

ANALYSIS, DESIGN AND DEVELOPMENT OF SOME CUSTOM
POWER DEVICES FOR POWER QUALITY ENHANCEMENT

By

Jayaprakash P

Centre for Energy Studies

Submitted

In fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



INDIAN INSTITUTE OF TECHNOLOGY, DELHI
HAUZ KHAS, NEW DELHI-110 016, INDIA
MARCH 2011

CERTIFICATE

This is to certify that the thesis entitled “Analysis, Design and Development of Some Custom Power Devices for Power Quality Enhancement”, being submitted by Mr. Jayaprakash P for the award of degree of Doctor of Philosophy, is a record of bona fide research work carried out by him in the Centre for Energy Studies of Indian Institute of Technology, Delhi.

Mr. Jayaprakash P has worked under our supervision and has fulfilled the requirement for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained here in have not been submitted in part or full to any other university or institute for award of any degree.

Dated:

Signature of supervisors

Prof. Bhim Singh

Dept. of Electrical Engg.

Indian Institute of Technology, Delhi.

Hauz khas, New Delhi – 110016, India.

Prof. D.P. Kothari

Vellore Institute of Technology,

Vellore,

Tamil Nadu, India.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and indebtedness to Prof. Bhim Singh and Prof. D.P.Kothari, for their valuable guidance and continuous monitoring of my research work. Deep insight of Prof. Bhim Singh about the subject, great experience and exposure in international forum and his strong perception helped me to do this research work. The encouragement, support and valuable guidance by Prof. D P Kothari, even when he changed his workplace, have always been a driving force to complete my work. If I learnt a little bit of the art of time management and planning, it is due to the inspiration from the working style of Prof. Singh only. It is a life time experience to work under these two professors which I am cherished always.

My heartfelt thanks and deep gratitude to Prof. Avinash Chandra, Prof. T S Bhatti, Dr. G. Bhuvaneswari and all SRC members who have given me valuable guidance and advice to improve quality of my work. I would like to convey my sincere gratitude and respect to Prof. S C Kaushik and Prof. T S Bhatti for their immense support and co-operation as Head of the Centre and PhD coordinator respectively. Thanks are also due to prof. J K Chatterjee and Prof. R K Patney for their kind permission for conducting experiments in the electrical laboratory.

I am extremely grateful to Shri Gurcharan Singh, Sh. Srichand, Sh. Puran Singh, Sh. Jugbeer Singh and other staffs of Electrical Engineering's Drives and Simulation Lab, IIT Delhi for providing me immense facilities and assistance to carry out my research work. I am thankful to the staffs of PG Section, Central Library and Central Computer Centre for their co-operation. I am grateful to the staffs of the office, Library and Computer lab of Centre for Energy Studies for their valuable co-operation and support. I am also thankful to Mr. Mohit Mahajan of FITT for processing my patents in time with his suggestions. The financial

support from the Department of Technical Education, Kerala and the AICTE under QIP programme are also duly acknowledged.

I would like to extend my sincere thanks to Dr. R. Saha, Mr. D. Madhan Mohan, Mr. Jitendra Solanki, Mr. Somayajulu, Mr. Sunil Kumar, Dr. Sanjay Gairola and Dr. Gaurav Kumar Kasal for providing me initial support to my research work. It will remain incomplete if I don't mention the support and co-operation of my friends and the research group members Sh. Kalyanaraman, Sh. Ashish, Sh. Sanjeev Singh, Sh. V.Rajagopal, Sh. Shailendra Sharma, Sh. Ramniwas, Sh. Arya and Sh. Jeevanand. I am also grateful to all those who have directly or indirectly helped me to complete my thesis work.

If I get any success today for my research work, the entire credit and honor should go to my wife Sheeja, who was supporting me in various roles. I would like to express my deep concern to my little son, Master Bhagath for his consideration during the long hours of absence from home. My deepest love and indeptness go to my parents for their support, encouragement and understanding. I do always indebted to my co-brother and family for their kind support to manage my family matters during many of my study days in Delhi.

At last, not the least, I thank to almighty for their blessings without which completion of my research work would have been impossible.

Date:

Jayaprakash P

Place: New Delhi

(2006 ESZ8165)

ABSTRACT

The upcoming use of sensitive and critical equipments in the distribution system has resulted in the awareness of the *power quality* (PQ) issues. The PQ problems are the concern for both the electric utilities and end users of the electric power. The PQ problems in the ac current include high reactive power burden, harmonics currents, poor voltage regulation, unbalanced loads and excessive neutral current. The PQ problems in the voltage are sag, swell, unbalance and harmonic distortion in the supply voltages. The group of devices used for power quality enhancement is called by the generic name *Custom Power Devices* (CPDs). The CPD includes shunt connected *Distribution Static Synchronous Compensator* (DSTATCOM) for improving the power quality of the current, series connected *Dynamic Voltage Restorer* (DVR) for mitigating the power quality problems in the voltage and the *Unified Power Quality Conditioner* (UPQC) is a combination of series and shunt active devices. The UPQC is used to reduce both current and voltage based power quality problems. The custom power devices enhance the quality and reliability of the power that is delivered to customers.

The unplanned expansion of distribution system and the increase of non-linear loads drawing non-sinusoidal currents have resulted in excessive neutral current in the distribution system. The neutral conductor is overloaded resulting in busting of it. The passive devices such as a zig-zag transformer and a star/ delta transformer are reported in the literature to mitigate the neutral current in the source neutral conductor. Some new methods for the neutral current compensation are developed based on transformer magnetics such as a T-connected transformer, a star/hexagon transformer and a star/polygon transformer. These methods are designed, modelled and their performance is simulated and then tested with hardware prototypes in the laboratory environment and a comparison is carried out with the existing techniques of the neutral current compensation.

The various control algorithms and topologies of three-phase three-wire and three-phase four-wire DSTATCOM are investigated for load compensation. The control strategies such as *synchronous reference frame theory* (SRFT) and Adaline based *neural network* (NN) are studied by simulation as well as by hardware implementation in the laboratory environment using dSPACE processor and *insulated gate bipolar transistor* (IGBT) based *voltage source converter* (VSC). The three-phase four-wire DSTATCOM is tested for reactive power compensation, harmonics elimination, load balancing and neutral current compensation. The proposed new topologies of three-phase four-wire DSTATCOM include configurations of isolated and non-isolated 3-leg VSC with transformers such as a zig-zag transformer, a star-delta transformer, a T-connected transformer, and a star-hexagon transformer. Similarly, another set of topologies of DSTATCOM are with isolated and non-isolated two-leg VSC with transformers such as a zig-zag transformer, a star-delta transformer, a T-connected transformer and a star-hexagon transformer. A comparison of the above topologies is carried out to identify the suitable topology of DSTATCOM considering reduced complexity and the cost for a given application.

An active series compensator such as *series active filter* (SAF) and a *dynamic voltage restorer* (DVR) are investigated for the desired performance with different control algorithms. The SAF is to compensate the harmonics in the source current thereby reducing the harmonic distortion of voltage at PCC at non-linear loads. Similarly, the performance of the battery supported and the capacitor supported DVR are studied for enhancement of power quality during various power quality disturbances like sag, swell, unbalance and harmonics in the PCC voltage. The operation of a DVR is demonstrated under different voltage injection schemes and a comparison of the performance with different schemes is performed for voltage quality improvement. The capacitor supported DVR is controlled by implementing the algorithm with the SRF theory and the Adaline based NN theory.

The UPQC is used for multiple power quality solutions both in the current and voltage. Some new configurations of three-phase four-wire UPQC are proposed for mitigating multiple power quality problems. An isolated reduced rating three-leg VSC with a T-connected transformer and another one with an isolated reduced rating two-leg VSC with a zig-zag transformer are proposed as a shunt controller of UPQC along with an isolated three-leg VSC based series controller for three-phase four-wire systems. The transformer of a shunt controller is used as a neutral current compensator and it provides the functions such as isolation and an optimum voltage selection for the shunt VSC. The shunt controller of UPQC supports the common dc link under various disturbances. The series compensator of UPQC is used to regulate the amplitude at the load voltage when the PCC voltage is affected by the sag, swell or harmonics.

TABLE OF CONTENTS

	Page No
Certificate	i
Acknowledgements	ii
Abstract	iv
Table of Contents	vii
List of Figures	xvi
List of Tables	xxxix
List of Symbols	xxxx
CHAPTER-I INTRODUCTION	1
1.1 General	1
1.2 State of Art on Custom Power Devices	3
1.2.1 Neutral Current Compensators	3
1.2.2 Active Shunt Compensator	3
1.2.3 Active Series Compensator	4
1.2.4 Unified Power Quality Conditioner	5
1.3 Scope of Work	6
1.3.1 Investigations on Neutral Current Compensation (NCC) Techniques in Three-Phase Four-Wire Distribution System	6
1.3.2 Investigations on Active Shunt Compensator for Power Quality Enhancement in Three-Phase System	6
1.3.3 Investigations on Active Series Compensator for Power Quality Enhancement in Three-Phase Distribution System	8
1.3.4 Investigations on Unified Power Quality Conditioner for Power Quality Enhancement in Three-Phase Distribution System	8
1.4 Outline of Chapters	9
CHAPTER-II LITERATURE REVIEW	14
2.1 General	14
2.2 Literature Review	14
2.2.1 Power Quality Standards	15
2.2.2 Neutral Current Problem and Compensation Techniques	16
2.2.3 Research and Development on DSTATCOM	17
2.2.3.1 Three-Phase Three-Wire DSTATCOM	19
2.2.3.2 Three-Phase Four-Wire DSTATCOM	20

2.2.3.3	Control methods of DSTATCOM	21
2.2.4	Research and development on Active Series Compensators	23
2.2.4.1	Research and Development on Dynamic Voltage Restorers (DVR)	23
2.2.4.2	Research and Development on Series Active Filters (SAF)	25
2.2.5	Research and development on Unified Power Quality Conditioner (UPQC)	26
2.3	Identified Research Areas	28
2.4	Conclusions	29
CHAPTER-III	DESIGN, MODELLING AND DEVELOPMENT OF	31
	MAGNETICS FOR NEUTRAL CURRENT COMPENSATION	
3.1	General	31
3.2	Neutral Current Problems	31
3.3	Neutral Current Problem and Compensation Techniques	32
3.3.1	Configuration using zig-zag Transformer in a three-phase four-wire system	36
3.3.2	Configuration using Star-Delta Transformer in a three-phase four-wire system	36
3.3.3	Configuration using Star-Hexagon Transformer in a three-phase four-wire system	36
3.3.4	Configuration using Star-Polygon Transformer in a three-phase four-wire system	36
3.3.5	Configuration using T-Connected Transformer in a three-phase four-wire system	38
3.3.6	Configuration using Scott-Connected Transformer in a three-phase four-wire system	38
3.4	Design of Magnetics for NCC	39
3.4.1	Design of Zig-zag Transformer for NCC	40
3.4.2	Design of Star-Delta Transformer for NCC	40
3.4.3	Design of Star-Hexagon Transformer for NCC	41
3.4.4	Design of Star-Polygon Transformer for NCC	41
3.4.5	Design of T-Connected Transformer for NCC	42
3.4.6	Design of Scott-Connected Transformer for NCC	43
3.5	MATLAB based Modeling of NCC Techniques	43
3.6	Results and Discussion	45
3.6.1	Simulation Results of NCC Techniques	46
3.6.1.1	Simulated performance of zig-zag Transformer	47

	for NCC	
3.6.1.2	Simulated performance of star/delta Transformer for NCC	48
3.6.1.3	Simulated performance of T-Connected Transformer for NCC	50
3.6.1.4	Simulated performance of Scott-Connected Transformer for NCC	52
3.6.1.5	Simulated performance of Star-Hexagon Transformer for NCC	53
3.6.1.6	Simulated performance of Star-Polygon Transformer for NCC	53
3.6.2	Hardware Implementation of NCC Techniques	54
3.6.2.1	Experimental performance of Zig-Zag Transformer for NCC	57
3.6.2.2	Experimental performance of Star-Delta Transformer for NCC	58
3.6.2.3	Experimental performance of Scott-Connected Transformer for NCC	61
3.6.2.4	Experimental performance of T-Connected Transformer for NCC	64
3.6.2.5	Experimental performance of Star-Hexagon Transformer for NCC	66
3.6.2.6	Experimental performance of Star-Polygon Transformer for NCC	66
3.7	Comparison of NCC Techniques	71
3.8	Conclusions	73

CHAPTER-IV DESIGN, MODELLING AND SIMULATION OF DSTATCOM FOR THREE- PHASE THREE- WIRE SYSTEMS

		74
4.1	General	74
4.2	Configurations of Three-Phase Three-Wire DSTATCOM	74
4.3	Design of Three-Phase Three-Wire DSTATCOM	75
4.3.1	Design of Three-leg VSC Based DSTATCOM	76
4.3.2	Design of Two-leg VSC and Midpoint Capacitor Based DSTATCOM	78
4.3.3	Design of Three Single Phase VSC Based DSTATCOM	81
4.4	Control of Three-Phase Three-Wire DSTATCOM	84
4.4.1	Control of Three-Leg VSC Based Three-phase Three-wire DSTATCOM	85
4.4.1.1	Instantaneous Reactive Power Theory	85

4.4.1.2	Synchronous Reference Frame Theory	87
4.4.1.3	Proportional-Integral Control Theory	90
4.4.1.4	Adaline Neural Network Theory	93
4.4.2	Control of Three Single Phase VSC Based Three-phase Three-wire DSTATCOM	96
4.4.3	Control of Two-Leg VSC Based Three-phase Three-wire DSTATCOM	96
4.5	MATLAB based Modeling of Three-Phase Three-Wire DSTATCOM	98
4.5.1	Modeling of Three-leg VSC Based DSTATCOM	98
4.5.2	Modeling of Three Single Phase VSC Based DSTATCOM	101
4.5.3	Modeling of Two-leg VSC Based DSTATCOM	102
4.6	Results and Discussion	103
4.6.1	Performance of SRFT Controlled Three-leg VSC Based DSTATCOM	103
4.6.2	Performance of Adaline Based NN Controlled Three-leg VSC Based DSTATCOM	105
4.6.3	Performance of SRFT controlled Two-leg VSC Based DSTATCOM	110
4.6.4	Performance of SRFT controlled Three Single Phase VSC Based DSTATCOM	113
4.7	Conclusions	116

CHAPTER-V	HARDWARE IMPLEMENTATION OF DSTATCOM FOR THREE- PHASE THREE- WIRE SYSTEMS	118
5.1	General	118
5.2	Configuration for Hardware Implementation of Three-phase Three-wire DSTATCOM	118
5.3	Design of Components of DSTATCOM for Hardware Implementation	121
5.3.1	Design of IGBT Based VSC	121
5.3.2	Design of Voltage Sensors	121
5.3.3	Design of Current Sensors	122
5.3.4	Design of Pulse Isolation Circuit	123
5.3.5	Design of Series Inductor	124
5.3.6	Design of Ripple Filter	125
5.3.7	DSP Processor	125
5.4	Software Implementation of Control Algorithms of DSTATCOM	127

5.4.1	Synchronous Reference Frame Theory	128
5.4.2	Adaline Based Neural Network Theory	130
5.5	Results and Discussion	132
5.5.1	Performance of Synchronous Reference Frame Theory Based Control Algorithm of DSTATCOM	132
5.5.2	Performance of Adaline Based Neural Network Theory Control Algorithm of DSTATCOM	137
5.6	Conclusions	141

CHAPTER-VI	DESIGN, MODELLING AND SIMULATION OF DSTATCOM FOR THREE- PHASE FOUR- WIRE SYSTEMS	143
6.1	General	143
6.2	Configurations of Three-Phase Four-Wire DSTATCOM	143
6.3	Design of Three-Phase Four-Wire DSTATCOM	149
6.3.1	Design of Four-leg VSC based DSTATCOM	149
6.3.2	Design of Three Single Phase VSC based DSTATCOM	152
6.3.3	Design of Three-leg VSC and Split Capacitor based DSTATCOM	152
6.3.4	Design of Non-isolated Three-leg VSC with Transformer Based Topologies of DSTATCOM	155
6.3.5	Design of Non-isolated Two-leg VSC with Transformer Based Topologies of DSTATCOM	160
6.3.6	Design of Isolated Three-leg VSC with Transformer Based Topologies of DSTATCOM	162
6.3.7	Design of Isolated Two-leg VSC with Transformer Based Topologies of DSTATCOM	165
6.4	Control Schemes of Three-Phase Four-Wire DSTATCOM	168
6.4.1	Control of Four-leg VSC Based DSTATCOM	170
6.4.2	Control of Three Single Phase VSC Based DSTATCOM	174
6.4.3	Control Scheme of Three-leg VSC with Split Capacitor based DSTATCOM	174
6.4.4	Control Scheme of Non-isolated Three-leg VSC with Transformer based Topologies of DSTATCOM	176
6.4.5	Control Scheme of Non-isolated Two-leg VSC with Transformer based Topologies of DSTATCOM	178
6.4.6	Control Scheme of Isolated Three-leg VSC with Transformer based Topologies of DSTATCOM	180
6.4.7	Control Scheme of Isolated Two-leg VSC with	

Transformer based Topologies of DSTATCOM	181
6.5 MATLAB based Modeling of Three-Phase Four-Wire DSTATCOM	183
6.6 Results and Discussion	184
6.6.1 Performance of Four-leg VSC Based DSTATCOM	188
6.6.2 Performance of Three Single Phase VSC based DSTATCOM	191
6.6.3 Performance of Three-leg VSC and Split Capacitor based DSTATCOM	193
6.6.4 Performance of Non-isolated Three-leg VSC and Transformer Based Topologies of DSTATCOM	196
6.6.5 Performance of Non-isolated Two-leg VSC and Transformer based Topologies of DSTATCOM	211
6.6.6 Performance of Isolated Three-leg VSC and Transformer based Topologies of DSTATCOM	225
6.6.7 Performance of Isolated Two-leg VSC and Transformer based Topologies of DSTATCOM	239
6.7 Conclusions	255

CHAPTER-VII HARDWARE IMPLEMENTATION OF DSTATCOMS FOR THREE- PHASE FOUR- WIRE SYSTEMS	260
7.1 General	260
7.2 Configurations of DSTATCOM for Three-Phase Four-Wire System	261
7.3 Design of Components of DSTATCOM for Hardware Implementation	265
7.4 Software Implementation of Control Algorithms of DSTATCOM	269
7.5 Results and Discussion	271
7.5.1 Performance of Three-leg VSC and Transformer based Topologies of DSTATCOM	273
7.5.1.1 Performance of Three-leg VSC and a zig-zag transformer based DSTATCOM	273
7.5.1.2 Performance of Three-leg VSC and a Star-delta transformer based DSTATCOM	284
7.5.1.3 Performance of Three-leg VSC and a T-connected transformer based DSTATCOM	292
7.5.1.4 Performance of Two-leg VSC and Star-hexagon transformer based DSTATCOM	295
7.5.2 Performance of Isolated Three-leg VSC and Non-	

isolated Transformer based Topologies of DSTATCOM	301
7.5.2.1 Performance of an Isolated Three-leg VSC and a zig-zag transformer based DSTATCOM	302
7.5.2.2 Performance of an Isolated Three-leg VSC and a Star-delta transformer based DSTATCOM	305
7.5.2.3 Performance of an Isolated Three-leg VSC and a Star/Hexagon transformer based DSTATCOM	312
7.6 Conclusions	319
CHAPTER-VIII DESIGN AND CONTROL OF SERIES ACTIVE COMPENSATORS FOR THREE PHASE SYSTEMS	321
8.1 General	321
8.2 Principle of Three-phase Series Active Compensators	322
8.2.1 Principle of Dynamic Voltage Restorer	322
8.2.2 Principle of Series Active Filter	329
8.3 Design of Three-phase Series Active Compensators	331
8.3.1 Design of Dynamic Voltage Restorer	333
8.3.2 Design of Series Active Filter	336
8.4 Control Algorithms for three-phase Series Active Compensators	339
8.4.1 Control algorithms for Dynamic Voltage Restorer	339
8.4.1.1 Synchronous Reference Frame Theory based Control of DVR	339
8.4.1.2 Adaline based Neural Network Theory based Control of DVR	343
8.4.1.3 Current Mode Control of DVR	348
8.4.2 Control algorithms for Series Active Filter	349
8.4.2.1 Source Current Detection Control of SAF	350
8.4.2.2 Hybrid Control of SAF	353
8.4.2.3 Neural Network Theory based Hybrid Control of SAF	354
8.5 Results and Discussion	356
8.6 Conclusions	357
CHAPTER-IX MODELLING AND SIMULATION OF SERIES COMPENSATORS FOR THREE PHASE SYSTEMS	358
9.1 General	358
9.2 Configuration of Three-phase Series Active Compensators for Three Phase System	358
9.2.1 Configurations of Dynamic Voltage Restorer	359
9.2.2 Configurations of Series Active Filters	362

9.3	MATLAB Modeling of Three-phase Series Active Compensators	363
9.3.1	MATLAB Modeling of Three-phase Dynamic Voltage Restorer	363
9.3.1.1	Modelling of Synchronous Reference Frame Theory Controlled DVR	364
9.3.1.2	Modelling of Adaline Based Neural Network Theory Controlled DVR	365
9.3.1.3	Modelling of Current mode controlled DVR	366
9.3.2	MATLAB Modeling of Series Active Filters	367
9.3.2.1	Modelling of Source Current Detection Controlled SAF	368
9.3.2.2	Modelling of Hybrid Controlled SAF	370
9.3.2.3	Modelling of Neural Network based Hybrid Control of SAF	371
9.4	Results and Discussion	372
9.4.1	Performance of Dynamic Voltage Restorer	372
9.4.1.1	Performance of Synchronous Reference Frame Theory based BESS supported DVR	372
9.4.1.2	Performance of Synchronous Reference Frame Theory based Capacitor supported DVR	376
9.4.1.3	Performance of Neural Network Theory based DVR	380
9.4.1.4	Performance of Current Mode Controlled DVR	383
9.4.2	Performance of Series Active Filter	386
9.4.2.1	Performance of Source Current Detection Controlled SAF	386
9.4.2.2	Performance of Hybrid Controlled SAF	388
9.4.2.3	Performance of Neural Network based Hybrid Controlled SAF	390
9.5	Conclusions	392

CHAPTER-X	DESIGN AND CONTROL OF UPQC FOR THREE PHASE SYSTEMS	394
10.1	General	394
10.2	Topologies of UPQC for Three-phase Systems	395
10.3	Design of UPQC for Three-phase Systems	404
10.3.1	Design of shunt controller (SHUC) of UPQC	405
10.3.1.1	Design of Isolated 3-leg VSC with T-connected transformer based SHUC	405

10.3.1.2	Design of Isolated 2-leg VSC with zig-zag transformer based SHUC	407
10.3.2	Design of Series Controller (SERC) of UPQC	408
10.4	Control Algorithms for UPQC for Three-phase Systems	410
10.4.1	Control of shunt controller (SHUC) of UPQC	410
10.4.1.1	Control of Isolated 3-leg VSC with T-connected transformer based SHUC	410
10.4.1.2	Control of Isolated 2-leg VSC with zig-zag transformer based SHUC	412
10.4.2	Control of series controller (SREC) of UPQC	414
10.5	Results and Discussion	415
10.6	Conclusions	416
CHAPTER-XI	MODELLING AND SIMULATION OF UNIFIED POWER QUALITY CONDITIONER FOR THREE- PHASE SYSTEMS	417
11.1	General	417
11.2	Configurations of UPQC for Three-phase Systems	418
11.3	MATLAB Modelling of UPQC for Three-phase Systems	419
11.3.1	Modelling of shunt controller of UPQC	420
11.3.2	Modelling of series controller of UPQC	425
11.4	Results and Discussion	426
11.4.1	Performance of UPQC with isolated three-leg VSC and a T-connected transformer based SHUC and three-leg VSC based SERC.	426
11.4.2	Performance of UPQC with isolated two-leg VSC and a Zig-Zag transformer based SHUC and three-leg VSC with Injection Transformer based SERC.	429
11.5	Conclusions	435
CHAPTER-XII	MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK	437
12.1	General	437
12.2	Main Conclusions	438
12.3	Suggestions for Further Work	441
REFERENCES		443
APPENDICES		471
LIST OF PUBLICATIONS		481
BIO-DATA		486