POWER QUALITY IMPROVEMENT IN THREE–PHASE INPUT AC MAINS FED SWITCHED MODE POWER SUPPLY

By

R KALPANA
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 2012

CERTIFICATE

This is to certify that the thesis entitled, "**Power Quality Improvement In Three-Phase Input AC Mains Fed Switched Mode Power Supply,**" being submitted by **Mrs. R Kalpana** for the award of the degree of **Doctor of Philosophy** is a record of a bonafide research work carried out by her in the Department of Electrical Engineering of Indian Institute of Technology, Delhi.

Mrs. R Kalpana worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our 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: May , 2012

(Prof. G. Bhuvaneswari)
Electrical Engineering Department
Indian Institute of Technology, Delhi
Hauz Khas, New Delhi-110016, India

(Prof. Bhim Singh)
Electrical Engineering Department
Indian Institute of Technology, Delhi
Hauz Khas, New Delhi-110016, India

ACKNOWLEDGEMENTS

I wish to express profound gratitude and indebtness to **Prof. G. Bhuvaneswari** and **Prof. Bhim Singh** for providing me the lifetime opportunity to do the Ph.D. work under their supervision. Their sagacity and vision have played a very important role in guiding me throughout this study. Working under them has been a wonderful experience, which has provided me with a deep insight in the world of research. Continuous monitoring, valuable guidance and time management by them was an inspiring force for me to complete the work. From time to time, they encouraged me for excelling and it is their quest for excellence that has actuated me to improve my work and constantly introspect myself.

My thanks are due for **Prof. Balasubramanian**, **Dr. Sukumar Mishra** and **Dr. B. K. Panigrahi,** all SRC members, for their valuable suggestions during my research work.

The author is grateful to IIT Delhi for providing the research facilities. Thanks are due for **Sh. Gurucharan Singh**, **Sh. Negi, Sh. Srichand** and **Sh. Puran Singh**, Lab Staff of Power Electronics and PG Machines labs for providing all the facilities and help at their disposal during this work.

I extend my special thanks to the fellow research scholars **Ms. Shikha Singh**, **Mr. Chandrasekhar**, **Mr. Anmol Saxena**, **Mr. Sandeep Madishetti**, **Mr. N K Swami Naidu**, **Mr. Sabharaj Arya**, **Mr. S Jeevanand**, **Mr. M. Rajesh**, **Mr. Vuddanti Sandeep**, **Mr. Ashish Srivastava**, **Mr. Priyesh Chauhan**, **Mr. Shanker**, **Ms. Swati Narula**, **Ms. Priya Nayar** and **Ms. Neha Adhikari**. My thanks are also due to **Dr. Gaurav Kasal**, **Dr. Sanjay Gairola**, **Dr. Madan Mohan**, **Dr. Sarsing Gao**, **Dr. Rajagopal**, **Dr. Sanjeev**

Singh and **Dr. Shailendra Sharma** who have been with me for some time during this period and have shown exemplary attitude and dedication for research.

I am indebted for the encouragement and support received from my **parents** and **in-laws**. My special thanks to **Mrs. Laxmi Chandrasekhar** for supporting me indirectly during the research. I gratefully acknowledge the unconditional support of my husband **Mr. V. Ramesh Babu** and thank him for all the patience, co-operation and help, without which this work would not have been possible. Finally, I thank my daughters **R. Charulata** and **R. Divya** who missed me a lot during this period, their sacrifice is unexplainable in words.

Once again, I bow to all those who directly or indirectly helped me but their name are leftout.

May , 2012 **(R Kalpana)**
New Delhi

ABSTRACT

Three-phase ac-dc power converters are widely used as front-end converters in various switched mode power supplies for telecommunications systems, aerospace, military environment etc. Traditionally, ac–dc power conversion has been dominated by diode bridge rectifiers which act as non-linear loads on the power systems and draw input currents which are rich in harmonics and have poor power factor, thus creating the power quality problem for the power distribution network. Different international standards like IEEE-519 and IEC-1000-3-2 have been proposed to maintain the THD (Total Harmonic Distortion) and the Power Factor (PF) within the acceptable levels. This is especially important for guaranteeing universal applicability of telecommunication rectifier systems. Conventional power supplies in the telecommunication systems are being replaced by improved power quality converters, due to the advantages of operational behavior, systems technology, high efficiency and low cost. Different methods for improving the power quality at the three-phase input ac mains feeding medium capacity switched mode power supplies for telecommunication system are investigated in this research work.

The basic requirements of the state-of-the-art telecommunication power supply equipments are to have a sinusoidal unity power factor input current, and also galvanic isolation of the regulated dc output voltage. Single-phase ac mains fed SMPSs meeting this requirement are well known and extensively used. However, for medium power supplies (6kW-18kW) three-phase ac–dc converter topologies are required at the front-end. The challenge is to provide a suitable utility interface with a simple, efficient, low cost and robust three-phase ac-dc converter.

This research work aims at mitigating the harmonics in the input ac mains of three-phase ac-dc converters for medium power 12kW telecom power supplies using various configurations of front-end converters. The ac-dc converters with higher number of pulses known as multipulse converters based on various autoconnected transformer configurations are used to improve the power quality indices at the ac mains.

In this research work, different configurations of autoconnected transformer based multipulse ac-dc converter such as twelve, eighteen, twenty-four pulse converters feeding a medium capacity SMPS are designed, modeled and implemented for improving the power quality at input ac mains. The autoconnected transformers are considered in various configurations such as star, delta, polygon, delta-polygon, hexagon, fork, zig-zag connections etc. The main emphasis has been on reduction of magnetic rating, simpler configuration and ability to perform well under varying load conditions on the SMPS. It is also well known that increasing the number of supply phases also improves the power quality indices in ac-dc converters. Hence, in this work, autoconnected transformer based nine-phase ac-dc converters are also designed, simulated and studied in detail for front-end converters in these SMPSs.

It is practically observed in this research work that the power quality indices in twelve-pulse ac-dc converter feeding 12kW SMPS are not within the IEEE standard limits. In order to reduce the harmonic current at the input ac mains further, a detailed study of combination of twelve pulse ac-dc converter and a passive filter is made through design, simulation and hardware implementation. The effect of different configurations of the twelve-pulse converter and passive shunt filter on power quality indices is also studied for the front-end of telecom power supplies. A novel configuration of twelve-pulse ac-dc converter with a

reduced rating passive shunt filter has been designed, and developed which is able to perform well even under varying load conditions.

Non-conventional pulse numbered ac-dc converters are based on the rectifier having number of input phases, which are not multiples of three. These ac-dc converters can be visualized as a combination of phase staggering and multiphase techniques. In this work, non-isolated non-conventional twenty and twenty-eight pulse ac-dc converters have been designed, modeled and simulated to study their performance for front-end converters of telecom power supplies.

Furthermore, the recent telecom power supplies use three-phase modular converters as the front-end converters. This technology completely eliminates the power transformer at the front-end thereby reducing the size, weight and cost of the overall system. For medium capacity telecom power supplies isolated full-bridge and push-pull modular converters are preferred for low THD and power factor close to unity at the ac mains. In this circuit configuration, three identical single-phase buck/boost ac–dc converters are connected to the three-phase ac mains. Three-phase three-wire, four-wire and three-phase three-wire with virtual neutral configurations have been designed, modeled and simulated for modular ac-dc converters to improve the power quality at the front-end of the telecom power supplies.

The final stage of the SMPS consists of full-bridge or push-pull isolated dc-dc converter. A high speed digital signal processor is used to implement the control for the dc-dc converter in the SMPS. This control has ensured that the output dc voltage is regulated irrespective of supply and load variations and also the supply current drawn is sinusoidal at unity power factor.

TABLE OF CONTENTS

		Page No.
Certificate		i
Acknowledgements		ii
Abstract		iv
Table of Contents		vii
List of Figures		xiv
List of Tables		xxix
List of Symbols		xxxii
CHAPTER I	**INTRODUCTION**	
1.1	General	1
1.2	State of the Art	3
1.3	Objectives and Scope of Study	7
1.3.1	Analysis, Design and Development of Multipulse AC-DC with Passive Filter for Three-Phase AC Mains Fed SMPS	7
1.3.2	Analysis, Design and Development of Multipulse AC-DC Converters for Three-Phase AC Mains Fed SMPS	8
1.3.3	Analysis and Design of Multiphase AC-DC Converters for Three-Phase AC Mains Fed SMPS	8
1.3.4	Analysis, Design and Development of Non-Conventional AC-DC Converters for Three-Phase AC Mains Fed SMPS	8
1.3.5	Analysis and Design of Single-Stage Modular Converters for Three-Phase AC Mains Fed SMPS	9
1.4	Outline of Chapters	9
CHAPTER II	**LITERATURE REVIEW**	
2.1	General	12
2.2	Significant Developments	13
2.3	Literature Review	
2.3.1	12-Pulse AC-DC Converters with Passive Filter	14
2.3.2	18-Pulse AC-DC Converters	15
2.3.3	24-Pulse AC-DC Converters	16
2.3.4	Multiphase AC-DC Converters	17
2.3.5	Non-Conventional AC-DC Converters	18
2.3.6	Single-Stage Modular Buck DC-DC Converters	19
2.3.7	Single-Stage Modular Boost DC-DC Converters	20
2.4	Identified Research Areas	22
2.5	Conclusions	23
CHAPTER III	**CONFIGURATIONS OF THREE-PHASE AC MAINS FED SWITCHED MODE POWER SUPPLY**	
3.1	General	24

3.2 Configuration of the Proposed Three-Phase AC Mains Fed SMPS 25
3.3 Classification of Improved Front-end Power Quality Converters for Three-Phase AC Mains Fed SMPS 26
3.3.1 Multipulse AC-DC Converters with Passive Filter for Three-Phase SMPS 27
3.3.2 Multipulse AC-DC Converters for Three-Phase SMPS 29
3.3.3 Multiphase AC-DC Converters for Three-Phase SMPS 30
3.3.4 Non-Conventional AC-DC Converters for Three-Phase SMPS 31
3.3.5 Modular Single-Stage Converters for Three-Phase SMPS 32
3.4 Classification of DC-DC Converter Topologies for Three-Phase AC Mains Fed Switched Mode Power Supplies 34
3.4.1 Fly-back DC-DC Converter fed Three-Phase SMPS 36
3.4.2 Forward DC-DC Converter fed Three-Phase SMPS 37
3.4.3 Push-Pull DC-DC Converter fed Three-Phase SMPS 38
3.4.4 Half-Bridge DC-DC Converter fed Three-Phase SMPS 39
3.4.5 Full-Bridge DC-DC Converter fed Three-Phase SMPS 39
3.5 Design of Components for Three-Phase SMPS
3.5.1 Design of Full-Bridge DC-DC Converter 40
3.5.2 Design of High Frequency Transformer 41
3.5.3 Design of Rectifier Diodes 45
3.5.4 Design of Output Filter 46
3.6 Control Techniques of DC-DC Converter for Three-Phase SMPS
3.6.1 Voltage-Mode PWM Controller 48
3.6.2 Current-Mode PWM Controller 49
3.7 Hardware Implementation of Controller for Three-Phase SMPS
3.7.1 DSP-dSPACE DS1104 52
3.7.2 Gating Signal Isolation and Amplification Circuit 52
3.7.3 Voltage Sensor Circuit 53
3.7.4 Real Time Modeling Using DSP-dSPACE 54
3.8 Performance of DC-DC Converters for Three-Phase SMPS 56
3.9 Conclusions 60

CHAPTER IV POWER QUALITY IMPROVEMENT IN THREE-PHASE INPUT AC MAINS FED SMPS BASED ON TWELVE-PULSE AC-DC CONVERTER WITH PASSIVE FILTER

4.1 General 62
4.2 Configurations of Twelve-pulse AC-DC Converters for Three-Phase SMPS 63
4.3 Design of Twelve-Pulse AC-DC Converter for Three-Phase SMPS 64
4.4 Analysis of Twelve-Pulse AC-DC Converter for Three-Phase SMPS 69
4.4.1 Efficiency of Overall System 76
4.4.1.1 Losses in the converter 76
4.4.1.2 Losses in the diode bridge rectifier 76
4.4.1.3 Losses in the dc-dc converter 77
4.4.1.4 Losses in the high frequency transformer 77
4.4.1.5 Losses in the output diode 77

4.5	Design of Shunt Passive High Pass Filter	78
4.6	MATLAB Based Modeling and Simulation	79
4.7	Hardware Implementation of Twelve-Pulse Converters with Passive Filter for Three-Phase SMPS	81
4.8	Results and Discussion	81
4.9	Conclusions	92

CHAPTER V POWER QUALITY IMPROVEMENT IN THREE-PHASE INPUT AC MAINS FED SMPS BASED ON EIGHTEEN - PULSE AC-DC CONVERTERS

5.1	General	93
5.2	Configurations of an Eighteen-Pulse AC-DC Converters for Three-Phase SMPS	94
5.3	Design of an Eighteen-Pulse AC-DC Converters for Three-Phase SMPS	95
5.4	Analysis of an Eighteen-Pulse AC-DC Converters for Three-Phase SMPS	100
5.5	MATLAB Based Modeling and Simulation	108
5.6	Hardware Implementation of an Eighteen-Pulse AC-DC Converter for Three-Phase SMPS	109
5.7	Results and Discussion	110
5.8	Conclusions	120

CHAPTER VI POWER QUALITY IMPROVEMENT IN THREE-PHASE INPUT AC MAINS FED SMPS BASED ON TWENTY FOUR -PULSE AC-DC CONVERTERS

6.1	General	121
6.2	Configurations of Twenty Four-Pulse AC-DC Converters for Three-Phase SMPS	122
6.3	Design of Twenty Four -Pulse AC-DC Converter for Three-Phase SMPS	123
6.4	Analysis of Twenty Four -Pulse AC-DC Converter for Three-Phase SMPS	128
6.5	MATLAB Based Modeling and Simulation	134
6.6	Hardware Implementation of Twenty Four -Pulse AC-DC Converters for Three-Phase SMPS	135
6.7	Results and Discussion	135
6.8	Conclusions	143

CHAPTER VII POWER QUALITY IMPROVEMENT IN THREE-PHASE INPUT AC MAINS FED SMPS BASED ON NINE-PHASE AC-DC CONVERTERS

7.1	General	145
7.2	Configurations of Nine-Phase AC-DC Converters for Three-Phase SMPS	145
7.3	Design of Nine-Phase AC-DC Converter for Three-Phase SMPS	147
7.4	Analysis of Nine-Phase AC-DC Converter for Three-Phase SMPS	151
7.5	MATLAB Based Modeling and Simulation	159

7.6 Results and Discussion 160
7.7 Conclusions 168

CHAPTER VIII POWER QUALITY IMPROVEMENT IN THREE-PHASE INPUT AC MAINS FED SMPS BASED ON NON - CONVENTIONAL MULTIPULSE AC-DC CONVERTERS

8.1 General 170
8.2 Configurations of Non-conventional Multipulse Converters for Three-Phase SMPS 171
8.2.1 20-pulse AC-DC converter 171
8.2.2 28-pulse AC-DC converter 172
8.3 Design and Analysis of Non-Conventional Multipulse AC-DC Converters for Three-Phase SMPS
8.3.1 Design of 20-Pulse AC-DC Converter 173
8.3.2 Analysis of 20-Pulse AC-DC Converter 175
8.3.3 Design of 28-Pulse AC-DC Converter 182
8.3.4 Analysis of 28-Pulse AC-DC converter 185
8.4 MATLAB Based Modeling and Simulation
8.4.1 Matlab Model of 20-Pulse AC-DC Converter 192
8.4.2 Matlab Model of 28-pulse AC-DC Converter 193
8.5 Hardware Implementation of Non-Conventional Multipulse AC-DC Converters 195
8.6 Results and Discussion 195
8.6.1 Performance of 20-Pulse AC-DC Converter for Three-Phase SMPS 195
8.6.2 Performance of 28-pulse AC-DC Converter for Three-Phase SMPS 203
8.7 Conclusions 209

CHAPTER IX POWER QUALITY IMPROVEMENT IN THREE-PHASE SINGLE-STAGE MODULAR BOOST DC-DC CONVERTERS

9.1 General 210
9.2 Configurations of Modular Full-Bridge Boost DC-DC Converters fed Three-Phase SMPS 211
9.2.1 Three-Phase Line to Line Full-Bridge DC-DC Converter Fed Three-Phase SMPS 211
9.2.2 Three-Phase Line to Neutral Full-Bridge DC-DC Converter Fed Three-Phase SMPS 212
9.2.3 Three-Phase Line to Virtual Neutral Full-Bridge DC-DC Converter Fed Three-Phase SMPS 212
9.3 Design of Single-Phase Full-Bridge Boost DC-DC Converter Module for Three-Phase SMPS 214
9.3.1 Design Example of Single Phase Full-Bridge Boost DC-DC Converter Module 220
9.4 Configurations of Modular Push-Pull Boost DC-DC Converters fed Three-Phase SMPS 221

9.4.1 Three-Phase Line to Line Push-Pull DC-DC Converter fed Three-Phase SMPS 221
9.4.2 Three-Phase Line to Neutral Push-Pull DC-DC Converter fed Three-Phase SMPS 222
9.4.3 Three-Phase Line to Virtual Neutral Push-Pull DC-DC Converter fed Three-Phase SMPS 223
9.5 Design of Single Phase Push–Pull Boost DC-DC Converter Module for Three-Phase SMPS 223
9.5.1 Design Example of Single Phase Push-Pull DC-DC Converter Module 227
9.5.2 Efficiency of the Converter 228
9.6 Control Technique Implementation for DC-DC Converters fed Switched Mode Power Supplies 232
9.7 MATLAB Based Modeling and Simulation 232
9.7.1 Modeling of Three-Phase Line to Line Full-Bridge Boost DC-DC Converter fed Three-Phase SMPS 233
9.7.2 Modeling of Three-Phase Line to Neutral Full-Bridge Boost DC-DC Converter fed Three-Phase SMPS 233
9.7.3 Modeling of Three-Phase Line to Virtual Neutral Full-Bridge Boost DC-DC Converter fed Three-Phase SMPS 233
9.7.4 Modeling of Three-Phase Line to Line Push-Pull Boost DC-DC Converter fed Three-Phase SMPS 236
9.7.5 Modeling of Three-Phase Line to Neutral Push-Pull Boost DC-DC Converter fed Three-Phase SMPS 236
9.7.6 Modeling of Three-Phase Line to Virtual Neutral Push-Pull Boost DC-DC Converter fed Three-Phase SMPS 238
9.8 Results and Discussion 238
9.8.1 Performance of Three-Phase Line to Line Full-Bridge Boost DC-DC Converter fed Three-Phase SMPS 238
9.8.2 Performance of Three-Phase Line to Neutral Full-Bridge Boost DC-DC Converter fed Three-Phase SMPS 241
9.8.3 Performance of Three-Phase Line to Virtual Neutral Full-Bridge Boost DC-DC Converter fed Three-Phase SMPS 243
9.8.4 Performance of Three-Phase Line to Line Push-Pull Boost DC-DC Converter fed Three-Phase SMPS 246
9.8.5 Performance of Three-Phase Line to Neutral Push-Pull Boost DC-DC Converter fed Three-Phase SMPS 248
9.8.6 Performance of Three-Phase Line to Virtual Neutral Push-Pull Boost DC-DC Converter fed Three-Phase SMPS 251
9.9 Conclusions 253

CHAPTER X POWER QUALITY IMPROVEMENT IN THREE-PHASE SINGLE-STAGE MODULAR BUCK DC-DC CONVERTERS

10.1 General 254
10.2 Configurations of Modular Full-Bridge Buck DC-DC Converters for 255

Three-Phase SMPS
10.2.1 Three-Phase Line to Line fed Full-Bridge DC-DC Converter Fed Three-Phase SMPS 255
10.2.2 Three-Phase Line to Neutral Full-Bridge DC-DC Converter Fed Three-Phase SMPS 256
10.2.3 Three-Phase Line to Virtual Neutral Full-Bridge DC-DC Converter Fed Three-Phase SMPS 257
10.3 Design of Single-Phase Full-Bridge Buck DC-DC Converter Module for Three-Phase SMPS 257
10.3.1 Design Example of Single-Phase Full-Bridge Buck DC-DC Converter Module 264
10.3.2 Design of Zig-Zag Transformer 265
10.4 Configurations of Modular Push-Pull Buck DC-DC Converters for Three-Phase SMPS 267
10.4.1 Three-Phase Line to Line Push-Pull DC-DC Converter Fed Three-Phase SMPS 268
10.4.2 Three-Phase Line to Neutral Push-Pull DC-DC Converter Fed Three-Phase SMPS 269
10.4.3 Three-Phase Line to Virtual Neutral Push-Pull DC-DC Converter Fed Three-Phase SMPS 269
10.5 Design of Single-Phase Push–Pull Buck DC-DC Converter Module for Three-Phase SMPS 270
10.5.1 Design Example of Single-Phase Push-Pull DC-DC Converter Module 276
10.6 MATLAB Based Modeling and Simulation
10.6.1 Modeling of Three-Phase Line to Line Full-Bridge DC-DC Converter fed Three-Phase SMPS 278
10.6.2 Modeling of Three-Phase Line to Neutral Full-Bridge DC-DC Converter fed Three-Phase SMPS 279
10.6.3 Modeling of Three-Phase Line to Virtual Neutral Full-Bridge DC-DC Converter fed Three-Phase SMPS 280
10.6.4 Modeling of Three-Phase Line to Line Push-Pull DC-DC Converter fed Three-Phase SMPS 280
10.6.5 Modeling of Three-Phase Line to Neutral Push-Pull DC-DC Converter fed Three-Phase SMPS 281
10.6.6 Modeling of Three-Phase Line to Virtual Neutral Push-Pull DC-DC Converter fed Three-Phase SMPS 282
10.7 Results and Discussion
10.7.1 Performance of Three-Phase Line to Line Full-Bridge Buck DC-DC Converter fed Three-Phase SMPS 283
10.7.2 Performance of Three-Phase Line to Neutral Full-Bridge Buck DC-DC Converter fed Three-Phase SMPS 285
10.7.3 Performance of Three-Phase Line to Virtual Neutral Full-Bridge Buck DC-DC Converter fed Three-Phase SMPS 289
10.7.4 Performance of Three-Phase Line to Line Push-Pull Buck DC-DC Converter fed Three-Phase SMPS 293

10.7.5 Performance of Three-Phase Line to Neutral Push-Pull Buck DC-DC Converter fed Three-Phase SMPS 297
10.7.6 Performance of Three-Phase Line to Virtual Neutral Push-Pull Buck DC-DC Converter fed Three-Phase SMPS 299
10.8 Conclusions 301

CHAPTER XI MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK
11.1 General 303
11.2 Main Conclusions 303
11.3 Suggestions for Further Work 309

REFERENCES 312

APPENDICES 337

LIST OF PUBLICATIONS 348

BIO-DATA 349