.4 Voltage Sensor Circuit	215
7.4.5 Amplification and Isolation Circuit	215
7.5 Software Implementation	216
7.6 Results and Discussion	217
7.6.1 Performance of IVFC for IAG under Linear loads	218
7.6.2 Performance of IVFC for IAG under Non-linear loads	224
7.6.3 Performance of IVFC for IAG under Dynamic loads	231
7.6.4 Power Quality Performance of IVFC for IAG	236
7.7 Conclusions	242

CHAPTER –VIII MODELING OF THREE-PHASE THREE-WIRE DECOUPLED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION

8.1 General	243
8.2 Configurations and Operating Principle	243
8.2.1 Three-Leg VSC Based Decoupled Voltage and Frequency Controllers	244
8.2.2 Two-Leg VSC Based Decoupled Voltage and Frequency Controllers	244
8.3 Control Algorithm	245
8.4 MATLAB Based Models of IAG with Three-Phase Three-Wire DVFCs	245
8.4.1 Three-Leg VSC Based Decoupled Voltage and Frequency Controllers	246

8.4.2	Two-Leg VSC Based Decoupled Voltage and Frequency Controllers	247
8.5	Results and Discussion	247
8.5.1	Performance of Three-leg voltage source converter based decoupled voltage and frequency controllers	248
8.5.1.1	Performance of VFC for IAG under Linear Loads	249
8.5.1.2	Performance of VFC for IAG under Non-linear Loads	249
8.5.1.3	Power Quality Performance of VFC for IAG.	249
8.5.2	Performance of Two-leg voltage source converter based decoupled voltage and frequency controllers	252
8.5.2.1	Performance of VFC for IAG under Linear Loads	253
8.5.2.2	Performance of VFC for IAG under Non-linear Loads	253
8.5.2.3	Power Quality Performance of VFC for IAG	256
8.6	Conclusions	257
CHAPTER –IX DEVELOPMENT OF THREE-PHASE THREE-WIRE DECOUPLED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
9.1	General	258
9.2	Configuration and Operating Principle	258
9.3	Control Algorithm	259
9.4	Hardware Implementation	261
9.5	Software Implementation	263
9.6	Results and Discussion	264
9.6.1	Performance of VFC for IAG under linear loads	264
9.6.2	Performance of VFC for IAG under Non-linear loads	268
9.6.3	Performance of VFC for IAG under Dynamic loads	274
9.6.4	Power Quality Performance of VFC for IAG	283
9.7	Conclusions	289
CHAPTER –X MODELING OF THREE-PHASE FOUR-WIRE INTEGRATED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
10.1	General	290
10.2	Configurations, Operating Principle and Control	290
10.2.1	Six-leg VSC Based Integrated Voltage and Frequency Controllers	291
10.2.2	Four-leg VSC Based Integrated Voltage and Frequency Controllers	292
10.2.3	Three-leg VSC with Mid-point Capacitor Based Integrated Voltage and Frequency Controllers	294
10.2.4	Three-leg VSC Based Integrated Voltage and Frequency Controllers with Isolated Transformer	295

10.2.5	Three-leg VSC Based Integrated Voltage and Frequency Controllers with Non-isolated Transformer	297
10.2.6	Two-leg VSC Based Integrated Voltage and Frequency Controllers with Isolated Transformer	300
10.2.7	Two-leg VSC Based Integrated Voltage and Frequency Controllers with Non-isolated Transformer	303
10.3	MATLAB Based Models of IAG with Three-Phase Four-Wire VSC Based Integrated Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	305
10.4	Results and Discussion	326
10.4.1	Performance of Six-Leg Voltage Source Converter Based Integrated Voltage and Frequency Controllers	313
10.4.2	Performance of Four-Leg Voltage Source Converter Based Integrated Voltage and Frequency Controllers	316
10.4.3	Performance of Three-Leg VSC with Mid-point Capacitor Based Integrated Voltage and Frequency Controllers	319
10.4.4	Performance of Three-Leg Voltage Source Converter Based Integrated Voltage and Frequency Controllers with Isolated Transformer	322
10.4.5	Performance of Three-Leg Voltage Source Converter Based Integrated Voltage and Frequency Controllers with Non-isolated Transformer	325
10.4.6	Performance of Two-Leg Voltage Source Converter Based Integrated Voltage and Frequency Controllers with Isolated Transformer	326
10.4.7	Performance of Two-Leg Voltage Source Converter Based Integrated Voltage and Frequency Controllers with Non-isolated Transformer	332
10.5	Conclusions	335
CHAPTER –XI DEVELOPMENT OF THREE-PHASE FOUR-WIRE INTEGRATED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
11.1	General	336
11.2	Configurations, Operating Principle and Control Algorithm of Integrated Voltage and Frequency Controllers for IAGs in Small Hydro Power Generation	337
11.2.1	Isolated zigzag-star transformer based integrated voltage and frequency controllers	337
11.2.2	Isolated zigzag-three single phase transformer based integrated voltage and frequency controllers	340
11.2.3	Non-isolated T-connected transformer based integrated voltage and frequency controllers	345
11.3	Hardware Implementation	348
11.4	Software Implementation	349
11.5	Results and Discussion	353
11.5.1	Performance of isolated zigzag-star transformer based integrated voltage and frequency controllers	353

11.5.1.1	Performance of VFC for IAG under Linear Loads	353
11.5.1.2	Performance of VFC for IAG under Non-linear Loads	359
11.5.1.3	Power Quality Performance of VFC for IAG	362
11.5.2	Performance of isolated zigzag-three single phase transformer based integrated voltage and frequency controllers	368
11.5.2.1	Performance of VFC for IAG under Linear Loads	368
11.5.2.2	Performance of VFC for IAG under Non-linear Loads	377
11.5.2.3	Power Quality Performance of VFC for IAG	383
11.5.3	Performance of non-isolated T-connected transformer based integrated voltage and frequency controllers	387
11.5.3.1	Performance of VFC for IAG under Linear Loads	387
11.5.3.2	Performance of VFC for IAG under Non-linear Loads	395
11.5.3.3	Power Quality Performance of VFC for IAG	399
11.6	Conclusions	408
CHAPTER –XII MODELING OF THREE-PHASE FOUR-WIRE DECOUPLED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
12.1	General	409
12.2	Configurations, Operating Principle and Control Algorithm	409
12.2.1	Six-leg VSC Based Decoupled Voltage and Frequency Controllers	410
12.2.2	Four-leg VSC Based Decoupled Voltage and Frequency Controllers	411
12.2.3	Three-leg VSC with Mid-point Capacitor Based Decoupled Voltage and Frequency Controllers	412
12.2.4	Three-leg VSC Based Decoupled Voltage and Frequency Controllers with Non-isolated Transformer	412
12.2.5	Three-leg VSC Based Decoupled Voltage and Frequency Controllers with Isolated Transformer	418
12.2.6	Two-leg VSC Based Decoupled Voltage and Frequency Controllers with Non-isolated Transformer	420
12.2.7	Two-leg VSC Based Decoupled Voltage and Frequency Controllers with Isolated Transformer	422
12.3	MATLAB Based Models of IAG with Three-Phase Four-Wire VSC Based Decoupled Voltage and Frequency Controllers	427
12.4	Results and Discussion	432
12.4.1	Performance of Six-Leg Voltage Source Converter Based Decoupled Voltage and Frequency Controllers	433
12.4.2	Performance of Four-Leg Voltage Source Converter Based Decoupled Voltage and Frequency Controllers	435
12.4.3	Performance of Three-Leg VSC with Mid-point Capacitor Based Decoupled Voltage and Frequency Controllers	438
12.4.4	Performance of Three-Leg Voltage Source Converter with Non-	441

	isolated Star/Delta Transformer Based Decoupled Voltage and Frequency Controllers	
12.4.5	Performance of Three-Leg Voltage Source Converter with Isolated Zigzag/Star Transformer Based Decoupled Voltage and Frequency Controllers	444
12.4.6	Performance of Two-Leg Voltage Source Converter with Non-isolated Star/Polygon Transformer Based Decoupled Voltage and Frequency Controllers	447
12.4.7	Performance of Two-Leg Voltage Source Converter with Isolated T-T Connected Transformer Based Decoupled Voltage and Frequency Controllers	450
12.5	Conclusions	453
CHAPTER –XIII DEVELOPMENT OF THREE-PHASE FOUR-WIRE DECOUPLED VOLTAGE AND FREQUENCY CONTROLLERS FOR ASYNCHRONOUS GENERATORS IN ISOLATED SMALL HYDRO POWER GENERATION		
13.1	General	455
13.2	Configurations, Operating Principle and Control Algorithm	456
13.2.1	Isolated Zigzag-Star Transformer Based Decoupled Voltage And Frequency Controllers	456
13.2.2	Non-Isolated Star/Delta Transformer Based Decoupled Voltage and Frequency Controllers	459
13.3	Hardware Implementation	463
13.4	Software Implementation	465
13.5	Results and Discussion	467
13.5.1	Performance of isolated zigzag-star transformer based decoupled voltage and frequency controllers	467
13.5.1.1	Performance of VFC for IAG under Linear Loads	467
13.5.1.2	Performance of VFC for IAG under Non-linear Loads	474
13.5.1.3	Power Quality Performance of VFC for IAG	480
13.5.2	Performance of non-isolated star/delta transformer based decoupled voltage and frequency controllers	486
13.5.2.1	Performance of VFC for IAG under Linear Loads	486
13.5.2.2	Performance of VFC for IAG under Non-linear Loads	493
13.5.2.3	Power Quality Performance of VFC for IAG	501
13.6	Conclusions	507
CHAPTER – XIV MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK		
14.1	General	508
14.2	Main Conclusions	509
14.3	Suggestions for Further Work	512

REFERENCES	513
APPENDICES	524
LIST OF PUBLICATIONS	526
BIO-DATA	528