

**POWER QUALITY IMPROVEMENT AND SENSOR
REDUCTION IN PERMANENT MAGNET SYNCHRONOUS
MOTOR DRIVES**

by

SANJEET KUMAR DWIVEDI

Department of Electrical Engineering

Submitted,

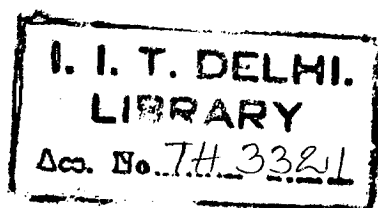
**In fulfillment of the requirements of the degree of Doctor of
Philosophy,**

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
MAY 2006**

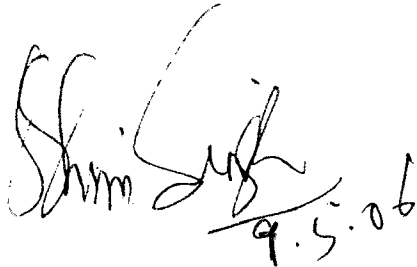
Sensor reduction - motor drives
Permanent magnet motor drives



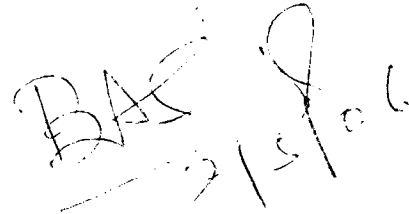
Th
621.318.2/.3
DWI-P

CERTIFICATE

Certified that the thesis entitled “**Power Quality Improvement and Sensor Reduction in Permanent Magnet Synchronous Motor Drive**” which is being submitted by **Mr. Sanjeet Kumar Dwivedi** for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student’s own work carried out by him under our joint supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.



(Prof. BHIM SINGH)
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi – 110 016, INDIA
Email: bsingh@ee.iitd.ac.in
bhimsinghr@gmail.com



(Prof. B. P. SINGH)
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi – 110 016, INDIA
Email: bsingh@ee.iitd.ac.in

ACKNOWLEDGEMENTS

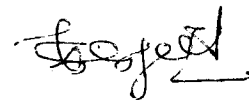
The author wishes to express profound gratitude and indebtedness to his supervisors **Prof. Bhim Singh** and **Prof. B.P. Singh** for providing invaluable guidance, support and encouragement during the course of this research work. The author is grateful to the members of the research committee, namely, **Prof. J.K. Chatterjee, Prof. T.S. Bhatti and Dr. (Mrs.) G. Bhuvaneshwari** for their valuable suggestions and critical comments throughout the course of this work.

The author is thankful to **Mr. Meharban Singh, Mr. Gurucharan Singh, Mr. Sreechand and Mr. Puran Singh** and other staff members of the P.G. Machines and Drives Laboratory, at I.I.T. Delhi for their sustained help and cooperation during this research work.

The author extends his special thanks to his fellow research scholars **Mr. Vishal Verma, Dr. Mukesh, Dr. S. Ghatak Choudhary, Mr. Sanjay Gairola, Mr. Vipin, Mr. Gaurav, Mr. Madhan** and M. Tech Scholars **Mr. Rajesh Kumar Singh, Mr. Jitendra Solanki and Mr. Devendra Goyal** for their help and cooperation.

The sponsorship provided by the parent institute, **Indira Gandhi Engineering College Sagar, (M.P.)** and the QIP scholarship awarded by the ministry of H.R.D., Govt. of India are gratefully acknowledged.

The author appreciates the encouragement and support received from his parents **Smt. Pushpa Dwivedi and Shri Bhanu Pratap Dwivedi**, his sisters **Ad. Savita, Dr. Sarita, Ms. Samidha** and brother **Abhishek**. The author gratefully acknowledges unstinted support of his wife **Alka** and thanks her for her patience, cooperation and help in completing this research work. Finally, the author thanks his daughter **Gargi**, and son **Gaurav** who missed a lot of enjoyable time.



(Sanjeet Kumar Dwivedi)

9th May, 2006
New Delhi

ABSTRACT

The availability of improved quality Permanent Magnet (PM) material has generated a lot of interest in the development of Permanent Magnet Brushless (PMBL) motors. This has gained further impetus from the development of high power low cost switching devices and high-speed digital signal processors. Together, they have made the drive system flexible, compact and the overall cost of the PMBL motor drive has been reduced considerably. These motors are, therefore becoming an attractive option for applications in Heating Ventilating and Air-conditioning (HVAC) systems, refrigerators, washing machines and many other cases. Considering these attractive features, the PMBL motor drive is selected for this study with a view to improving its performance and identifying therefrom some aspects of the problem worthy of further investigation.

PMBL motors have two types of flux distribution, the one with sinusoidal distribution is named as Permanent Magnet Synchronous Motor (PMSM), while the other with trapezoidal flux-distribution is named as Permanent Magnet Brushless DC Motor (PMBLDCM). In closed loop variable speed drive (VSD) applications, PMSMs utilize two types of controls, namely the Vector Control (VC) and the Direct Torque and Flux Control (DTC). These two control techniques are having their own inherent advantages and disadvantages, and depending upon the requirement of application either the vector control or the direct torque control technique is used for the control of PMSM drive. Both techniques have been considered in this work with a view to comparing their usefulness for PMSM drive used in small ratings domestic appliances such as, washing machines, air-conditioners and refrigerators.

The investigation reported in this thesis deals with the hardware development of vector controlled and direct torque controlled PMSM drives. This includes the development of power circuit, interfacing circuit and control circuit. The control algorithm alongwith the

generation of switching signals are developed in assembly language and are executed in a Digital Signal Processor (DSP), namely, ADMC401 developed by Analog Devices (AD). The experimental responses are obtained for different operating conditions, such as starting, speed reversal, load perturbation and steady-state conditions for both VC and DTC techniques. The simulated results are compared with test results obtained from the DSP based implementation of the system to validate the developed model of the PMSM drive systems. The results of vector controlled and direct torque controlled PMSM drives are compared to examine the usefulness of the control techniques.

The transient response of the drive system is greatly affected by the choice of speed controller. Four different types of speed controllers, namely the Proportional Integral (PI) controller, the sliding mode controller (SMC), the fuzzy pre-compensated PI (FPPI) controller and the hybrid fuzzy PI (HFPI) speed controller have been considered in this work and their effectiveness have been examined with a view to selecting an appropriate controller for a given application. These controllers for the PMSM drives are implemented in the assembly language and executed in DSP for both VC and DTC techniques.

Sensor reduction, both electrical and mechanical, has been one of the important aims of system designer with a view to enhancing the reliability of the drive and reducing its overall cost. Advances in digital signal processors have facilitated the development of mechanical sensorless control of ac drives. However, they still suffer from the degraded performance at low speeds owing to the difficulty in flux estimation without the sensing of speed. Methods based on standard motor model are affected by errors in sensing and are sensitive to stator resistance variation. In this work, the effectiveness of some of the existing schemes of sensorless control have been examined with a view to developing a suitable scheme for the operation of PMSM drive in sensorless mode. A stator terminal based sensing technique has been investigated for speed estimation without using a mechanical sensor. The mechanical

sensorless control scheme developed for PMSM drive is implemented on DSP and the test results are compared with simulated results to validate the algorithm.

In both, the vector and direct torque controlled PMSM drives, the ac mains experiences poor power quality due to the presence of diode bridge rectifier, which is utilized for feeding power to the voltage source inverter of the PMSM drive. The diode bridge rectifier has a low operating power factor, in addition to causing distortion in input supply current and harmonics injection into the ac mains. Therefore, the necessity of power quality improvement in PMSM drive has led to the development of improved power quality ac-dc converters by using different passive and /or active waveshaping topologies. For improving the power quality of input ac mains, different types of passive waveshaping topologies are investigated for feeding power to the single-phase diode bridge rectifier of the PMSM drive. These filters are designed and mathematically modeled to study their effectiveness. The dynamic as well as the steady state performances of the drive are simulated in MATLAB environment with PSB/Simulink toolboxes. The developed prototypes of these topologies for feeding power to PMSM drives are tested to validate the design and to obtain the corresponding simulated performance.

The passive waveshaping topologies are not capable to regulate the dc-link voltage of VSI of PMSM drive. For regulation of dc-link voltage as well as to achieve the improved power quality performance, the boost power factor correction (PFC) converter topologies both in unidirectional and bi-directional modes of power flow are used. In this investigation, three unidirectional power flow active waveshaping converter topologies, namely, the single switch boost PFC converter, two switch asymmetrical and symmetrical boost PFC converters along with one bi-directional power flow converter topology, namely, the voltage source converter have been designed and analysed. The performance simulation of different topologies has been carried out using the MATLAB along with its toolboxes. The corresponding hardware

implementation of these topologies includes development of power circuit, interfacing circuit, the control circuit for single switch boost PFC converter, and symmetrical two-switch boost PFC converter respectively. The control algorithm alongwith the generation of PWM switching signals are developed in assembly language and executed in DSP with a view to reducing the hardware. The PMSM drive system using one or the other of these waveshapers is analysed and the resulting improvement in the power quality is compared under varying loads.

While using these topologies with active waveshaping techniques the isolation between ac and dc is not possible which is desired in a number of applications, and also they require voltage and current sensors for their control. The use of high frequency transformer in isolated topologies of ac-dc converters in discontinuous conduction mode requires only the dc link voltage feedback for improving the power quality at the ac mains. Due to the isolation of the input and output, these converters prove to be a better alternative among the front end PFC converters in the small rating drives used in the domestic appliances, medical equipments and many other applications. In this investigation, different topologies of high frequency transformer isolated ac-dc converters are modeled in the PSIM software. The hardware developments of isolated active waveshaping ac-dc converter topologies include development of buck-boost converter in discontinuous conduction mode of operation with reduced sensor requirement and improved power quality features. The performance of the PMSM drive system with varying loads is compared and analysed for the improvement in power quality.

TABLE OF CONTENTS

	Page No.
CERTIFICATE	i
ACKNOWLEDGMENTS	ii
ABSTRACT	iii
TABLE OF CONTENTS	vii
LIST OF FIGURES	xv
LIST OF TABLES	xxvi
LIST OF SYMBOLS	xxvii
 CHAPTER I INTRODUCTION	 1
1.1 General	1
1.2 Development of PMBL Motors	3
1.3 Vector control of Permanent Magnet Synchronous Motor	4
1.4 Direct Torque Control of Permanent Magnet Synchronous Motor	5
1.5 Power Quality and Sensor Reduction Problems	6
1.6 Some Important Aspects of Work	7
1.7 Scope of Work	11
1.8 Outline of Chapters	14
 CHAPTER II LITERATURE SURVEY	 17
2.1 General	17
2.2 Development of Permanent Magnet Synchronous Motor Drives	17
2.3 Vector Controlled PMSM Drives	18
2.4 DTC Based PMSM Drives	21
2.5 Sensor Reduction in PMSM Drives	23
2.6 Power Quality Improvements in PMSM Drives	25
2.7 Conclusions	30
 CHAPTER III MODELING AND IMPLEMENTATION OF VECTOR CONTROLLED PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE	 31
3.1 General	31
3.2 Operating Principle of Vector Control Technique	31
3.3 Mathematical Model of Vector Controlled PMSM Drives	32
3.3.1 Modeling of Speed Controllers	32
3.3.1.1 PI Controller	33
3.3.1.2 Sliding Mode Controller	33
3.3.1.3 Fuzzy Precompensated PI Controller	35
3.3.1.3.1 Fuzzy Pre-compensator	36

3.3.1.3.11	Fuzzy Logic control	36
3.3.1.3.12	Fuzzification	36
3.3.1.3.13	Decision Making	37
3.3.1.3.14	Defuzzification	37
3.3.1.4	Hybrid Fuzzy PI Controller	37
3.3.2	Modeling of Reference Winding Currents Generation	41
3.3.3	Modeling of PWM Current Controller	41
3.3.4	Modeling of PMSM	43
3.3.5	Modeling of VSI	44
3.4	MATLAB Based Model of Vector Controlled PMSM Drive System	45
3.4.1	Modeling using Power System Blockset (PSB) Toolbox	45
3.4.1.1	Speed Controller	45
3.4.1.2	Field Weakening Controller	47
3.4.1.3	Reference Winding Current Generation	47
3.4.1.4	Current Controller Pulse Width Modulator	47
3.5	Description of DSP Based Vector Controlled PMSM Drive	47
3.5.1	Development of signal Conditioning Circuits	49
3.5.2	Development of Power circuits of the Drive	52
3.6	DSP Based Software Implementation of Vector Controlled PMSM Drive	52
3.6.1	Reference Speed Input	52
3.6.2	Sensing of Rotor Position Signals	53
3.6.3	Speed Sensing	53
3.6.4	Speed Controller	53
3.6.5	Reference Winding Current Generation	55
3.6.6	Switching Signal Generation for Voltage Source Inverter	55
3.7	Testing of Vector Controlled PMSM Drive	55
3.7.1	Testing of Control Circuits	55
3.7.2	Testing of Power Circuits	56
3.8	Results and Discussion	57
3.8.1	Starting Dynamics of Vector Controlled PMSM Drive	58
3.8.2	Load Perturbation of Vector Controlled PMSM Drive	61
3.8.3	Speed Reversal Dynamics of Vector Controlled PMSM Drive	62
3.8.4	Steady State Performance of Vector controlled PMSM Drive	68
3.8.5	Comparative Study Among different Speed Controller	68
3.9	Conclusions	84

CHAPTER IV	MODELING AND IMPLEMENTATION OF DIRECT TORQUE CONTROLLED PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE	85
4.1	General	85
4.2	Operating Principle of Direct Torque Controlled PMSM Drive	85
4.3	Mathematical Model of DTC Based PMSM Drive	87
4.3.1	Modeling of Speed Controllers	90

4.3.2	Modeling of Field Weakening Controller	90
4.3.3	Modeling of Torque, Flux and Sector Estimator	90
4.3.3.1	Estimation of Stator Flux Linkages	91
4.3.3.2	Estimation of Developed Electromagnetic Torque	92
4.3.3.3	Estimation of Sector	92
4.3.4	Modeling of Torque and Flux Hysteresis Comparator	92
4.3.5	Modeling of VSI	93
4.3.6	Modeling of PMSM	93
4.4	MATLAB Based Model of Direct Torque Controlled PMSM Drive System	94
4.4.1	Modeling using Power System Blockset (PSB) Toolbox	94
4.4.1.1	Speed Controller	94
4.4.1.2	Field Weakening Controller	95
4.4.1.3	Torque, Flux and Sector Estimation	95
4.4.1.4	Torque and Flux Hysteresis Comparator	95
4.5	DSP Based Implementation of Direct Torque Controlled PMSM Drive	96
4.5.1	Development of Signal Conditioning Circuits	97
4.5.2	Development of Power Circuits of the Drive	97
4.6	DSP Based Software Implementation of Direct Torque Controlled PMSM Drive	97
4.6.1	Reference Speed Input	100
4.6.2	Sensing of Rotor Position Signals	100
4.6.3	Speed Sensing	100
4.6.4	Speed Controller	101
4.6.5	Field Weakening Controller	101
4.6.6	Estimation of Flux, Torque and Sector	101
4.6.7	Flux and Torque Hysteresis Comparator	101
4.6.8	Optimal Switching Signal Generation for Voltage Source Inverter	102
4.7	Testing of DTC Based PMSM Drive	102
4.7.1	Testing of Control Circuits	102
4.7.2	Testing of Power Circuits	103
4.8	Results and Discussion	104
4.8.1	Starting Dynamics of Direct Torque Controlled PMSM Drive	105
4.8.2	Load Perturbation on Direct Torque Controlled PMSM Drive	112
4.8.3	Speed Reversal Dynamics of Direct Torque Controlled PMSM Drive	113
4.8.4	Steady State Performance of Direct Torque Controlled PMSM Drive	118
4.8.5	Comparative Performance of Vector Controlled and DTC Based PMSM Drive	118
4.9	Conclusions	134
CHAPTER V	SENSOR REDUCTION IN VECTOR CONTROLLED PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE	136
5.1	General	136
5.2	Sensors Requirements in Vector Controlled PMSM Drive	136
5.3	Review of Mechanical Sensors Reduction Techniques in PMSM Drive	137
5.3.1	Back Emf Based Rotor Position Estimation Technique	138

5.3.2	Stator Voltage and Winding Currents Based Techniques	138
5.3.3	Observer Based Sensorless Estimation of Position and Speed	138
5.3.4	High Frequency Carrier signal Injection Method for Estimation of Position and Speed	138
5.3.5	Stochastic Filtering Based Sensorless Estimation of Position and Speed	139
5.3.6	Current and Voltage Model Based Sensorless Algorithms	139
5.3.7	Artificial Intelligence Based Position and Speed Estimation	140
5.4	Electrical Sensors Reduction in PMSM Drive	140
5.5	Sensorless Vector Controlled PMSM Drives	142
5.5.1	Stator Voltage Estimation	144
5.5.2	Winding Current Estimation	144
5.5.3	Flux Estimation	145
5.5.4	Position Estimation	145
5.5.5	Speed Estimation	146
5.6	MATLAB Based Model of Sensorless Vector Controlled PMSM Drive	146
5.6.1	Flux Estimator	147
5.6.2	Position and Speed Estimation	147
5.6.3	Speed Controller	147
5.6.4	Reference Winding Current Generation	147
5.6.5	Current Controlled Pulse Width Modulator	149
5.7	DSP Based Hardware Implementation of Sensorless Vector Controlled PMSM Drive	149
5.7.1	Development of Signal Conditioning Circuits	150
5.7.2	Development of Power Circuits of the Drive	150
5.8	DSP Based Software Implementation of Sensorless Vector Controlled PMSM Drive	150
5.8.1	Reference Speed Input	152
5.8.2	Estimation of stator Flux and Position of Rotor	152
5.8.3	Speed Estimation	152
5.8.4	Speed Controller	152
5.8.5	Reference Winding Currents Generation	153
5.8.6	Switching Signal Generation for Voltage Source Inverter	153
5.9	Testing of Sensorless Vector Controlled PMSM Drive	153
5.9.1	Testing of Control Circuits	154
5.9.1	Testing of Power Circuits	154
5.10	Results and Discussion	155
5.10.1	Starting Dynamics of Sensorless PMSM Drive	155
5.10.2	Load Perturbation of Sensorless PMSM Drive	156
5.10.3	Speed Reversal Dynamics of Sensorless PMSM Drive	159
5.10.4	Steady State Performance of Sensorless PMSM Drive	159
5.11	Conclusions	159

CHAPTER VI	SENSOR REDUCTION IN DIRECT TORQUE CONTROLLED PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE	164
6.1	General	164
6.2	Sensors Requirements in Direct Torque Controlled PMSM Drive	164
6.3	Mechanical Sensors Reduction Techniques in DTC PMSM Drive	165
6.4	Electrical Sensors Reduction in PMSM Drive	165
6.5	Sensorless Direct Torque Controlled PMSM Drives	165
6.5.1	Stator Voltage Estimation	167
6.5.2	Winding Current Estimation	167
6.5.3	Flux Estimation	169
6.5.4	Speed Estimation	169
6.6	MATLAB Based Model of Sensorless DTC PMSM Drive	169
6.6.1	Flux and Torque Estimator	170
6.6.2	Sector and Speed Estimation	170
6.6.3	Speed Controller	170
6.6.4	Field Weakening Controller	171
6.6.5	Torque and Flux Hysteresis Comparator	171
6.7	DSP Based Hardware Implementation of Sensorless Direct Torque Controlled PMSM Drive	171
6.7.1	Development of Signal Conditioning Circuits	173
6.7.2	Development of Power Circuits of the Drive	173
6.8	DSP Based Software Implementation of Sensorless Direct Torque Controlled PMSM Drive	174
6.8.1	Reference Speed Input	174
6.8.2	Estimation of Stator Flux	174
6.8.3	Speed Estimation	176
6.8.4	Speed Controller	176
6.8.5	Flux and Torque Hysteresis Comparator	176
6.8.6	Optimal Switching Signal Generation for Voltage Source Inverter	176
6.9	Testing of Sensorless Direct Torque Controlled PMSM Drive	177
6.10	Results and Discussion	177
6.10.1	Starting Dynamics of Sensorless Direct Torque Controlled PMSM Drive	178
6.10.2	Load Perturbation of Sensorless Direct Torque Controlled PMSM Drive	178
6.10.3	Speed Reversal Dynamics of Sensorless DTC PMSM Drive	181
6.10.4	Steady State Performance of Sensorless Direct Torque Controlled PMSM Drive	181
6.11	Comparison of Sensorless Vector Controlled and Direct Torque Controlled PMSM Drive	185
6.12	Conclusions	185

CHAPTER VII	PASSIVE WAVESHAPING TECHNIQUES FOR POWER QUALITY IMPROVEMENTS IN PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE	187
7.1	General	187
7.2	Classification of Passive Waveshaping Techniques	188
7.2.1	Diode Bridge with DC Capacitive Filter	189
7.2.2	Diode Bridge with DC Inductive-Capacitive Filter	189
7.2.3	Diode Bridge with AC Series Inductive-Capacitive Filter	189
7.2.4	Diode Bridge with AC Series Inductive and Compensating Capacitor Filter	189
7.3	Design and Modeling of Passive Waveshaping Topologies	191
7.3.1	Design and Modeling for DC Capacitive Filter	191
7.3.2	Design and Modeling for DC Inductive-Capacitive Filter	193
7.3.3	Design and Modeling for AC Series Inductive-Capacitive Filter	194
7.3.4	Design and Modeling for AC Series Inductive and Compensating Capacitor Filter	195
7.4	MATLAB Based Model of Passive Waveshaping Techniques for Feeding Vector Controlled PMSM Drive	196
7.5	Hardware Implementation of Passive Waveshaped Diode Bridge Converters for Feeding Vector Controlled PMSM Drive	197
7.6	Results and Discussion	198
7.6.1	Starting Performance	198
7.6.2	Load Perturbation Performance	201
7.6.3	Steady State Performance	211
7.6.4	Power Quality Improvements	211
7.6.5	Comparison of Different Passive Waveshaping Topologies	214
7.7	Conclusions	214
CHAPTER VIII	ACTIVE WAVESHAPING TECHNIQUES FOR POWER QUALITY IMPROVEMENTS IN PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE	220
8.1	General	220
8.2	Classification of Active Waveshaping Techniques	221
8.2.1	Single Switch Boost PFC Converter	221
8.2.2	Symmetrical Two Switch Boost PFC Converter	222
8.2.3	Asymmetrical Two Switch Boost PFC Converter	222
8.2.4	Voltage Source Converter (VSC)	223
8.3	Design and Modeling of Active Waveshaping Converters	223
8.3.1	Design and Modeling of Single Switch Boost PFC Converter	225
8.3.2	Design and Modeling of Two Switch Boost PFC Converter	230
8.3.3	Design and Modeling of Asymmetrical Two Switch Boost PFC Converter	232
8.3.4	Design of and Modeling Voltage Source Converter (VSC)	233
8.4	MALAB Based Model of Single Phase Improved Power Quality Converters for Feeding VC PMSM Drive	234

8.5	Hardware Implementation of Single Phase Improved Power Quality Converters for Feeding PMSM Drive	235
8.5.1	Development of Power Circuits for Improved Power Quality AC-DC Converters	235
8.5.2	Development of Control Circuits for Improved Power Quality AC-DC Converters	235
8.5.3	Development of Signal Conditioning Circuits	239
8.6	DSP Based software Implementation of Two Switch AC-DC Converter	239
8.6.1	Reference DC Link Voltage Input	240
8.6.2	Sensing of AC Mains and DC Link Voltage Signal	240
8.6.3	Voltage Controllers	240
8.6.4	Reference Inductor Currents Generation	243
8.6.5	Switching signal Generation for Two switch Boost AC-DC Converter	243
8.7	Testing of Two Switch AC-DC Converter	243
8.7.1	Testing of Control Circuit	243
8.7.2	Testing of Power Circuit	244
8.8	Results and Discussion	245
8.8.1	Starting Response of PMSM Drive with AC-DC Converters	248
8.8.2	Load Perturbation Performance of the Converters	248
8.8.3	Speed Reversal Performance	249
8.8.4	Steady State Performance	249
8.8.5	Power Quality Improvements	258
8.8.6	Comparison of Active Waveshaping AC-DC Converter Topologies	261
8.9	Conclusions	261

CHAPTER IX	ISOLATED ACTIVE WAVESHAPING TECHNIQUES FOR POWER QUALITY IMPROVEMENTS IN PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE	268
9.1	General	268
9.2	Classification of Isolated Active Waveshaping Techniques in AC-DC Converter Feeding VC Based PMSM Drive	269
9.3	Design of Isolated Active Waveshaping Converters in DCM of Operation	271
9.3.1	Design of AC-DC Cuk Converter	271
9.3.2	Design of AC-DC Sepic Converter	279
9.3.3	Design of AC-DC Flyback Converter	285
9.3.4	Design of AC-DC Zeta Converter	290
9.4	PSIM based Simulation of High Frequency Isolated AC-DC Converters for Feeding PMSM Drive	296
9.5	DSP Based Hardware Implementation of Single Phase Improved Power Quality Converters for Feeding PMSM Drive	299
9.5.1	Development of Signal Conditioning Circuits	300
9.5.2	Development of Power Circuits of the Converter	300
9.6	DSP Based Software Implementation of High Frequency Isolated AC-DC Converters	303

9.6.1	Reference DC Link Voltage Input	303
9.6.2	Filtering of Sensed DC Link Voltage	303
9.6.3	PI Voltage Controller	304
9.6.4	Switching Signal Generation for Isolated AC-DC Converter	304
9.7	Testing of High Frequency Isolated AC-DC Converters	304
9.7.1	Testing of Power Circuit	305
9.7.2	Testing of Control Circuit	305
9.8	Results and Discussion	305
9.8.1	Starting Performance	308
9.8.2	Steady State Performance	308
9.8.3	Load Perturbation Performance	309
9.8.4	Power Quality Improvements	309
9.8.5	Comparison of different Isolated AC-DC Converters Topologies	326
9.9	Conclusions	340
CHAPTER X	MAIN CONCLUSIONS AND SUGGESTION FOR FURTHER WORK	342
10.1	General	342
10.2	Main Conclusions	343
10.3	Suggestions for Further Work	345
		347
REFERENCES		371
APPENDICES		380
LIST OF PUBLICATIONS		383
BIO-DATA		