

**ANALYSIS DESIGN AND CONTROL OF MULTI-PULSE
STATIC SYNCHRONOUS COMPENSATOR**

By

RADHESHYAM SAHA
Department of Electrical Engineering

Submitted

In fulfillment of the requirements of the degree of
DOCTOR OF PHILOSOPHY

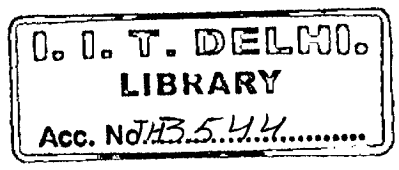
to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

DECEMBER 2007

- ① electric apparatus - Regulation
- ② Automatic control




TH
621.316.7 : 681.51
SATHI - A



CERTIFICATE

This is to certify that the thesis entitled, "Analysis, Design and Control of Multi-Pulse Static Synchronous Compensator", being submitted by Mr. Radheshyam Saha 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. Radheshyam Saha 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.


(Prof. Bhim Singh) 31.12.07

Electrical Engineering Department

Indian Institute of Technology, Delhi

Hauz Khas, New Delhi- 110 016, India.

Email:- bhimsinghr@gmail.com,

bsingh@ee.iitd.ernet.in

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 up a new horizon of state-of-the-art knowledge on FACTS technology applied immensely in controlling transmission and distribution system. 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 have immensely helped me to do the research work. His continuous monitoring, valuable guidance and input, have been always the 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. I have been always rejuvenated and when I have got the opportunity to discuss with Mrs. Singh. I do express my sincere gratitude to her.

My heartfelt thanks and deep gratitude to Prof. D. P. Kothari, Prof. P. R. Bijwe, Dr. Sanjay Roy (later joined BIT, Pillani) and Dr. G. Bhuvaneswari, 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. M. L. Kothari, Prof. B. P. Singh and Prof. Balasubramanian who have taught me all the relevant course works in IITD and helped a great deal to enrich my knowledge bank. I have really gained a lot from Dr. K. K. Sen who is one of the pioneer in FACTS technology. I do convey my heartfelt thanks and gratitude to him and his family.

Central Electricity Authority (CEA) is my parent organization who has always envisioned to improve and enrich the knowledge and quality of officers. I have got the opportunity to do the

research work at IITD under the sponsorship of CEA. I am proud of being a CEA engineer. I express my profound gratitude to Dr. Subrata Mukhopadhyay, Chief Engineer, CEA (retired), Sh. V. Ramakrishna, Member (PS) and specially to Sh. A. K. Asthana, Chief Engineer, CEA, for extending their valuable supports, co-operation and advice in pursuing the research work.

I am grateful to the staffs of PG section, Central library, Electrical Engineering Department Library for their valuable co-operation. I am extremely grateful to Shri Gurcharan Singh, Sh. Meherban (retired), Sh. Srichand, Sh. Puran Singh, Sh. Jugbeer 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 extremely grateful to Sh. K. P. Singh, Assistant Register (PGS&R), Sh. Ashok Kumar Vashistha and other staffs of PG section for their assistance and co-operation.

I would like to earnestly extend my sincere thanks to Dr. Alope Kanti Deb, Sh. D. Madhan Mohan, Sh. Gaurav Kasal, Sh. Sanjay Gairola, Dr. S. K. Dwivedi, Dr. Sumit Ghatak Choudhury, Dr. Mrs. Sushama Gupta, Dr. Gopinath, Sh. Ilango, Sh. Arun Kumar, Sh. Ravi Kumar for their valuable assistances and co-operation. I am really to appreciate the towering efforts, relentless supports and utmost sincerity provided by Sh. Madhan Mohan, research scholar in the journey to complete my thesis work. It is an exemplary and I am to always cherish his valuable contribution. 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. Sharmila Saha, Raktim Saha(son) and Shreya Saha(daughter) 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 elder brothers, Sh. N. C. Saha and Sh. Basudeb Saha who have always provided the moral supports and enthusiasm in conducting this research work.

I am beholden to almighty and to my param-guru Thakur Ramakrishna Paramhansadeb, holy mother Ma-Sarada Devi, Swami Vivekananda, Swami Ranganathananda (my guru) and Swami Gokulanand. From the place of heaven, they have and will give me the light of strength, knowledge, wisdom and determination to achieve what I have achieved so far.

31/12/07
(R. SAHA)

ABSTRACT

The FACTS (Flexible Alternating Current Transmission System) technology employing self-commutating solid state devices based voltage source converters (VSC) has made a paradigm shift to control power system variables dynamically within sub-cycle period. In this category, STATCOM is a state-of-the art dynamic shunt controller being widely used to control the reactive power in power industries and utilities. It is more versatile than the line-commutating thyristor based static var compensator (SVC) and increasingly used due to its various attributes such as quick response (sub-cycle), less space requirement, optimum voltage platform, versatile operational flexibility, unique controllability, excellent dynamic characteristics and wide area of applications. However, it is yet to be proved economical compared to SVC. In the present power system scenario, applications of STATCOMs are very significant in respect of maximum utilization of transmission system, fast reactive power control and improving security and stability of the network. In view of extensive commercial applications of STATCOMs, investigations on further technological improvement of such controllers are carried out in this thesis.

Out of the multi-pulse and multi-level converter topologies used in STATCOMs, high-pulse order GTO-VSCs based STATCOMs e.g 48-pulse employing eight elementary 6-pulse VSCs interconnected through magnetic circuits, are built for application in high voltage transmission system. The high pulse-order STATCOM has increased the number of solid state devices and magnetic components and thus added to the cost. To minimize converter loss which increases almost proportionally with switching frequency of the controllable switches and quadratically

with the DC voltage, the high power rating STATCOMs generally employ high power GTO based VSCs (GTO-VSC) operated at fundamental frequency switching

Although high-pulse GTO-VSC based STATCOMs are well matured and extensively used in power utilities, it is felt that there is a scope of component level optimization viz. converters, quantum of magnetics etc. without compromising its operating performance. Accordingly, in this thesis low-pulse, two level high power rating STATCOM configurations such as 12-pulse using two elementary 6-pulse VSCs, 18-pulse using three elementary 6-pulse VSCs pulse, 24-pulse using four elementary 6-pulse VSCs are addressed to obtain a competitive operational performance in transmission system application. Such STATCOMs make the compensator economically viable.

It is also felt that employing three level architecture in such low-pulse STATCOMs using NPC GTO-VSCs facilitates the improved performance equivalent to double pulse number STATCOM. These aspects are investigated in this thesis and the various STATCOM simulation models are realized and included as research work.

In addition, it is observed that magnetics is a major component in STATCOMs. With the increase in pulse-order, requirement of magnetics increases proportionally and thus added to the cost of the compensator. It is felt that there is a scope of reduction in magnetics in high power rating GTO-VSCs based STATCOMs and thus saving in cost without compromising harmonics and other operational performances in transmission system applications. The different magnetics configurations requiring less magnetics and leading to saving in cost are addressed for 24-pulse and 48-pulse STATCOMs using two level as well as three level topologies. These issues are successfully investigated in this thesis and the outcome is encouraging.

TABLE OF CONTENTS

	Page No.
Certificate	i
Acknowledgements	iii
Abstract	vii
Table of Contents	ix
List of Figures	xv
List of Tables	xxiii
List of Symbols	xxv
CHAPTER-I INTRODUCTION	1
1.1 General	1
1.2 State of Art	2
1.2.1 Static Synchronous Compensator (STATCOM) Technology and Applications	5
1.2.2 Power Semiconductor Devices used in STATCOM	7
1.2.3 Voltage Sourced Converter Topologies in STATCOM	8
1.2.4 Switching Techniques in STATCOM	10
1.2.5 Multi-Level and Multi-Pulse Topology in STATCOM	10
1.2.6 Magnetics for STATCOM	14
1.2.7 Control Algorithms for STATCOM	15
1.2.8 STATCOM Modeling	16
1.3 Objectives and Scope of Study	20
1.3.1 Analysis, Design and Control of Two-level 12-Pulse STATCOM	20
1.3.2 Analysis, Design and Control of Three-level 12-Pulse STATCOM	21
1.3.3 Analysis, Design and Control of Two-level 18-Pulse STATCOM	21
1.3.4 Analysis, Design and Control of Three-level 18-Pulse STATCOM	21
1.3.5 Analysis, Design and Control of Two-level 24-Pulse STATCOM	22
1.3.6 Analysis, Design and Control of Three-level 24-Pulse STATCOM	22
1.3.7 Analysis, Design and Control of Two-level 48-Pulse STATCOM	22
1.3.8 Analysis, Design and Control of Three-level 48-Pulse STATCOM	23
1.4 Outline of Chapters	23

CHAPTER-II LITERATURE REVIEW	27
2.1 General	28
2.2 Significant Developments	28
2.3 Literature Review on STATCOM Controllers	28
2.3.1 State-of-Art Technology	29
2.3.2 GTO device based VSC-STATCOM	30
2.3.3 PWM-VSC based STATCOM	30
2.3.4 Multi-Level and Multi-Pulse Topologies	32
2.3.5 Control Methodologies	35
2.3.6 STATCOM with Energy Storage	37
2.3.7 STATCOMs in Power System Control	38
2.4 Identified Research Areas	39
2.5 Conclusions	40
CHAPTER-III ANALYSIS, DESIGN AND CONTROL OF TWO-LEVEL 12-PULSE STATCOM	43
3.1 General	43
3.2 Operating Principle and Circuit Configuration	44
3.3 Design of Components	51
3.4 Control Algorithm	55
3.5 MATLAB Based Modeling of STATCOM	55
3.6 Results and Discussion	59
3.6.1 Voltage Regulation	62
3.6.2 Power Factor Control	63
3.6.3 Power Quality Aspects	68
3.7 Conclusions	68
CHAPTER-IV ANALYSIS, DESIGN AND CONTROL OF THREE-LEVEL 12-PULSE STATCOM	71
4.1 General	71
4.2 Operating Principle and Circuit Configuration	72
4.3 Design of Components	76

4.4	Control Algorithm	77
4.5	MATLAB Based Modeling of STATCOM	78
4.6	Results and Discussion	80
4.6.1	Voltage Regulation	81
4.6.2	Dynamic Characteristics	83
4.6.3	Power Quality Aspects	83
4.7	Conclusions	84
CHAPTER-V ANALYSIS, DESIGN AND CONTROL OF TWO-LEVEL 18-PULSE STATCOM		87
5.1	General	87
5.2	Operating Principle and Circuit Configuration	88
5.3	Design of Components	89
5.4	Control Algorithm	92
5.5	MATLAB Based Modeling of STATCOM	92
5.6	Results and Discussion	95
5.6.1	Voltage Regulation	95
5.6.2	Power Factor Control	101
5.6.3	Power Quality Aspects	102
5.7	Conclusions	106
CHAPTER-VI ANALYSIS, DESIGN AND CONTROL OF THREE-LEVEL 18- PULSE STATCOM		107
6.1	General	107
6.2	Operating Principle and Circuit Configuration	108
6.3	Design of Components	112
6.4	Control Algorithm	113
6.5	MATLAB Based Modeling of STATCOM	114
6.6	Results and Discussion	117
6.6.1	Voltage Regulation	118
6.6.2	Dynamic Characteristics	120
6.6.3	Power Quality Aspects	120
6.7	Conclusions	122

CHAPTER-VII	ANALYSIS, DESIGN AND CONTROL OF TWO-LEVEL	123
	24 – PULSE STATCOM	
7.1	General	123
7.2	Operating Principle and Circuit Configuration	123
7.3	Design of Components	125
7.4	Control Algorithm	126
7.5	MATLAB Based Modeling of STATCOM	127
7.6	Results and Discussion	128
	7.6.1 Voltage Regulation	129
	7.6.2 Power Factor Control	131
	7.6.3 Power Quality Aspects	133
7.7	Conclusions	135
CHAPTER-VIII	ANALYSIS, DESIGN AND CONTROL OF THREE-LEVEL	137
	24- PULSE STATCOM	
8.1	General	137
8.2	Operating Principle and Circuit Configuration	138
8.3	Design of Components	141
8.4	Control Algorithm	143
8.5	MATLAB Based Modeling of STATCOM	143
8.6	Results and Discussion	146
	8.6.1 Voltage Regulation	147
	8.6.2 Dynamic Characteristics	149
	8.6.3 Power Quality Aspects	149
8.7	Conclusions	150
CHAPTER-IX	ANALYSIS, DESIGN AND CONTROL OF TWO-LEVEL 48-PULSE	153
	STATCOM	
9.1	General	153
9.2	Operating Principle and Circuit Configuration	154
9.3	Design of Components	155
9.4	Control Algorithm	159
9.5	MATLAB Based Modeling of STATCOM	160

9.6	Results and Discussion	163
9.6.1	Voltage Regulation	164
9.6.2	Power Factor Control	167
9.6.3	Power Quality Aspects	169
9.7	Conclusions	174
CHAPTER-X ANALYSIS, DESIGN AND CONTROL OF THREE-LEVEL 48- PULSE STATCOM		175
10.1	General	175
10.2	Operating Principle and Circuit Configuration	176
10.3	Design of Components	179
10.4	Control Algorithm	182
10.5	MATLAB Based Modeling of STATCOM	182
10.6	Results and Discussion	188
10.6.1	Voltage Regulation	191
10.6.2	Dynamic Characteristics	192
10.6.3	Power Quality Aspects	193
10.7	Conclusions	194
CHAPTER-XI MAIN CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK		197
11.1	General	197
11.2	Main Conclusions	199
11.3	Suggestions for Further Work	203
REFERENCES		205
APPENDICES		229
LIST OF PUBLICATIONS		241
BIO-DATA		242