



**HARMONIC ELIMINATION PULSE WIDTH  
MODULATION FOR THREE-PHASE CASCADED  
MULTILEVEL INVERTER USING PARTICLE  
SWARM OPTIMIZATION**

by

**BAHARUDDIN BIN ISMAIL  
(1240910803)**

A thesis submitted  
In fulfilment of the requirements for the degree of  
Doctor of Philosophy in Electrical Systems Engineering

**School of Electrical Systems Engineering  
UNIVERSITI MALAYSIA PERLIS**

2016

# UNIVERSITI MALAYSIA PERLIS

## DECLARATION OF THESIS

Author's full name : **BAHARUDDIN BIN ISMAIL**  
Date of birth : **13 JULY 1976**  
Title : **HARMONIC ELIMINATION PULSE WIDTH MODULATION FOR  
THREE-PHASE CASCADED MULTILEVEL INVERTER USING  
PARTICLE SWARM OPTIMIZATION**  
Academic Session : **2012 - 2016**

I hereby declare that the thesis becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This thesis is classified as :

- CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)\*
- RESTRICTED** (Contains restricted information as specified by the organization where research was done)\*
- OPEN ACCESS** I agree that my thesis is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this thesis in whole or in part for the purpose of research or academic exchange only (except during a period of \_\_\_\_\_ years, if so requested above).

Certified by:

**SIGNATURE**

BAHARUDDIN BIN ISMAIL  
760713-02-6043

Date :

**SIGNATURE OF SUPERVISOR**

PROF. MADYA DR. MUZAMIR BIN ISA

Date :

**NOTES** : \* If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction.

## Acknowledgements

Alhamdulillah, thankful to Allah for giving me the strength and courage to complete this project. My utmost gratitude to Prof. Dr. Syed Idris Syed Hassan, for his unconditional supports through the doctoral process and for his academic advice. His guidance, ideas, encouragement, affable nature, kindness and support were greatly helpful. Even with his busy schedule, he spent a considerable amount of time helping me through the different phases of this project. I would like to thank my co-supervisors Assoc. Prof. Dr. Muzamir Isa and Assoc. Prof. Dr. Rizalafande Che Ismail for the support, suggestions for revision of this project and for the countless interesting discussions. Deepest gratitude is also to the members of the supervisory committee, Mr. Azralkummin Azmi, Mr. Shahril Noor Shah, Dr. Faridun Naim Tajuddin, Mr. Mohd Hafiz Arshad where without their knowledge and assistance, this study would not be successful.

Special gratitude to all my helpful friends, especially members of the School of Electrical System Engineering, UniMAP, for sharing the literature and reaching out with invaluable assistance.

Last but not least, sincere thanks and gratitude to my wife Yusnita bt. Khalid, my children, Nurul Ain Maisarah, Nurul Nadia and Akmal Muhaimin, my parents; Ismail bin Saad, Tom Bte Hashim, my sisters and brothers for the support and motivation and also for the continuous encouragement, patience and prayers, which enable the project to be completed as required.

May God bless them all.

Wassalam

## TABLE OF CONTENTS

	PAGE
<b>DECLARATION OF THESIS</b>	i
<b>ACKNOWLEDGEMENTS</b>	ii
<b>TABLE OF CONTENTS</b>	iii
<b>LIST OF TABLES</b>	vii
<b>LIST OF FIGURES</b>	viii
<b>LIST OF ABBREVIATIONS</b>	xvi
<b>LIST OF SYMBOLS</b>	xviii
<b>ABSTRAK</b>	xix
<b>ABSTRACT</b>	xx
<b>CHAPTER 1 INTRODUCTION</b>	
1.1 Background of Study	1
1.2 Problem Statement	3
1.3 Research Objectives	4
1.4 Research Scope	5
1.5 Thesis Organization	6
<b>CHAPTER 2 LITERATURE REVIEW</b>	
2.1 Introduction	8
2.2 Inverter Topologies	8
2.3 Total Harmonic Distortion	10
2.4 Multilevel Voltage Sources Inverter	11
2.4.1 Cascaded Multilevel Inverters	12
2.5 Harmonic Elimination Pulse Width Modulation (HEPWM) for Cascaded Multilevel Inverter	18

2.6	Solving Algorithm and Techniques	19
2.6.1	Calculus Techniques	19
2.6.2	Soft Computing Techniques	22
2.6.2.1	Genetic Algorithm	22
2.6.2.2	Artificial Bee Colony	29
2.6.2.3	Particle Swarm Optimization (PSO)	29
2.7	Summary	35

### **CHAPTER 3 METHODOLOGY**

3.1	Introduction	36
3.2	Problem Formulation	36
3.2.1	Five-level HEPWM with Non-notch Waveform	38
3.2.2	Five-level HEPWM with Notch Waveform	39
3.2.3	Seven-level HEPWM with Non-notch Waveform	41
3.2.4	Seven-level HEPWM with Notch Waveform	42
3.3	Calculation Switching Angles Using PSO	44
3.4	Solving HEPWM Switching Angles	45
3.5	Three-phase Cascaded Multilevel Inverters Simulation using PSIM	49
3.6	FPGA Software Implementation	50
3.6.1	Degree Angle to Time Conversion	52
3.6.2	Three-phase Output with Variable Frequency	54
3.6.3	Programming the Switching Angles Profile	56
3.6.3.1	Non-notch Switching Angle Profile	58
3.6.3.2	Notch Switching Angle Profile	60
3.7	FPGA Hardware Selection and Specifications	63

3.8	Hardware Implementation of Three-phase Cascaded Multilevel Inverter	65
3.8.1	Switching Element	67
3.8.2	Gate Driver Circuits	67
3.9	Testing of Hardware	68
3.10	Summary	69

## **CHAPTER 4 RESULTS AND DISCUSSION**

4.1	Introduction	71
4.2	Switching Angles Computation	71
4.2.1	Trajectories for Non-notch Five-level Waveforms	72
4.2.2	Trajectories for Notch Five-level Waveforms	73
4.2.3	Trajectories for Non-notch Seven-level Waveforms	75
4.2.4	Trajectories for Notch Seven-level Waveforms	77
4.3	Simulation and Experimental Results	81
4.3.1	Five-level Non-notch Waveform	81
4.3.2	Five-level Notch Waveform	87
4.3.3	Seven-level Non-notch Waveform	106
4.3.4	Seven-level Notch Type Waveform	116
4.4	Summary	153

## **CHAPTER 5 CONCLUSION AND FUTURE WORK**

5.1	Conclusion	154
5.2	Significant Contributions Towards the Research	156
5.3	Recommendations for Future Works	158

<b>REFERENCES</b>		159
<b>APPENDIXES</b>		
<b>APPENDIX A</b>	<b>COMPARATIVE STUDY OF PSO AND GA TECHNIQUES FOR HEPWM PROBLEM</b>	166
<b>APPENDIX B</b>	<b>LIST OF PUBLICATIONS</b>	170
<b>APPENDIX C</b>	<b>AWARDS AND MEDALS</b>	172
<b>APPENDIX D</b>	<b>PATENT/COPYRIGHT</b>	175

©This item is protected by original copyright

## LIST OF TABLES

NO.		PAGE
2.1	Summary of harmonics limit and THD for different standards	11
2.2	Summary of the GA related work in HEPWM with unipolar and bipolar switching	27
2.3	Summary of the GA related work in HEPWM with non-notch and notch switching	28
2.4	Summary of the PSO related work in HEPWM with bipolar and unipolar switching	33
2.5	Summary of the PSO related work in HEPWM with non-notch and notch switching	34
3.1	Pre-calculated angle resolution and counter values	54
3.2	Notch switching angles example	61
3.3	Specifications for MOSFET IRFP250	67
4.1	Measured experimental harmonics component for $M = 1.53$ and $M = 1.65$ at a 50 Hz operating frequency for the five-level with 7/9 switching distribution	105
4.2	Measured experimental harmonics component for $M = 1.74$ , $M = 2.07$ , $M = 2.67$ and $M = 2.73$ at a 50 Hz operating frequency	152



## LIST OF FIGURES

NO.		PAGE
2.1	Power circuit of H-bridge VSI	9
2.2	Output waveform of VSI with unipolar switching	9
2.3	Output waveform of VSI with bipolar switching	10
2.4	Power circuit for the three-phase five-level cascaded inverter	14
2.5	Power circuit for the three-phase seven-level cascaded inverter	14
2.6	The five-level phase voltage ( $V_{AN}$ ) output waveform with (a) non-notch type, (b) notch type	15
2.7	The seven-level phase voltage ( $V_{AN}$ ) output waveform with (a) non-notch type, (b) notch type	16
2.8	Roulette wheel approach	23
2.9	Flowchart of GA	24
3.1	Research framework	37
3.2	Five-level non-notch type HEPWM output voltage of the cascaded multilevel inverter	39
3.3	Five-level notch type HEPWM output voltage of the cascaded multilevel inverter	39
3.4	Seven-level non-notch type HEPWM output voltage of the cascaded multilevel inverter	42
3.5	Seven-level notch type HEPWM output voltage of the cascaded multilevel inverter	42
3.6	Flowchart of the PSO algorithm	48
3.7	Simulation model for five-level inverter	49
3.8	Simulation model for seven-level inverter	50
3.9	Multilevel inverter gate switching generation	51
3.10	Three-phase output sub-program flow	56
3.11	Verilog programming template	57
3.12	Non-notch switching angles for each stage	59

3.13	Verilog programming template for non-notch switching	60
3.14	Notch switching angles (half cycle)	61
3.15	Verilog programming template for notch switching	62
3.16	Layout of the Altera DE-0 FPGA board	63
3.17	DE-0 board block diagram	65
3.18	Block diagram of a hardware setup	66
3.19	Power circuit of three-phase cascaded multilevel inverter	66
3.20	Experimental test rig setup for three-phase cascaded multilevel inverters	69
4.1	Switching angles trajectories against modulation index for five-level with non-notch switching	72
4.2	Percentage of 5 <sup>th</sup> harmonic versus modulation index for five-level with non-notch switching	73
4.3	Switching angles trajectories against modulation index for 7/9 switching distribution	74
4.4	Percentage of eliminated harmonic versus modulation index for 7/9 switching distribution	75
4.5	Switching angles trajectories against modulation index for seven-level with non-notch switching	76
4.6	Percentage of 5 <sup>th</sup> and 7 <sup>th</sup> harmonic versus modulation index for seven-level with non-notch switching	77
4.7	Switching angles trajectories against modulation index for 5/5/7 switching distribution	79
4.8	Percentage of harmonic versus modulation index for 5/5/7 switching distribution	79
4.9	Switching angles trajectories against modulation index for 3/5/9 switching distribution	80
4.10	Percentage of harmonic versus modulation index for 3/5/9 switching distribution	80
4.11	Phase voltage output waveform ( $V_{AN}$ ) and its harmonic spectrum for five-level non-notch type cascaded multilevel inverter with $M = 1.7$	82

4.12	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for five-level non-notch type cascaded multilevel inverter with $M = 1.7$ at 50 Hz operating frequency	84
4.13	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for five-level non-notch type cascaded multilevel inverter with $M = 1.7$ at 40 Hz operating frequency	85
4.14	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for five-level non-notch type cascaded multilevel inverter with $M = 1.7$ at 80 Hz operating frequency	86
4.15	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	88
4.16	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	89
4.17	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	90
4.18	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	91
4.19	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	93
4.20	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	94
4.21	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	95
4.22	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	96

4.23	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	97
4.24	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.53$ at 7/9 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	98
4.25	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	99
4.26	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	100
4.27	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	101
4.28	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	102
4.29	Simulation results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	103
4.30	Experimental results for five-level notch type cascaded multilevel inverter with $M = 1.65$ at 7/9 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform. (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	104
4.31	Phase voltage output waveform ( $V_{AN}$ ) and its harmonic spectrum for seven-level non-notch type cascaded multilevel inverter with $M = 2.4$	107
4.32	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for seven-level non-notch types cascaded multilevel inverter with $M = 2.4$ at 50 Hz operating frequency	108
4.33	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for seven-level non-notch type cascaded multilevel inverter with $M = 2.4$ at 40 Hz operating frequency	109

4.34	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for seven-level non-notch type cascaded multilevel inverter with $M = 2.4$ at 80 Hz operating frequency	110
4.35	Phase voltage output waveform ( $V_{AN}$ ) and its harmonic spectrum for seven-level non-notch type cascaded multilevel inverter with $M = 2.76$	112
4.36	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for seven-level non-notch types cascaded multilevel inverter with $M = 2.76$ at 50 Hz operating frequency	113
4.37	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for seven-level non-notch types cascaded multilevel inverter with $M = 2.76$ at 40 Hz operating frequency	114
4.38	Three-phase line-to-line output voltage and its harmonic spectrum ( $V_{AB}$ ) for seven-level non-notch types cascaded multilevel inverter with $M = 2.76$ at 80 Hz operating frequency	115
4.39	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 1.74$ at 5/5/7 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	117
4.40	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 1.74$ at 5/5/7 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	118
4.41	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 1.74$ at 5/5/7 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	119
4.42	Experimental results for seven level notch type cascaded multilevel inverter with $M = 1.74$ at 5/5/7 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	120
4.43	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 1.74$ at 5/5/7 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	121
4.44	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 1.74$ at 5/5/7 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	122

4.45	Simulation results for seven-level notch type cascaded multilevel inverter with $M=1.74$ at 5/5/7 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	123
4.46	Experimental results for seven-level notch type cascaded multilevel inverter with $M=1.74$ at 5/5/7 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	124
4.47	Simulation results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	126
4.48	Experimental results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	127
4.49	Simulation results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	128
4.50	Experimental results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	129
4.51	Simulation results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	130
4.52	Experimental results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	131
4.53	Simulation results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	132
4.54	Experimental results for seven-level notch type cascaded multilevel inverter with $M=2.07$ at 5/5/7 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	133

4.55	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	135
4.56	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	136
4.57	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	137
4.58	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	138
4.59	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	139
4.60	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution at 40 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	140
4.61	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	141
4.62	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.67$ at 3/5/9 switching distribution at 80 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	142
4.63	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	144
4.64	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution. (a) Phase voltage output waveform ( $V_{AN}$ ). (b) Harmonic spectrum of the phase voltage	145
4.65	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution at 50 Hz operating frequency. (a) Three-phase line-to-line voltage output waveform . (b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	146

4.66	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution at 50 Hz operating frequency.	
	(a) Three-phase line-to-line voltage output waveform .	
	(b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	147
4.67	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution at 40 Hz operating frequency.	
	(a) Three-phase line-to-line voltage output waveform .	
	(b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	148
4.68	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution at 40 Hz operating frequency.	
	(a) Three-phase line-to-line voltage output waveform .	
	(b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	149
4.69	Simulation results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution at 80 Hz operating frequency.	
	(a) Three-phase line-to-line voltage output waveform .	
	(b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	150
4.70	Experimental results for seven-level notch type cascaded multilevel inverter with $M = 2.73$ at 3/5/9 switching distribution at 80 Hz operating frequency.	
	(a) Three-phase line-to-line voltage output waveform .	
	(b) Harmonic spectrum of the line-to-line voltage ( $V_{AB}$ )	151



## LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
AC	Alternating Current
API	Application Programming Interface
AS	Active Serial
CDF	Cumulative Distribution Function
CLK	Clock
CSI	Current Source Inverter
DC	Direct Current
EEPROM	Electrically Erasable Read Only Memory
FPGA	Field Programmable Gate Array
GA	Genetic Algorithm
HB	H-bridge
HEPWM	Harmonic Elimination Pulse Width Modulation
Hz	Hertz
IEEE	Institute Electric and Electronic Engineering
I/O	Input/Output
JTAG	Joint Test Action Group
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MVSI	Multilevel Voltage Source Inverter
PSIM	Software for Power Electronics Simulation
PROG	Program
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulation

RCGA	Real Code Genetic Algorithm
SC	Soft Computing
SDRAM	Single Data Rate Synchronous Dynamic Random Access Memory Chip
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector PWM
THD	Total Harmonic Distortion
USB	Universal Serial Bus
USB	Universal Serial Bus
VSI	Voltage Source Inverter
WTHD	Weight Total Harmonic Distortion

©This item is protected by original copyright

## LIST OF SYMBOLS

$\theta$	Switching angle
$C_1, C_2$	Constriction factors
$G_{best}$	Global best
$G$	Getting signals
$k$	Harmonics order
$L$	Number of level for phase voltage
$M$	Modulation index
$n$	Number of line-to-line voltage level
$N$	Number of switching angles
$P_{best}$	Best present
$s$	Number of H-bridge connected in cascaded multilevel inverters per phase
$S$	Number of eliminated harmonic
$V_1$	Fundamental voltage component
$V_{AN}$	Phase A voltage respect to neutral point
$V_{BN}$	Phase B voltage respect to neutral point
$V_{CN}$	Phase C voltage respect to neutral point
$V_{AB}$	Line-to line voltage between phase A and B
$V_{BC}$	Line-to line voltage between phase B and C
$V_{CA}$	Line-to line voltage between phase C and A
$V_{dc}$	Input DC voltage
$W$	Inertia weight
$Y$	Real-valued random variable

## Penghapusan Harmonik Modulasi Lebar Denyut untuk Penyongsang Lataan Tiga-fasa Berbilang Aras Menggunakan *Particle Swarm Optimization*

### ABSTRAK

Kajian ini bertujuan untuk mengkaji prestasi algoritma *Particle Swarm Optimization* (PSO) dalam mengira sudut-sudut penghapusan harmonik modulasi lebar denyut (HEPWM) bagi lima dan tujuh aras penyongsang lataan tiga-fasa pensuisan jenis *non-notch* dan *notch*. Masalah utama dengan teknik pensuisan HEPWM adalah pengiraan sudut-sudut pensuisan bagi penyongsang berbilang aras melibatkan persamaan tak linear yang perlu diselesaikan. Tambahan pula, peralihan dari satu aras ke aras yang lain dalam penyongsang berbilang aras mengenakan kekangan tambahan mengenai aturan sudut-sudut pensuisan. Kekangan ini boleh menyebabkan prosedur pengiraan untuk sudut-sudut pensuisan menjadi lebih rumit. Oleh itu, *Dynamic inertia weight* PSO dilaksanakan dalam persekitaran MATLAB dan persamaan tak linear transendental bagi penyongsang lima dan tujuh aras dikira untuk pelbagai indek modulasi ( $M$ ). Dua dan tiga sudut pensuisan dikira bagi penyongsang lima dan tujuh aras pensuisan jenis *non-notch*. Bagi penyongsang lima aras jenis pensuisan *notch*, enam belas sudut pensuisan dengan 7/9 agihan pensuisan diselesaikan. Manakala, bagi penyongsang tujuh aras jenis pensuisan *notch*, tujuh belas sudut pensuisan dengan 5/5/7 dan 3/5/9 agihan pensuisan diselesaikan. Kelebihan utama algoritma ini adalah penyelesaian HEPWM bagi sudut trajektori yang diperolehi adalah bebas daripada sebarang keadaan yang terputus-putus. Oleh itu, kelancaran operasi HEPWM bagi penyongsang-penyongsang lataan tiga-fasa berbilang aras boleh diperolehi. Di samping itu, rangkuman julat  $M$  yang lebih luas adalah penting bagi membolehkan penggunaan HEPWM kepada aplikasi-aplikasi penyongsang lataan tiga-fasa berbilang aras berkuasa tinggi. Keberkesanan algoritma PSO ini disahkan dengan melakukan simulasi dan eksperimen. Simulasi untuk penyongsang-penyongsang lataan tiga-fasa lima dan tujuh aras telah dijalankan dalam perisian PSIM. Pengesahan secara eksperimen dibuat dengan membangunkan perkakasan prototaip penyongsang lataan tiga-fasa lima dan tujuh aras. *Field Programmable Gate Array (FPGA)* telah digunakan bagi menjana sudut pensuisan yang telah dikira untuk pelbagai indek modulasi pada operasi frekuensi yang berbeza bagi penyongsang lima dan tujuh aras bagi pensuisan jenis *non-notch* dan *notch*. Kelebihan penyongsang lataan berbilang aras yang telah dibangunkan disahkan dengan penghapusan harmonik ke- 5, 7, 11, 13, 17, 19, 23, 25, 29, 31, 35, 37, 41, 43, 47, 49 dan harmonik-harmonik triplen yang berjaya dikeluarkan daripada spektrum harmonik voltan keluaran penyongsang tujuh aras bagi pensuisan jenis *notch*. Kedua-dua keputusan-keputusan simulasi dan eksperimen didapati mempunyai persetujuan yang baik dengan jangkaan-jangkaan teori. Keputusan-keputusan eksperimen juga menunjukkan bahawa penyongsang lataan tiga-fasa berbilang aras mampu bekerja dalam operasi frekuensi yang berbeza daripada 10 Hz hingga 90 Hz. Adalah dijangkakan bahawa HEPWM yang dicadangkan dengan algoritma PSO ini boleh menjadi sangat berguna dalam mereka bentuk penyongsang lataan tiga-fasa berbilang aras berprestasi tinggi yang praktikal dan murah.

# Harmonic Elimination Pulse Width Modulation for Three-phase Cascaded Multilevel Inverter Using Particle Swarm Optimization

## ABSTRACT

This research aims to investigate the performance of the Particle Swarm Optimization (PSO) algorithm in computing the harmonic elimination pulse width modulation (HEPWM) switching angles of a five and seven-level three-phase cascaded inverter for non-notch and notch switching. The main problem with HEPWM switching technique is computing the switching angles for a multilevel inverter as it involves a nonlinear equation to be solved. Furthermore, the transition between one level to another level in the multilevel inverter imposes an additional constraint on the sequencing of the switching angles. This constraint can cause the computational procedures for the switching angles calculation to become more complicated. Therefore, the dynamic inertia weight PSO algorithm is implemented in MATLAB environment and the nonlinear transcendental equations for five and seven-level inverter are calculated for the entire modulation index ( $M$ ). Two and three switching angles are determined for five and seven-level inverter with the non-notch switching type. For five-level inverter notch switching type, sixteen switching angles with 7/9 switching distribution are solved. Whereas, for seven-level inverter notch switching type, seventeen switching angles with 5/5/7 and 3/5/9 switching distribution are solved. The main advantage of this algorithm is the HEPWM solution angles trajectories obtained are free from any discontinuity. Hence, a smooth operation of HEPWM for three-phase cascaded multilevel inverters can be obtained. In addition, a wider range of  $M$  has been covered which is valuable for extending the applications of HEPWM for three-phase cascaded multilevel inverters to high power applications. The effectiveness of the PSO algorithm is verified by performing simulation and experimental. The simulation for five and seven-level three-phase cascaded multilevel inverters were performed in PSIM software. The experimental verification is carried out by constructing a hardware prototype of five and seven-level three-phase cascaded multilevel inverter. A Field Programmable Gate Array (FPGA) is utilized to generate the calculated switching angle for various modulation indexes at different operating frequency for five and seven-level inverter with non-notch and notch switching type. The advantage of the developed cascaded multilevel inverter is confirmed with elimination of 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, 13<sup>th</sup>, 17<sup>th</sup>, 19<sup>th</sup>, 23<sup>rd</sup>, 25<sup>th</sup>, 29<sup>th</sup>, 31<sup>st</sup>, 35<sup>th</sup>, 37<sup>th</sup>, 41<sup>st</sup>, 43<sup>rd</sup>, 47<sup>th</sup>, 49<sup>th</sup> harmonics order and triplen harmonics are successfully removed from the harmonic spectrum of the output voltage for seven-level inverter with notch switching type. Both simulation and experimental results are in good agreement with the theoretical predictions. Experimental results also demonstrate that the three-phase cascaded multilevel inverter is able to work at a variable operating frequency from 10 Hz to 90 Hz. It is envisaged that the proposed HEPWM with PSO algorithm can be very useful in the design of a practical high performance and low cost three-phase cascaded multilevel inverter.

# CHAPTER 1

## INTRODUCTION

### 1.1 Background of Study

Multilevel voltage source inverter (MVSI) has increasingly gaining attention in recent years for an electric power conversion in medium and high power DC-AC converters (Rodríguez, Lai, & Peng, 2002; Dahidah & Agelidis, 2008; Dahidah, Konstantinou, & Agelidis, 2012). This is because the MVSI has the capability to produce a high output voltage even when it only uses power switches with a lower rating (Amjad, Salam & Saif, 2015). The stepped output nature of MVSI not only reduces the pressure on the power switches, it also improves the frequency spectrum of the output waveform and at the same time contributes to a lower harmonics distortion (Rodríguez, Lai, & Peng, 2002; Gabbar, Islam, Isham, & Trivedi, 2012). Furthermore, the high output voltage offers the possibility of removing the step-up transformer, which is always undesirable due to the additional cost, ohmic losses and space restrictions (Gabbar et al., 2012).

A lot of MVSI configurations or topologies have been reviewed and investigated by researchers for different applications over the past decades (Farokhnia, Vadizadeh, Fathi, & Anvariasl, 2011; Colak, Kabalci, & Bayindir, 2011; Amjad & Salam, 2014; Dahidah, Konstantinou, & Agelidis, 2015). The widely used MVSI topologies are classified into three main categories such as the cascaded H-bridge (CHB) (Marzoughi, Imaneini, & Moeini, 2013), Flying Capacitor (FC) (Khazraei, Sepahvand, Corzine, &

Ferdowsi, 2012) and the Neutral Point Clamped (NPC) (Pulikanti, Konstantinou, & Agelidis, 2013). Each topology has its own advantages and disadvantages, as summarized by (Lai & Peng, 1996; Rodríguez et al., 2002). Among the above MVSI topologies, the H-bridge or cascaded multilevel inverter is particularly attractive due to its modular structure (Konstantinou, Dahidah, & Agelidis, 2012).

There are a variety of switching schemes that can be applied to the cascaded multilevel inverter. Normally the switching schemes used for the cascaded multilevel inverters are the Sinusoidal Pulse Width Modulation (SPWM), staircase modulation, Space Vector PWM (SVPWM) and Harmonic Elimination Pulse Width Modulation (HEPWM) (J. Mathew, Mathew, Azeez, Rajeevan, & Gopakumar, 2013; Rodríguez et al., 2002; Colak, Kabalci, & Bayindir, 2011; K. Mathew et al., 2013). Among them, HEPWM seems to be the most popular switching scheme (Salehi, Farokhnia, Abedi & Fathi, 2011). This is due to its greater harmonics profile (Dahidah & Agelidis, 2008; Farokhnia, Fathi, Salehi, Gharehpetian, & Ehsani, 2012; Kavousi et al., 2012; Taghizadeh & Hagh, 2010).

Despite of these virtues, solving the non-linear equations that define the HEPWM switching angles is very challenging. This is because these non-linear equations are simultaneous and their trigonometric functions are highly correlated to each other (Patel & Hoft, 1973; Patel & Hoft, 1974). In addition, the number of equations that needs to be solved depends on the number of harmonics to be eliminated (Patel & Hoft, 1973; Amjad, Salam & Saif, 2015).

In this work, the effectiveness of the Particle Swarm Optimization (PSO) to solve the HEPWM switching angles problems is validated by using five and seven-level three-phase cascaded multilevel inverter. Both single switching (non-notch types) and

multiple switching (notch types) HEPWM problems of three-phase cascaded multilevel inverter are investigated. The five and seven-level inverter with non-notch and notch switching are purposely chosen to enable a direct comparison to be made with the most advance work published in literatures (Gupta & Mahanty, 2015; Salam, Yee, and Saleem, 2013; Kavousi et al., 2012; Konstantinou et al., 2012; Amjad, Salam & Saif, 2015). The PSO algorithm is developed in the MATLAB software. The computed switching angles are analyzed in the PSIM simulation and are experimentally validated by using the Field Programmable Gate Array (FPGA) based three-phase cascaded multilevel inverter prototype. The results obtained are the proofs of the advantages of having PSO on other Soft Computing (SC) methods for the HEPWM problems of the three-phase cascaded multilevel inverter. The HEPWM solution angles trajectories obtained are free from any discontinuity. Hence, a smooth operation of HEPWM for three-phase cascaded multilevel inverter can be achieved. In addition, a wider range of modulation index ( $M$ ) has been covered which is valuable in extending the applications of HEPWM for the three-phase cascaded multilevel inverter to the high power applications. Furthermore, a wider range of operating frequency has been covered which is valuable in extending the application of three-phase cascaded multilevel inverter to the variable frequency drive.

## 1.2 Problem Statement

The common problem with HEPWM switching technique is computing the switching angles for a multilevel inverter as it involves a non-linear equation to be solved. In order to get a good quality output waveform, a large number of harmonics need to be eliminated. This consequently demands a lot of equations to be solved, which often leads to numerical non-convergence. Furthermore, the transition between one