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

by

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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

LIST OF SYMBOLS

θ	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^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th}, 23^{rd}, 25^{th}, 29^{th}, 31^{st}, 35^{th}, 37^{th}, 41^{st}, 43^{rd}, 47^{th}, 49^{th} 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