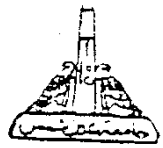


AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

ELECTRICAL POWER AND MACHINES DEPARTMENT

A Microprocessor Based Reactive Power Compensator

A Thesis Submitted in Fulfillment of the Requirement of the Degree of Doctor of Philosiphy of Science in Electrical Engineering To Ain Shams University, Faculty of Engineering, Elect. Power & Machines Dept.

ومنالة

BY

ADEL ABDEL-MONEIM SAYED AHMED

B.Sc. Elect. Eng., Ain Shams University, 1982,
M.Sc. Elect. Eng., Ain Shams University, 1988.

621.3916
A . A

Supervised by

Prof. Dr. A. A. EL SATTAR

Elect. Power and Machine Dept., Faculty of Engineering, Ain Shams University

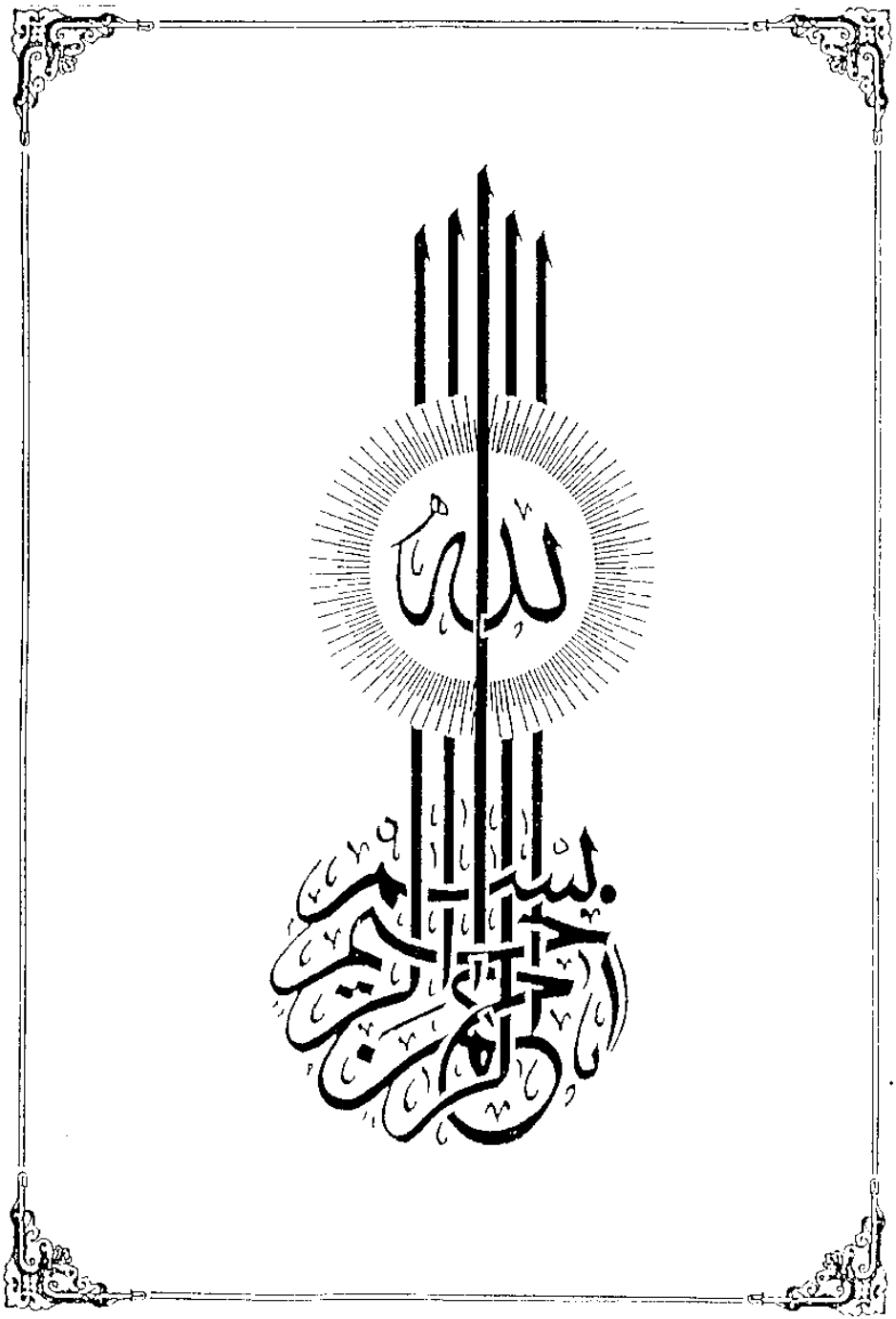
Dr. P. MEHTA & **Dr. M. K. DARWISH**

Electrical Engineering & Electronics, Brunel University, U.K.

CAIRO 1993

Central Library - Ain Shams University

Central Library - Ain Shams University



Central Library - Ain Shams University

EXAMINERS COMMITTEE

Name, Title & Affiliation *Signature*

1. ***Prof. Dr.*** **A.M. El Tobshy**
   Professor, Dept. of Electrical Power and Machines, Faculty of Engineering, Cairo University

2. ***Prof. Dr. M. S. Morsy***
   Professor, Dept. of Electrical Power and Machines, Faculty of Engineering, Ain Shams University

3. ***Prof. Dr. A. A.Sattar***
   Professor, Dept. of Electrical Power and Machines, Faculty of Engineering, Ain Shams University

4. ***Dr. P. Mehta***
   Reader,Department of Electrical Engineering and Electronics, Brunel University , U. K.

Central Library - Ain Shams University

STATEMENT

This dissertation is submitted to Ain Shams University for the degree of Doctor of Philosiphy in Electrical Engineering.

This work included in this thesis was carried out by the author. No part of this thesis has been submitted for a degree or a qualification at other university or institution.

Date :

Signature :

Name : Adel Abdel Moniem Sayed Ahmed

Central Library - Ain Shams University

ACKNOWLEDGEMENT

The author gratefully acknowledges his indebtedness to *Prof. A. A. El-Sattar* for his invaluable guidance and encouragement throughout the course of this research work.

The auther wishes to express his deep and sincere gratitude to his supervisors, *Dr. P. Mehta* and *Dr. M. Darwish* for their enlightened supervision, kind assistance, encouragement and constructive suggestion throughout the course of this research work. Thanks is due to *Dr. Mostafa Darwish* for his valuable assistance discussions and many help.

The auther is grateful to the Head and all staff members of Electrical Power & Machines Departement in the Faculty of Engineering, Ain Shams University.

The auther wishes to thank professor G. Musgrave, Head of Department of Electrical Engineering and Electronics, Brunel University, for providing research facilities and his agreement for open the Channel Scheme between Ain Shams University and Brunel University.

He expresses his thanks due to the Arab Student Aid International (ASAI) for providing this opportunity and finacial support. Also, he would like to take this opportinuity to thank HRH prince *Turki Bin Abd UL Aziz* , the Chairman of ASAI.

He wishes to thank and acknowledges his wife for her continuous encouragement and help during this study and difficult times.

Central Library - Ain Shams University

CONTENTS

		Page
LIST OF FIGURES		vi
LIST OF SYMBOLS		xix
ABSTRACT		xxi
CHAPTER I : INTRODUCTION		1
1.1	General	1
1.2	Converter power factor	2
1.3	Network power factor correction	3
1.4	Converter power factor improvement	9
1.4.1	Extinction angle control	10
1.4.2	Symmetrical angle control	13
1.4.3	Pulse-width-modulation control	14
1.4.4	Sinusoidal pulse-width modulation	15
1.5	Source of harmonics and their proplems	16
1.6	Harmonic elimination	18
1.6.1	Shunt filters	19
1.6.2	Series filters	19
1.6.3	Phase multiplication	21
1.6.4	Harmonic injection (active filters)	22
1.7	Control of harmonics	25
1.8	The proposed technique	28

Central Library - Ain Shams University

Page

CHAPTER II : ANALYSIS OF SINGLE PHASE CONVERTER AND REGULATOR CIRCUITS 30

2.1 Introduction 30

2.2 Single phase converter circuits and waveforms 31

2.3 Single phase full converters without free wheeling diode (F.W.D.) loaded with R-L series load 35

2.4 Single phase full converter with F.W.D. 38

2.4.1 Series R-L load 38

2.4.2 Series R-L load with a back e.m.f. load 51

2.4.2.1 Continuous current operation 52

2.5 Single phase uncontrolled full converter loaded with parallel R-C load 57

2.6. Single phase ac voltage regulator with resistive load 61

CHAPTER III : SWITCHED CAPACITOR TECHNIQUE 66

3.1 Introduction 66

3.2 Semiconductor switch 67

3.2.1 Method of controlling the semiconductor switch 68

3.3 Expression for switching function, SF, in case of a uniform pattern 69

Central Library - Ain Shams University

Page

3.4 Types of switched-capacitor circuits 71
3.4.1 General 71
3.4.2 Single - switch single - capacitor circuit 72
3.4.3 Double - switch single - capacitor circuit 73
3.4.4 Double - switch Double - capacitor circuit 74
3.4.5 Triple switched configuration 75
3.5 Analysis of triple-switch double capacitor circuit 79

CHAPTER IV : POWER FACTOR COMPENSATION AND HARMONICS REDUCTION USING TRIPLE SWITCHED CAPACITOR CIRCUIT 90

4.1 Introduction 90
4.2 Power factor improvement in case of a single phase full converter without free wheeling diode (F.W.D.) loaded with R-L series load 92
4.3 Power factor improvement in case of a single phase full converter with free wheeling diode (F.W.D.) 97
4.3.1 series R-L load 97
4.3.2 series R-L with a back e.m.f.load 102
4.4 Power factor improvement in case of a single

Central Library - Ain Shams University

Page

phase ac regulator with resistive load 105

4.5 Harmonic current reduction in case of a single phase bridge rectifier loaded with capacitive load 108

4.5.1 General 108

4.5.2 Harmonic - current reduction by using a switched capacitor filter 110

4.5.3 Harmonic - current reduction by using a switched capacitor and a series parallel resonant filters 111

CHAPTER V : MICROPROCESSOR CONTROL OF SWITCHED CAPACITOR AND EXPERIMENTAL SET-UP 114

5.1 Introduction 114

5.2 Microprocessor control 115

5.2.1 General 115

5.2.2 8-bit (8085) and 16-bit (8086) microprocessor 116

5.2.3 Software program 118

5.3 Experimental set-up 120

5.3.1 The zero-crossing detector (Z.C.D.) 124

5.3.2 Dead-zone and complementary switching

Central Library - Ain Shams University

		Page
	function generator	126
5.4	The power MOSFET drive circuit	129
5.4.1	Optocouplers and isolation of gate-controlling signals from power circuits (MOSFETs)	129
5.4.2	The ICL 7667 CPA chip	131
5.5	Experimental results	132
5.51	General	132
5.5.2	Single phase full converter without F.W.D. loaded with R-L series load	134
5.5.3	Single phase full converters with F.W.D. loaded with R-L series load	141
5.5.4	Single phase full converters with F.W.D. loaded with R-L series load and a battery	146
5.6	Single phase ac regulator with pure resistive load	151
5.7	Harmonic current reduction in case of a single phase bridge rectifier with a parallel R-C load	151
CONCLUSION		159
REFERENCES		161
APPENDIX A		167
APPENDIX B		171

Central Library - Ain Shams University

LIST OF FIGURES

Figure No.	TITLE	Page
Fig.(1-1)	: Static compensator of thyristor switched capacitor	8
Fig.(1-2)	: Static compensator of the thyristor controlled reactor	9
Fig.(1-3)	: Single-phae commutated semiconverter a. Circuit b. Waveforms of input voltage, output voltage, and supply current	11
Fig.(1-4)	: Single phase forced commutated full converter	12
Fig.(1-5)	: Waveforms of input voltage, output voltage, and supply current in case of symmetrical angle control	13
Fig.(1-6)	: Waveforms of input voltage, output voltage, and supply current in case of pulse-width-modulation control	14
Fig.(1-7)	: Sinusoidal pulse-width-modulation	16
Fig.(1-8)	: Basic principle of passive filter	21
Fig.(1-9)	: Basic principle of active filter	22
Fig.(1-10)	: Combination of a series active and shunt passive filter	26
Fig.(1-11)	: Priciple of s-c compensator	29
Fig.(1-12)	: S-c and a series passive filters	29

Central Library - Ain Shams University

Fig.(2-1)	: Single phase circuit	31
Fig.(2-2)	: Different types of load	32
Fig.(2-3)	: Waveforms of output voltage and supply current in case of : a. Fully controlled bridge rectifier loaded with resistive load. b. Fully controlled bridge rectifier loaded with highly inductive load. c. Half-controlled bridge rectifier loaded with highly inductive load d. Fully controlled bridge rectifier loaded with series highly inductive load with a back e.m.f. load e. Fully controlled bridge rectifier loaded with a parallel R-C load	33
Fig.(2-4)	: Single phase full wave controlled converter without F.W.D. a. Circuit b. Waveforms of output voltage, load current, and supply current	37
Fig.(2-5a)	: Supply current waveform and its spectra at triggering angle equals to 0^{o} in case of a single phase full converter without F.W.D. loaded with R-L series	39
Fig.(2-5b)	: Supply current waveform and its spectra at triggering angle equals to 15^{o} in case of a single phase full converter without F.W.D. loaded with R-L series load	40
Fig.(2-5c)	: Supply current waveform and its spectra at triggering angle equals to 30^{o} in case of a single phase full converter without F.W.D. loaded with R-L series load	41

Central Library - Ain Shams University

Fig.(2-5d) : Supply current waveform and its spectra at triggering angle equals to 45^{o} in case of a single phase full converter without F.W.D. loaded with R-L series load 42

Fig.(2-6) : The variation of displacement and power factors vs the tiggering angle in case of a single phase full converter without F.W.D. loaded with R-L series 43

Fig.(2-7) : Single phase full wave controlled converter with F.W.D.
a. Circuit
b. Waveforms of output voltage, load current, and supply current 44

Fig.(2-8a) : Supply current waveform and its spectra at triggering angle equals to 15^{o} in case of a single phase full converter with F.W.D. loaded with R-L series load 48

Fig.(2-8b) : Supply current waveform and its spectra at triggering angle equals to 75^{o} in case of a single phase full converter with F.W.D. loaded with R-L series load 49

Fig.(2-9) : The variation of displacement and power factors vs the triggering angle in case of a single phase full converter with F.W.D. loaded with R-L series load 50

Fig.(2-10) : Single phase full converter with F.W.D.
a. Circuit
b. Waveforms of output voltage and load current 51

Fig.(2-11a) : Supply current waveform and its spectra at triggering angle equals to 30^{o} in case of a single

Central Library - Ain Shams University

phase full converter with F.W.D. loaded by series R-L with a back e.m.f. load 54

Fig.(2-11b) : Supply current waveform and its spectra at triggering angle equals to 120^{o} in case of a single phase full converter with F.W.D. loaded by series R-L with a back e.m.f. load 55

Fig.(2-12) : The variation of displacement and power factors vs the triggering angle in case of a single phase full converter with F.W.D. loaded by series R-L with a back e.m.f. load 56

Fig.(2-13) : The circuit and the waveform of the supply current in case of ac voltage regulator with resistive load 57

Fig.(2-14a) : Supply current waveform and its spectra at triggering angle equals to 30^{o} in case of ac voltage regulator with resistive load 58

Fig.(2-14b) : Supply current waveform and its spectra at triggering angle equals to 120^{o} in case of ac voltage regulator with resistive load 59

Fig.(2-15) : The variation of the displacement and power factors vs the triggering angle in case of ac voltage regulator with resistive load 60

Fig.(2-16) : Single phase uncontrolled full converter
a. Circuit
b. Waveforms of output voltage and supply current 62

Fig.(2-17) : Supply current waveform and its spectra in case of a single phase uncontrolled full converter with R-C load 65

Fig.(3-1) : Bidirectional switch and its symbol 68

Central Library - Ain Shams University