Minimum Switching Losses Evaluation for PMSM Drive based on Modified Space Vector PWM

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Abstract— **This paper presents a modified space vector pulse width modulation to drive permanent synchronous motor, the switching pattern of modified space vector pulse width modulation (MSVPWM), with certain notches, in the switching pattern of conventional type, are eliminated. These notches at relatively high modulation index have small width compared with switching period. The modified strategy has many features, such as increasing the utilization of dc input voltage and therefore higher output voltage, reducing the stress on power switches, and reducing switching power losses. The percentage reduction in the number of pulses for each switch device is about 33% of total number of switching pattern. This is due to the nature of space vector pulse width modulation. The proposed approach is analyzed and simulated, using Matlab Simulink . The obtained results prove that the proposed strategy has low power switching losses, and higher fundamental range and good quality of output voltage waveform compared with conventional space vector. Practical results have been obtained which validate the theoretical and simulation approaches.**

Keywords*- AC drive; Space vector pulse width modulation; PMSM; Switching Power losses.*

I. INTRODUCTION

The permanent magnet synchronous motor (PMSM) has been used in various applications due to its merits and features. Such applications are drive motion control, traction and industrial applications. The absence of coil in the rotor which replace by permanent magnet, made the PMSM higher efficiency due to negligible copper power loss, compact size and low weight compared with other types of synchronous motors. Also a highest torque to-weight ratio is achievable with high efficiency particularly when using rotor with magnet type Neodymium Iron Boride NeFeB[1,2]. Two types of PMSMs, have been used for applications requiring a wide speed range of constant-power operation, are surface permanent magnet and interior permanent magnet synchronous machines. The surface type which the rotor is made of iron and the magnet "glued afterword" [2,3], also uniform air gap which results no reluctance torque between rotor and stator field. While the interior type, the magnet buried in the rotor, which has many advantages like high speed, smaller size and good dynamic response due to the present of reluctance torque. Due to the simplicity construction of PMSM, most researches deal with d-q model of the PMSM[4], they were introduced modeling, using different pulse width modulation (PWM) strategies to drive system of PMSM based on Matlab/Simulink. Building of simulation system had been discussed in detail. Reference [5] has been used a high efficiency PMSM drive system, the control signal for driving motor is provided by using dc link voltage waveform of the inverter. The position of the magnet has been obtained by controlling terminal voltage of the PMSM. Also high efficiency can be obtained by controlling the motor power factor at almost unity. Reference [6] was presented efficiency optimization for interior permanent magnet synchronous motor drive using vector control, by controlling the optimum d-axis stator current based on "loss model" which is validated by experiment results.

The space vector pulse width modulation (SVPWM) strategy produces a high utilization of DC input voltage, compared with other types of PWM strategies, such as sinusoidal pulse width modulation (SPWM). Also in order to reduce the total harmonic distortion (THD), the switching frequency is required to be increased. This will cause an increase of the stress and switching energy loss of the power devices as well as increase the electromagnetic interference (EMI). Therefore this paper proposes a strategy called modify space vector pulse width modulation (MSVPWM) as a contribution to improve the performance of PMSM.

II. SPACE VECTOR PULSE WIDTH MODULATION APPROACH

Space vector pulse width modulation (SVPWM) is one of the most popular techniques which is widely used by industrial applications due to its features, such as its control strategy can be implemented in digital system and has efficient utilization of dc bus compared with other PWM strategies[7]. The theory of space vector is based on representing three-phase system $V_a(t)$, $V_b(t)$ and $V_c(t)$ by a rotating vector V_r as given in (1):

$$V_r = \frac{2}{3}[V_a(t) + a * V_b(t) + a^2 * V_c(t)] \qquad (1)$$

Where $a=1e^{j\frac{2}{3}\pi}$, $a^2=1e^{j\frac{4}{3}\pi}$

A six pulse voltage source inverter, is shown in Fig. 1, has eight permissible switching states $2^3 = 8$ .The upper switching power devices S1, S3and S5 are complementary in switching with the lower devices S4, S6and S2 respectively, to avoid short circuit across the dc link.

Table 1. shows the line and phase voltages corresponding to the switching states, note that the lower switches of the inverter legs aren't mention in table which take the opposite states of upper switches.

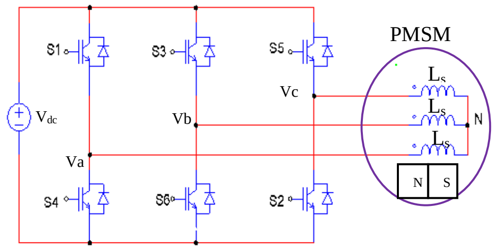


Fig.(1) Three phase voltage source inverter

Table 1. Line and phase voltages relationship with switching states

Vector	S1	S3	S5	V_{ab}	V_{bc}	V_{ca}	V_{an}	V_{bn}	V_{cn}
V_0=(000)	OFF	OFF	OFF	0	0	0	0	0	0
V_1=(100)	ON	OFF	OFF	$+V_{dc}$	0	$-V_{dc}$	$+2/3V_{dc}$	$-1/3V_{dc}$	$-1/3V_{dc}$
V_2=(110)	ON	ON	OFF	0	$+V_{dc}$	$-V_{dc}$	$+1/3V_{dc}$	$+1/3V_{dc}$	$-2/3V_{dc}$
V_3=(010)	OFF	ON	OFF	$-V_{dc}$	$+V_{dc}$	0	$-1/3V_{dc}$	$+2/3V_{dc}$	$-1/3V_{dc}$
V_4=(011)	OFF	ON	ON	$-V_{dc}$	0	$+V_{dc}$	$-2/3V_{dc}$	$+1/3V_{dc}$	$+1/3V_{dc}$
V_5=(001)	OFF	OFF	ON	0	$-V_{dc}$	$+V_{dc}$	$-1/3V_{dc}$	$-1/3V_{dc}$	$+2/3V_{dc}$
V_6=(101)	ON	OFF	ON	$+V_{dc}$	$-V_{dc}$	0	$+1/3V_{dc}$	$-2/3V_{dc}$	$+1/3V_{dc}$
V_7=(111)	ON	ON	ON	0	0	0	0	0	0

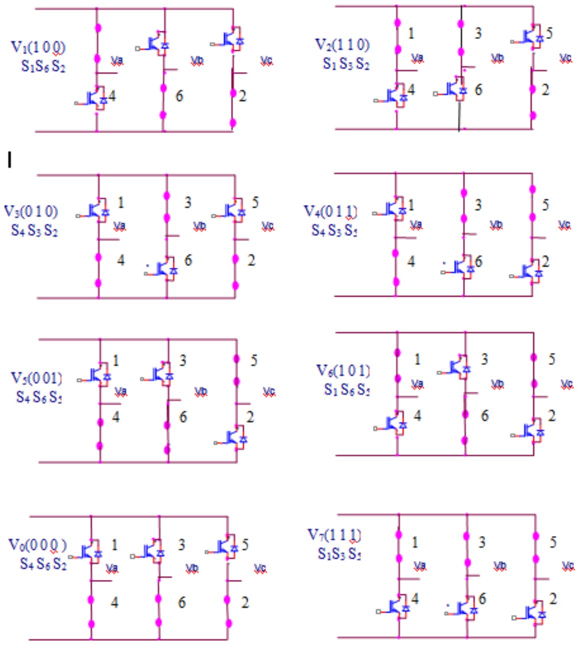


Fig.2. Eight states of voltage vector for six step voltage source inverter

The eight possible state vectors, for six step inverter, are summarized in Fig. 2.The six- IGBT switches combinations in the inverter have "eight permissible switching states". The active vectors ($V_1 \ldots V_6$) are represented by the axes of hexagonal that has the magnitude of 2/3 V_{dc}. The angle between any two adjacent active vectors is $\pi/3$ radians. The non-active vectors (V_0 and V_7) are presented at the origin as shown in Fig. 3. The space vector, according to the equivalence principle and following operation rules, are obtained as: V_1= -V_4, V_2= -V_5, V_3 = -V_6 and V_0=V_7=0. The value of reference vector (V_{ref}) is adjusted as in (2).

$$\overline{V}_{ref} = \frac{t0}{Tz}\overline{V}_0 + \frac{t1}{Tz}\overline{V}_1 + \cdots + \frac{t7}{Tz}\overline{V}_7 \tag{2}$$

Where $t_0, t_1 \ldots t_7$ are the ON sharing time of all the vectors $\overline{V}_0, \overline{V}_1 \ldots\ldots \overline{V}_7$, and T_Z is the complete sampling period. Equation (2) represents the decomposition of $\overline{V}_{ref}$ into $\overline{V}_0, \overline{V}_1 \ldots \overline{V}_7$ has infinite ways [8]. To make full use of ON times for active vectors, the reference vector splits in two nearest adjacent active vectors and two non-active vectors. For example, if the reference vector is in sector 1 for one sampling interval T_Z and with angle α along d-axes as shown in Fig. 3, then the relation between d-q axes voltage V_d and V_q with phase load voltage V_{an},V_{bn} and V_{cn} is given in (3) . Keeping in mind the maximum length of the active vectors are equal to ($2/3V_{dc}$), while the locus of V_{ref} is a circle and its maximum value is $1/\sqrt{3}\ V_{dc}$. This means that the maximum value of modulation index (M) in linear region is [$(1/\sqrt{3}\ V_{dc}) / (2/3V_{dc})$] = 0.866.

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \tag{3}$$

Where; $\alpha = \tan^{-1}(\frac{V_q}{V_d})$ and $\left|\overline{V}_{ref}\right| = \sqrt{V_d^{\,2} + V_q^{\,2}}$

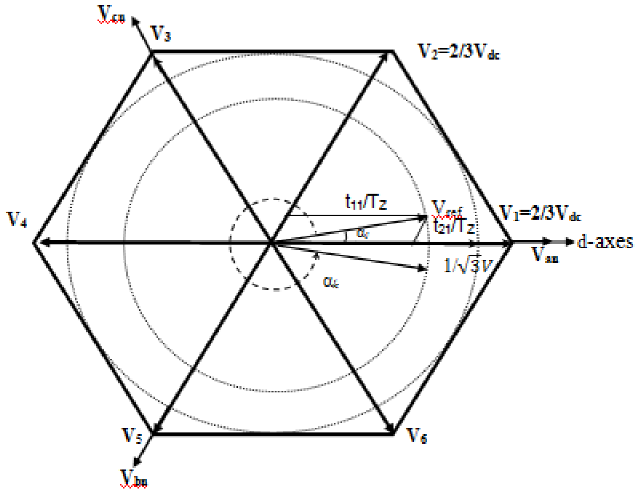


Fig. 3. Voltage space vectors

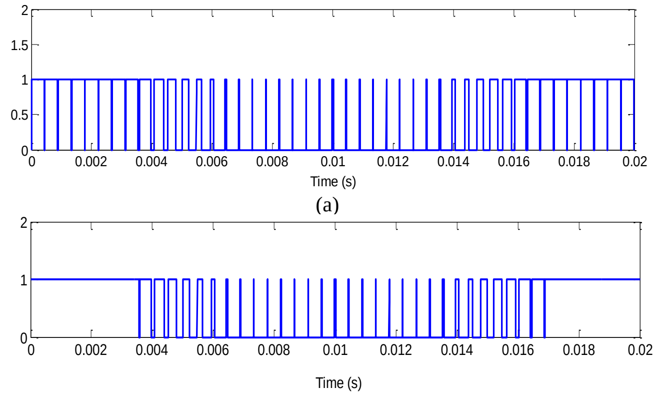
III. METHODOLOGY OF MSVPWM

When modulation index (M) value of SVPWM is higher than 0.8 and sampling number is relatively high, some of notches, appeared in the generated switching pattern within the pulses, are small with respect to sampling period T_Z. This means that the pulse width of the sample is equal to(t_1+ t_2+t_0/2) and the notche't_0/2' is relatively very small, compared with T_Z. Therefore the notch 't_0/2' can be eliminated by considering no change in switching state of the power to reduce the switching losses and the stress on the power switches. If the sampling frequency is multiple of six (i.e. 12,18,24…), then the total number of eliminated notches (N_{notch}) can be calculated according to N_{notch}=2*N, where N is the total number of samples in one sector and the rest number of pulses = W_f -N_{notch}+1 where W_f is the ratio of sampling frequency (f_s) to the operating frequency (f). This approach, based on MSVPWM, is keeping the THD of the PMSM current same as conventional SVPWM with less than 5% without using high pass filter.

A Three phase PMSM has the following specifications; The rating values are; 1.1Kw, 220V, 50 Hz, 2.85A, armature resistance is 6.34Ω, Ld=89mH, Lq=65mH, λ_f=0.6wb, and load torque T_L=7N.m. These rating have been used for PMSM simulation with SVPWM at sampling frequency f_s=2250Hz, M=0.85 and V_{dc}=300V. For calculation number of pulses, the frequency ratio W_f =2250/50=45, and the reference vector V_r, as given in Fig. 3, will rotate with angle equal to 360/45=8° which made the number of pulses in each sector equal to 7-8. For MSVPWM the number of eliminating notches is equal to (7+8=15), there is two sector in hexagonal have the width of t_0/2, therefore the number of pulses will be (45-15+1=31) and the effective dynamic sampling frequency will be 1550Hz while the dynamic sampling frequency is 2250.

Fig. 4(a), shows the switching pattern of SVPWM and Fig. 4(b) shows significant reduction of switching notches with MSVPWM.

Figs. 5(a) &(b) show the motor line voltages and their spectrums for SVPWM and MSVPWM respectively. The most significant harmonic orders are almost same. But the utilizing dc link voltage, with MSVPWM, is improved due to the increase of the fundamental voltage and the reduce of voltage stress on IGBT due to the significant reduction in switching, i.e. on and off , states has less effect.

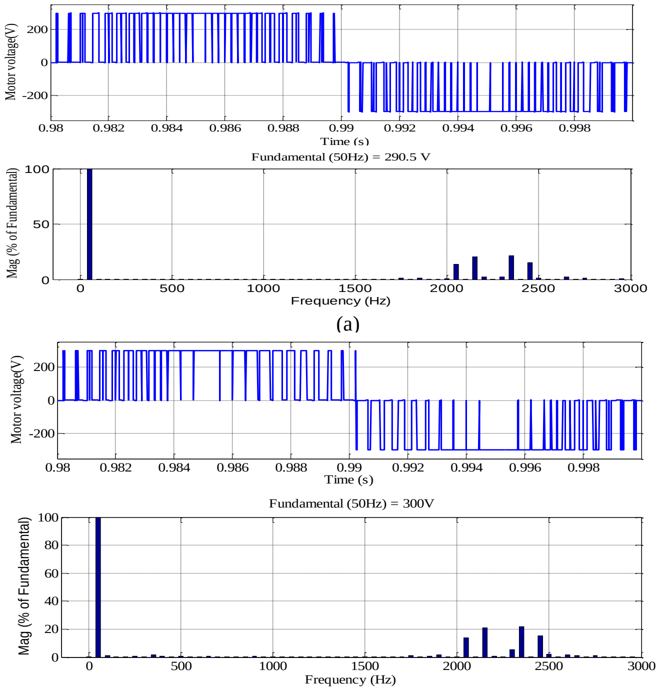


(a)

(b)

Fig. 4. Switching pattern (a) SVPWM (b)MSVPWM

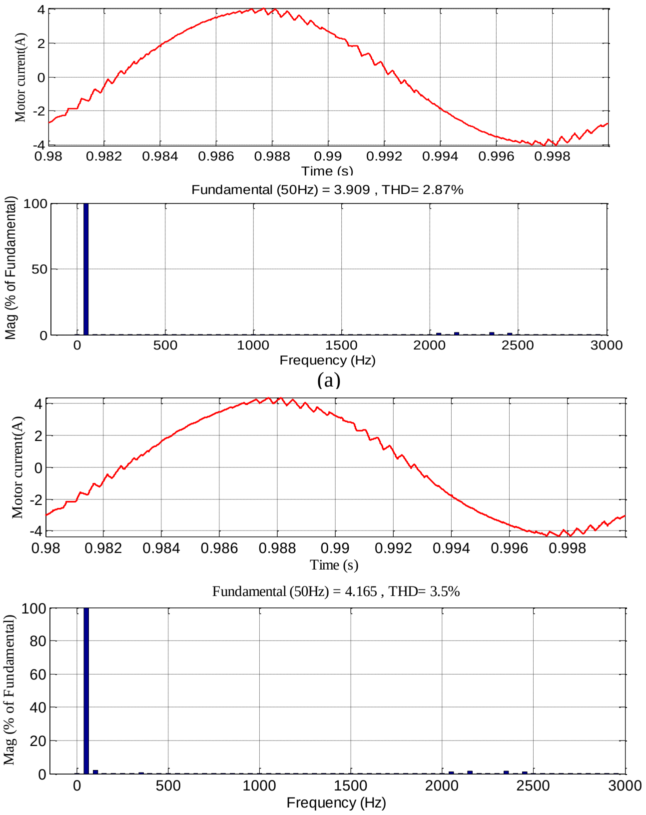
The motor current for SVPWM and MSVPWM are shown in Figs. 6(a) &(b) respectively and Figs. 7(a) &(b) and Figs. 8(a) &(b) show the electromagnetic torque and motor speed for SVPWM &MSVPWM respectively.



(a)

(b)

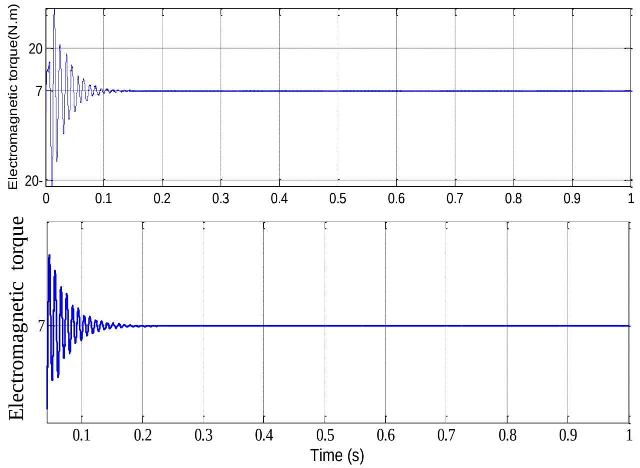
Fig.5Motor line voltage and spectrum
a) SVPWM b) MSVPWM



(a)

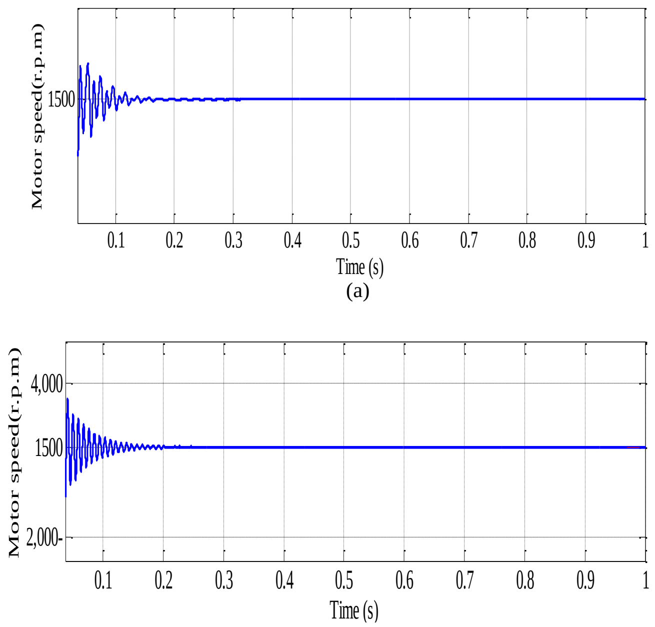
(b)

Fig.(6) Motor line current a) SVPWM b) MSVPWM



(b)

Fig. 7. Electromagnetic torque (a) SVPWM (b) MSVPWM



(a)

(b)

Fig. 8. Electromagnetic torque (a) SVPWM (b) MSVPWM

IV POWER LOSSES CALCULATION IN SVPWM AND MSVPWM INVERTER TEMPLATE

The power loss due to Power semiconductor switches, such as IGBT, can be classified into [9] conducting losses (P_{cond}), switching on and off power losses (P_{sw}) and blocking (P_b) or leakage loss which may be neglected. The total switching losses of power semiconductor switches become significant practically when the switching frequency and the switching stress are high[10].Two categories of power loss measurement in power electronic applications. The first is electrical methods which is based on the multiplication of both the instantaneous voltage and current ,for say IGBT to get instantaneous power, then the mean value of instantaneous power gives the power loss. The second is calorimetric method which measure the total power P_{loss} by mean of dissipates as heat within a measurement chamber. In general, two main types of electrical power measurement, analogue electrical and digital methods. The analogue type, such as electromechanical wattmeter, is inconvenient for measuring non-sinusoidal waveform or high frequency application, its suitable for dc or low frequency sinusoidal waveforms[11]. Digital measurement techniques, such as digital storage oscilloscope, FPGA, microprocessor, dspace, etc. are the convenient tools for power electronic applications, due to using high frequency sampling waveform of current and voltage and therefore the power losses can be predicted. The instantaneous power waveform is equal to multiplications of both instantaneous collector to emitter voltage v(t) and collector current i(t) , of IGBT. Therefore integrating instantaneous power over a period of T(sec) to obtain the real power P_{av} (watt) switching loss as expressed in (4).

$$P_{av} = \frac{1}{T}\int_0^T v(t).i(t)dt \tag{4}$$

The simulation-tool presents a relatively exact method for calculating power switching loss[12]. Switching and conduction losses can be directly calculated using Matlab/Simulink. For comparison, between traditional space vector and MSVPWM at f_s=2250Hz and modulation index M=0.8 with same loading condition, the total power loss is given in Fig. 9. This Figure shows that the power losses in IGBT switches in the VSI with MSVPWM technique are significantly less than in traditional SVPWM, due to the reduction in switching losses and the stresses on power switches.

V. RACTICAL TEST RESULTS

The Drive system is tested in a real time system in order to check its performance and the power losses. The base drive circuit has been built using optocoupler 6N137, and the six -pulse three phase power inverter circuit designed using IGBT's type FGW30N120HD, where its specifications are V_{ce}=1200V, I_c= 30A and V_{CEsat} =2V. The gate drive signals has been built based on the dSpace digital control system DS1103. Figs. 10 (a)&(b) show the practical gate drive pattern at M=0.85, f_s=2250Hz, for SVPWM and MSVPWM respectively.

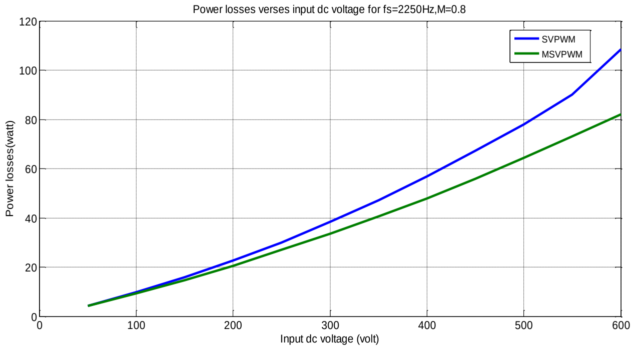
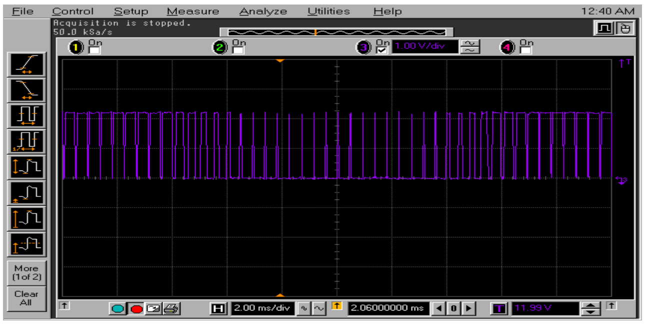
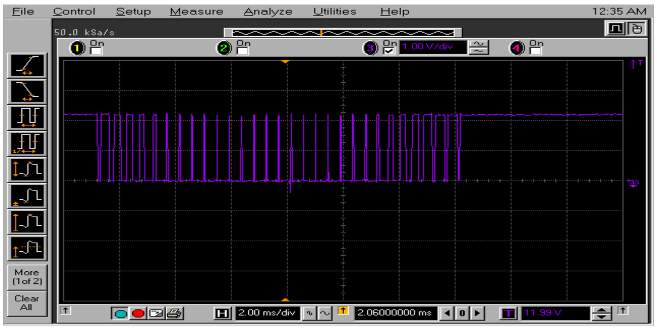


Fig. 9 Relation between input dc voltage and power losses for SVPWM and MSVPWM



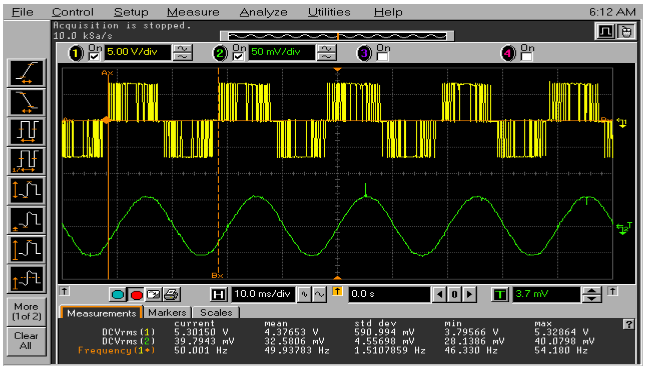
(a)



(b)

Fig. 10. practical gate signal (a) SVPWM (b) MSVPWM

Figs. 11(a)&(b) show the motor line voltage and current for SVPWM, MSVPWM respectively, while Figs.12(a)&(b) show the motor voltage spectrum for SVPWM, MSVPWM respectively, Fig.13. shows the practical calculation of power losses using digital oscilloscope for resistive load with certain load condition. Fig.(14) shows the practical relation between output line voltage and power losses for SVPWM and MSVPWM respectively. Fig.(15) shows the relation between line output voltage and input dc voltage.



```
             current      mean         std dev         min          max
DCVrms(1)    5.30150 V    4.37653 V    590.994 mV      3.79566 V    5.32864 V
DCVrms(2)    39.7943 mV   32.5806 mV   4.55698 mV      28.1386 mV   40.0798 mV
Frequency(1+) 50.001 Hz   49.93783 Hz  1.5107859 Hz    46.330 Hz    54.180 Hz
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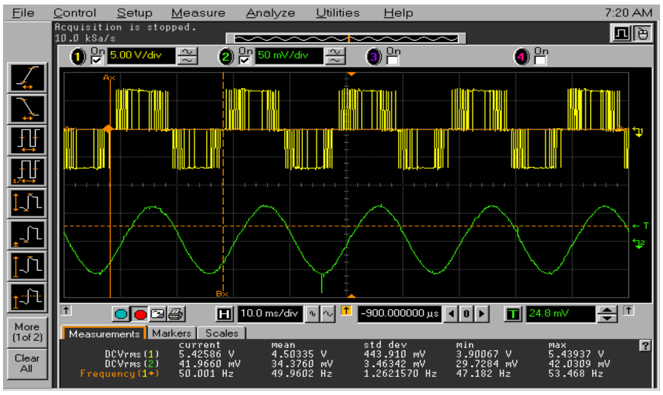
(a)



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             current      mean         std dev         min          max
DCVrms(1)    5.42586 V    4.50335 V    443.910 mV      3.90067 V    5.43937 V
DCVrms(2)    41.9660 mV   34.3760 mV   3.46342 mV      29.7284 mV   42.0309 mV
Frequency(1+) 50.001 Hz   49.9602 Hz   1.2621570 Hz    47.182 Hz    53.468 Hz
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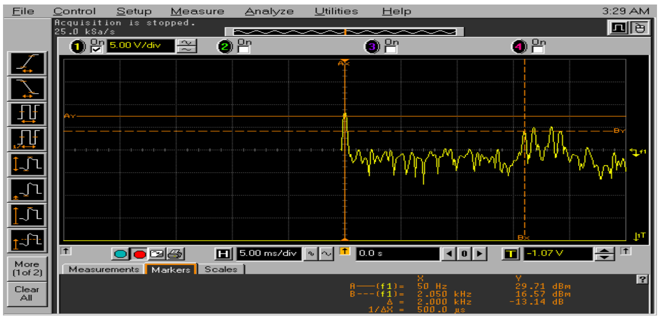
(b)

Fig. 11. Motor line voltage and current (a) SVPWM (b) MSVPWM



```
               X            Y
A——(f1)=   50 Hz        29.71 dBm
B---(f1)=  2.050 kHz    16.57 dBm
      Δ =  2.000 kHz   -13.14 dB
   1/ΔX =  500.0 µs
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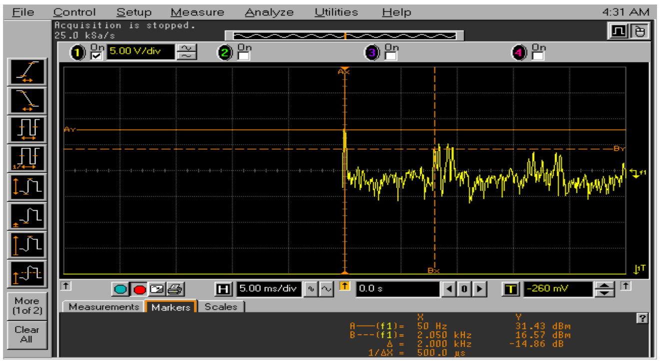
(a)



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               X            Y
A——(f1)=   50 Hz        31.43 dBm
B---(f1)=  2.050 kHz    16.57 dBm
      Δ =  2.000 kHz   -14.86 dB
   1/ΔX =  500.0 µs
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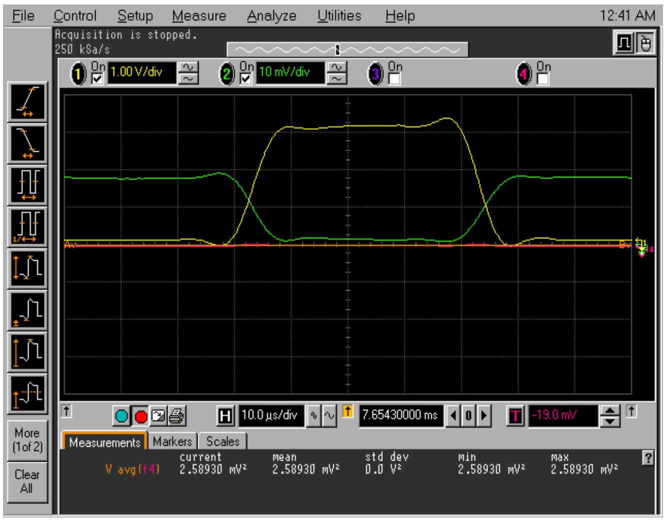
(b)

Fig. 12. Motor Lin voltage spectrum (a) SVPWM (b)MSVPWM



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             current         mean            std dev    min             max
V avg(f4)    2.58930 mV²     2.58930 mV²     0.0 V²     2.58930 mV²     2.58930 mV²
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Fig. 13. Ppracitcal calculation of power losses using digital oscillscope

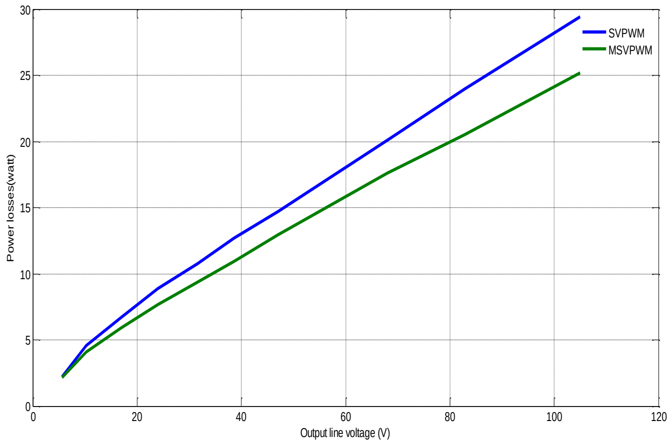

Fig. 14. Relation between power losses and output line voltage

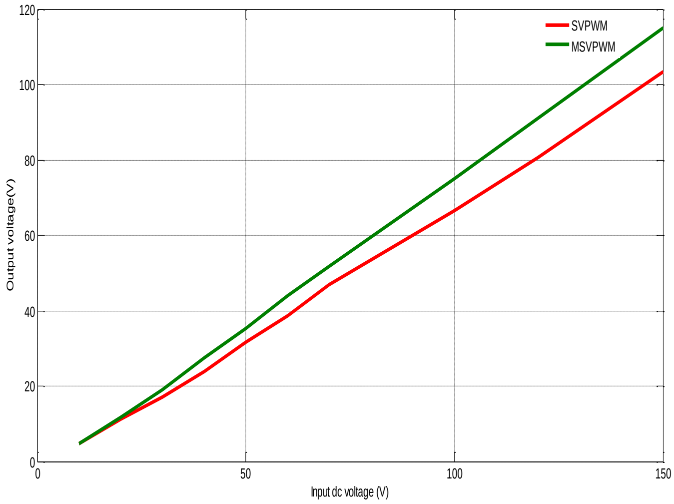

Fig. 15. Relation between output line voltage and input dc voltage

VI. CONCOLUSION

In this paper, the theory of the proposed modified space vector pulse width modulation for a three-phase voltage source inverter has been presented. A proposed MSVPWM is introduced by eliminating the small notching of the pulses. These notches are relatively small with respect to sampling period T_Z particularly at high modulation index higher than 0.8 . The proposed method confirms the following features; reduces the switching frequency, reduces the stress on power switching devices, improves the efficiency, increases the utilization of dc link source, and minimizes the susceptibility of fault for the complementary of the power transistors. For typical case, when M=0.85, V_{dc} =300V, using Matlab/ Simulink, the fundamental output line voltage is 290.5V when the switching frequency f_s=2250Hz, number of pulses=45 for SVPWM. While the fundamental output line voltage is 300V at effective sampling frequency f_s=1550Hz, after eliminate the notches which result number of pulses=31 for MSVPWM . The simulation results for calculation the power losses, as in Fig. 9, shows the power losses calculation based on MSVPWM has lower power losses compared with SVPWM. Therefore the proposed strategy has higher efficiency and reduces the stress on power switches. For verification, practical results shows that same harmonic component in the line voltage spectrum for both SVPWM and MSVPWM approaches, and determination of power losses and utilization of dc input voltage as in Figs. 14&15 show the MSVPWM has less power losses and higher output voltage.

REFERENCES

[1] Tomaz Rudricki and AleKsanderFrechowiz,"Permanent magnet Synchronous Motor Control Driver ", international conference Mixed design of integrated circuits and systems, Jun. 16-18 , 2011.pp545-547.

[2] Enrique L. Carrillo Arroyo, " Modeling and Simulation of Permanent Magnet Synchronous Motor Drive System ", M.Sc. Thesis, University of Puterto Rico , 2006.

[3] Seong Taek Lee ," Development and Analysis of Interior Permanent Magnet Synchronous Motor with Field Excitation Structure ", PhD. Thesis, University of Tennessee, Knoxville,2009.

[4] Zhuqiang Lu , Honggang Sheng and Herbert L. Hess ,"The Modeling and Simulation of a Permanent Magnet Synchronous Motor with Direct Torque Control Based on Matlab/Simulink IEEE" 2005 ,pp.1150-1156.

[5] Yoshinobu Nakamura Toshiaki Kudo, Fuminori Ishibashi, and Sadayoshi Hibino"High-Efficiency Drive Due to Power Factor Control of a Permanent Magnet Synchronous Motor"IEEE Transaction on power Electronics, Vol.10, No.2, March 1995,pp.247-253.

[6] Christos Mademlis, Member, Iordanis Kioskeridis, and Nikos Margaris" Optimal Efficiency Control Strategy for Interior Permanent Magnet Synchronous Motor Drives", IEEE Power&Energy Society, Volume:19 , No: 4 Dec. 2004 , pp 715 - 723.

[7] R. Arulmozhiyal K. Baskaran cole, "Space Vector Pulse Width Modulation Based Speed Control of Induction Motor using Fuzzy PI Controller," " International Jornal of Computer and Electrical Engineering, Vol. 1, No.1, Aperil 2009, pp.98-103.

[8] Dorin O. Neacsu " Space Vector Modulation –An Introduction" The 27th Annual Conference of the IEEE Industrial Electronics Society,2001.pp 1583- 1592.

[9] Muhamed H.Rashid "Power electronics circuits, Devices and applications"3rd Edition 2004, pp. 862.

[10] Z. John Shen, Yali Xiong, Xu Cheng, Yue Fu, and Pavan Kumar"Power MOSFET Switching Loss Analysis:A New Insight" IEEE, 2006 pp.1438-1442.

[11] Chucheng Xiao, Gang Chen, and Willem G. H. Odendaal" Overview of Power Loss Measurement Techniques in Power Electronics Systems "IEEE Transaction on Industry applications, Vol. 43, No. 3, May/June 2007,pp 657-664.

[12] Hsin-Ju Chen , George L. Kusic and Gregory F. Reed"Comparative PSCAD and Matlab/Simulink Simulation Models of Power Losses for SiC MOSFET and Si IGBT Devices" IEEE Power and Energy Conference ,2012,pp.1-5.