UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

PERFORMANCE EVALUATION OF SPACE VECTOR MODULATION (SVM) FOR MULTILEVEL INVERTERS

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A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled “Performance Evaluation of Space Vector Modulation (SVM) for Multilevel Inverters” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature	:	....
Supervisor Name	:	....
Date	:	....

DEDICATION

To my beloved mother, father and siblings

ABSTRACT

The Space Vector Modulation (SVM) technique has gained wide acceptance for many AC drive applications, due to a higher DC bus voltage utilization (higher output voltage compared with the Sinusoidal Pulse Width Modulation (SPWM)), lower harmonic distortions and easy digital realization. In recent years, the SVM technique was extensively adopted in multilevel inverters since it offers greater numbers of switching vectors for obtaining further improvements of AC drive performances. However, the use of multilevel inverters associated with SVM increases the complexity of control algorithm (or computational burden), in obtaining proper switching sequences and vectors. The complexity of SVM computation causes a microcontroller or digital signal processor (DSP) to execute the computation at a larger sampling time. This consequently may produce errors in computation and hence degrades the control performances of AC motor drives. This thesis reports the performance evaluation of SVM for two-level of VSI, three-level and five-level of Cascaded H-Bridge Multilevel Inverter (CHMI) and analyse in-depth the accuracy performances of SVM computation and the performance evaluation in variable speed drive systems (i.e. Direct Torque Control (DTC) using SVM). The SVM modulator is implemented using a hybrid controller approach, i.e. with combination between the DS1104 Controller Board and FPGA. In such way, the computational burden can be minimized as the SVM tasks are distributed into two parts, in which every part is executed by a single controller. This allows the generation of switching gates performed by FPGA at the minimum sampling time $DT_2 = 360\,ns$ to obtain precise desired output voltages, as verified via simulation and experimental results. Based on the accuracy performance analysis, it has revealed that the error of SVM computation in five-level inverter, even with a larger sampling time $DT_1 = 200\,\mu s$, can be restricted at 6.25% from that obtained in two-level inverter. This allows the use of low-speed microcontroller or DSP to have satisfactory control performances, however, with the suggestion to use higher levels of inverters.

ABSTRAK

Teknik Modulasi Vektor Ruang (SVM) telah mencapai penerimaan yang luas bagi kebanyakan aplikasi pemacu ulang-alik AC, disebabkan penggunaan voltan arus terus DC yang lebih tinggi (keluaran voltan yang lebih tinggi berbanding dengan SPWM), herotan harmonik yang rendah dan memudahkan pembangunan perkakasan secara digital. Tahun-tahun kebelakangan ini, teknik SVM secara meluasnya telah digunapakai dalam penyongsang bertingkat kerana ia menawarkan bilangan pensuisan vektor yang banyak untuk mencapai lanjutan penambahbaikan bagi prestasi pemacuan AC. Walaubagaimanapun, penggunaan penyongsang bertingkat dikaitkan dengan SVM meningkatkan kerumitan bagi algoritma kawalan (atau beban pengiraan), dalam mendapatkan aturan dan vektor pensuisan yang baik. Kerumitan bagi pengiraan SVM mengakibatkan sebuah pengawal mikro atau pemproses isyarat digital (DSP) melaksanakan pengiraan pada pensampelan masa yang lebih tinggi. Ini seterusnya boleh menghasilkan ralat dalam pengiraan dan kemudiannya menurunkan prestasi kawalan bagi pemacu motor AC. Tesis ini melaporkan penilaian prestasi bagi SVM untuk dua-peringkatan penyongsang VSI, tiga-peringkatan dan lima-peringkatan CHMI dan analisa secara mendalam prestasi ketepatan bagi pengiraan SVM dan prestasi penilaian kawalan laju motor AC (iaitu Kawalan Langsung Dayakilas (DTC) menggunakan SVM). Pemodulat SVM dibangunkan menggunakan sebuah pendekatan pengawal hibrid, iaitu dengan kombinasi papan pengawal DS1104 dan FPGA. Dengan cara ini, beban pengiraan boleh diminimakan oleh kerana tugasan SVM diagihkan kepada dua bahagian, yang mana setiap bahagian dilaksanakan oleh satu pengawal. Ini membenarkan penghasilan bagi get-get pensuisan yang dilakukan oleh FPGA pada pensampelan masa yang minimum $DT_2 = 360\,ns$ *untuk mendapatkan kejituan keluaran voltan yang dikehendaki, seperti yang disahkan menerusi keputusan simulasi dan ujikaji. Berpandukan kepada analisa prestasi kejituan, ia telah mendedahkan bahawa ralat bagi pengiraan SVM dalam penyongsang lima peringkatan, walaupun dengan pensampelan masa yang besar* $DT_2 = 200\,\mu s$*, boleh dihadkan pada 6.25% daripada yang diperoleh dalam penyongsang dua peringkatan. Ini membenarkan penggunaan bagi pengawal mikro atau DSP yang berkelajuan rendah untuk mempunyai kawalan prestasi yang memuaskan, tetapi dengan cadangan, kepada penggunaan penyongsang dengan peringkatan yang lebih tinggi.*

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DTC	-	Direct torque control
IM	-	Induction motor
VSI	-	Voltage source inverter
SPWM		Sinusoidal pulse width modulation
FOC	-	Field oriented control
DSC	-	Direct self control
DT	-	Sampling period
AC	-	Alternating current
DC	-	Direct current
UPS	-	Uninterruptible power supply
CSI	-	Current source inverter
HVDC	-	High voltage direct current
MOSFET	-	Metal oxide semiconductor field effect transistor
DSP	-	Digital signal processor
ADC	-	Analog digital converter
DAC		Digital analog converter
FPGA	-	Field programmer gate array
SVM	-	Space vector modulated
UB	-	Upper band
LB	-	Lower band
IGBT	-	Insulated gate bipolar transistor
CHMI	-	Cascaded H-bridge multilevel inverter
NPCMI	-	Neutral point clamp multilevel inverter
FCI	-	Flying capacitor inverter
PWM	-	Pulse width modulator
THD	-	Total harmonic distortion
PI	-	Proportional integral
IPD	-	In-phase disposition

POD	-	Phase opposition disposition
APOD	-	Alternate phase opposition disposition
DTC-SVM	-	Direct torque control space vector modulation
$\bar{v}_s^*$	-	Reference voltage vector
v_{sd}^* ,v_{sq}^*.	-	d and q components of the stator voltage in stationary feference frame
d ,q	-	Direct and quadrature of the stationary reference frame
v_m^*	-	Voltage modulating signal
v_{tri},	-	Triangular wave frequency
V_{l1}	-	Desired fundamental output voltage
i	-	Load current
i^*	-	Current reference
$v_{aM}^*, v_{bM}^*, v_{cM}^*$	-	Three phase sinusoidal voltage
M_i	-	Modulation index
T	-	Switching period
t	-	On times duration
L	-	Number of level
$V_{1,six-step}$	-	Fundamental output of six-step voltage
$\emptyset$	-	Phase shifts in inverter levels
θ_s	-	Angle of reference voltage
θ_{si}	-	Angle within Sector
d^r, q^r	-	Real and imaginary and real of the rotor
i_s , i_r	-	Stator and rotor current space vector in stationary reference frame
R_r R_s	-	Rotor and stator resistance
L_s	-	Stator self-inductance
L_r	-	Rotor self-inductance
L_m	-	Mutual inductance
$\bar{\varphi}_s, \bar{\varphi}_r$	-	Stator and rotor flux linkage space vector in reference frame
i_{rd} , i_{rq}	-	d and q components of the rotor current in stationary reference frame
i_{sd} , i_{sq}	-	d and q components of the stator current in stationary reference

		frame
v_{sd}, v_{sq}	-	d and q-axis of the stator voltage in stationary reference frame
$\varphi_{sd,}\varphi_{sq}$	-	d and q components of the stator flux in stationary reference frame
$\bar{v}_s$	-	Voltage vectors
n	-	Numbers of phase
$i_{a,}i_b\ i_c$	-	Current phase a,b and c
L	-	Self-inductance
T_e	-	Electromagnetic Torque
T_e^*	-	References of torque
ε_T	-	Output torque error
σ_T	-	Output torque status
θ_r	-	Angle within a sector
$v_{s\alpha}^*, v_{s\beta}^*$		α- and β-axis component of stator voltage
$\bar{v}_{so}^*$		Voltage vector reference based on α_o- and β_o-axis plane
$v_{\alpha o}^*, v_{\beta o}^*$		α- and β-axis component of stator voltage of triangles
δ_{sr}	-	Different angle between stator flux linkage and rotor flux linkage
V_{dc}	-	DC link voltage
P	-	Pairs of pole
ω_r	-	Rotor electrical speed in rad/s
v_{dc}	-	DC link voltage
ε_φ	-	Output flux error
φ_s^*	-	References of flux
φ_s	-	Flux estimate
σ_φ	-	Output flux status
σ	-	Total flux leakage factor
S_{sa}, S_{sb}, S_{sc}		Pre-switching State
$\bar{v}_{xN}$	-	Inverter phase voltage
v_{xN}	-	Phase stator voltages
S_x		Switch gate
$\bar{S}_x$		Complementary switch gate

Δ_j	Number of triangle
$\bar{v}_x$	Voltage vector
si	Number of Sector
d_x	Phase duty ratio

LIST OF PUBLICATIONS

Journal Paper

Syamim Sanusi, Auzani Jidin, Tole Sutikno, Kasrul Abdul Karim, Mohd Luqman Mohd Jamil, Siti Azura Ahmad Tarusan," Implementation of Space Vector Modulator for Cascaded H-Bridge Multilevel Inverters", *International Journal of Power Electronic and Drive System (IJPEDS)*.,Vol. 6, No. 4, December 2015, pp. 906~918., ISSN: 2088-8694.

Published Conference Proceeding

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Zulkifilie Bin Ibrahim, Md. Liton Hossain, **Syamim Binti Sanusi**, Nik Munaji Bin Nik Mahadi, Ahmad Shukri Abu Hasim, " Performance of Different Topologies for Three Level Inverter Based on Space Vector Pulse Width Modulation Technique," in *Clean Energy and Technology (CEAT) 2014, 3rd IET International Conference on. 2014*

Adeline Lukar Herlino, Auzani Jidin, Che Wan Faizal bin Che Wan Mohd Zalani, **Syamim Sanusi,** M.H Jopri,Mustafa Manap, " Comparative Study of Current Control Strategy for DC Motors," *Power Engineering and Optimization Conference (PEOCO), 2013 IEEE 7th International* on, 3-4 June 2013.

LIST OF ACHIVEMENTS

<u>Exhibition and Award</u>

Awarded UTeMEX 2013 **Gold medal** for the invention “PRO-SINE” at Expo Penyelidikan Dan Inovasi Utem 2012 (UtemEX) on 12 Dec 2013 , at Main Hall Utem.

Awarded UTeMEX 2014 **Bronze medal** for the invention “PRO-SINE” at Malaysia Technology Expo on 20-22 Feb 2014 , at PWTC, Kuala Lumpur.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Voltage Source Inverters (VSI) have evolved as the most popular power conversion for many AC drive applications. The evolvement of VSI is in line with the development of various Pulse Width Modulation (PWM) algorithms supported by the advent of solid state switching device technologies, fast digital signal processors, Field Programmable Gate Arrays (FPGA) and microcontrollers. Since a few decades ago, several PWM algorithms were developed to improve some performances of VSI such as high-power efficiency (Abu Bakar Siddique et al., 2015, Edpuganti and Rathore, 2015, Tong et al., 2015, Youssef et al., 2016), high-output voltage (Carrasco and Silva, 2013, Chai et al., 2016, Jana et al., 2013), and low-total harmonic distortion (THD) (Pramanick et al., 2015, Prieto et al., 2014). Apparently, the research about VSI has not reach to state of saturation up till now, as novel or simplified PWM methods is still continue to emerge for various topology inverter circuits and multilevel inverters (Gupta et al., 2016, Liu et al., 2016, Lopez et al., 2016, Narimani et al., 2016, Sakthisudhursun et al., 2016, Tan et al., 2016, Yi et al., 2016)]. Among various modulation strategies or PWM methods, the Space Vector Modulation (SVM) technique has received wide acceptance due to several advantages such as higher output voltages, lower THD, high-efficiency and flexible to be implemented in vector control systems (Chai et al., 2016, Kai et al., 2016, Liu et al., 2016, Thomas et al., 2015, Zheng et al., 2016, Zhifeng et al., 2010).