A SIMPLIFIED ULTRA FAST DSP BASED SPACE VECTOR PWM ALGORITHM WITH OPERATION IN UNDER AND OVERMODULATION REGIONS - ANALYSIS AND IMPLEMENTATION

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Abstract – **This paper proposes a simplified algorithm of space vector modulation for voltage-fed inverter. The simplified algorithm is faster and more flexible than any algorithm so far proposed in the literature and allows high switching frequency. Another relevant advantage of this proposed approach is that a single algorithm covers the undermodulation and overmodulation operation regions, and square wave with almost none additional computation cost. The simplification of the algorithm is achieved by exploring: i) the decoupling between the angle and amplitude of the command voltage vector in the final result of the algorithm; ii) extrapolation of the undermodulation strategy to go into the overmodulation region; iii) reduction of the number of equation to calculate the switching times; and iv) simplification of the sector identification strategy. As a result, the algorithm can be implemented using only basic mathematical operators (+, -, *), Boolean logical operators, and a small one-dimensional look-up table. This simplified algorithm permits higher frequency implementation of the space vector modulation without loosing any good feature of the conventional algorithm. Matlab/Simulink simulation results and experimental results using DSP TMS320F240 for a V/Hz controlled induction motor drive with 20 kHz switching frequency are provided and shown to be excellent.**

KEYWORDS: VFI, SVPWM, undermodulation, overmodulation, DSP application.

I. INTRODUCTION

The dc to ac power conversion is the basis of the modern ac motor drive applications. In these applications, the Pulse-Width-Modulated (PWM) voltage-fed inverter (VFI) is widely accepted. The fixed switching frequency and well-defined harmonic content makes the carrier-based PWM algorithms very popular. Among the carrier-based PWM algorithm, Space Vector PWM (SVPWM) is well ranked because of its superior harmonic quality and extended linear range of operation [1,2]. Different from others carrier based PWM algorithms, which modulates each of the three-phase individually, SVPWM modulates the command voltage vector as whole. Basically, this algorithm aims to have the average of the output voltage vector equals to the command reference vector. Because of the nature of its strategy, SVPWM requires very complex on-line computation, which usually limits its operation up to several kHz of switching frequency. The difficulty increases when operation in undermodulation and overmodulation regions is required. In this case different algorithms for each region are required. An operation strategy for each region was proposed in [3], where the overmodulation region was further divided into two regions, and consequently two additional algorithms, resulting in a total of three algorithms to cover under and overmodulation regions. Simplifications of the strategy for overmodulation, was proposed by [4] and [5]. Both approaches use only one algorithm for the overmodulation region, however to achieve such simplification, the harmonic quality in this region is sacrificed. Regardless of any mentioned simplification in the overmodulation range, if undermodulation and overmodulation range are required, then the SVPWM implementation will require at least two algorithms, one for undermodulation and one for overmodulation. More recently, another approach [6] simplified the SVPWM algorithm, proposed a saturation function, and artificial neural network to unify the algorithm for undermodulation and overmodulation regions.

This paper proposes a simplified algorithm of space vector modulation for voltage-fed inverter. The simplified algorithm is faster and more flexible than any algorithm so far proposed in the literature and allows high switching frequency. Another relevant advantage of this proposed approach is that a single algorithm covers the undermodulation and overmodulation operation regions, and square wave with almost none additional computation cost. The simplification of the algorithm is achieved by exploring: i) the decoupling between the angle and amplitude of the command voltage vector in the final result of the algorithm; ii) extrapolation of the undermodulation strategy to go into the overmodulation region; iii) reduction of the number of equation to calculate the switching times; and iv) simplification of the sector identification strategy. As a result, the algorithm can be implemented using only basic mathematical operator (+, -, *), Boolean logical operators, and a small one-dimensional look-up table. This simplified algorithm permits higher frequency implementation of space vector modulation .without loosing any good feature of the conventional space modulation algorithm.

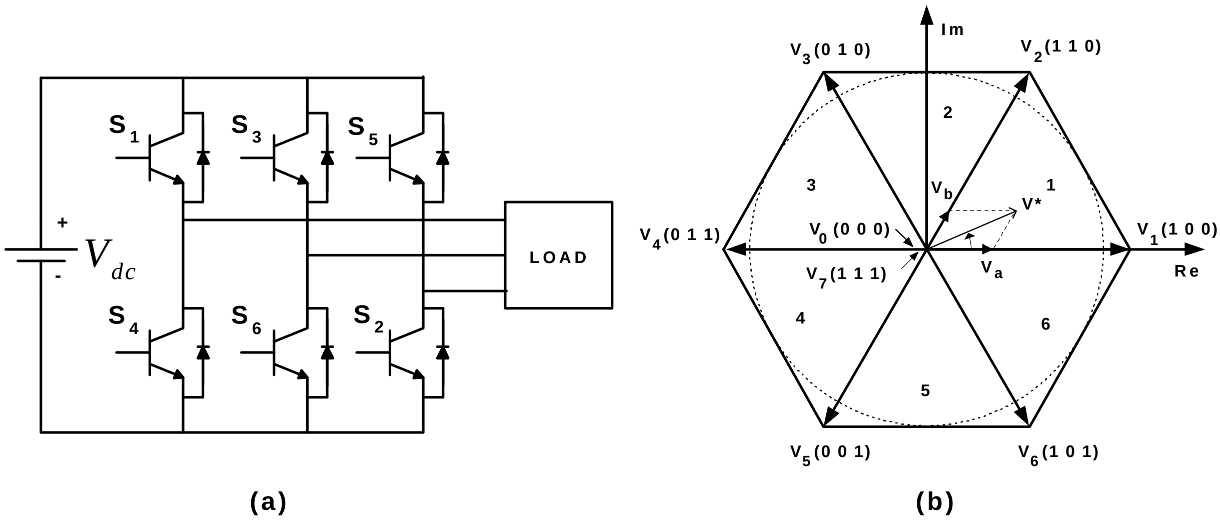


Fig. 1 – (a) Voltage-Fed Inverter (b) VFI Switching States

II. SPACE VECTOR MODULATION

Figure 1 shows a three-phase two-level voltage-fed inverter, and its eight switching states, of from six [V_1 (100) – V_6 (101)] are active state vectors to form a hexagon, and two [V_0(000) and V_7(111)] are zero state vectors that lie at the origin. It is also shown in figure 1 a command voltage vector V^* lying in sector 1. The operation in undermodulation and overmodulation is determined by the modulation index *m*, which is defined as the ratio between the magnitude of the command reference voltage vector and the peak value of the fundamental component of square wave voltage. The modulation index (*m*) varies between 0 and 1. In the undermodulation region ($0<m<0.907$), shown in Fig. 2(a), the reference voltage V^* remains within the hexagon. The overmodulation region is subdivided into two modes: mode 1 ($0.907<m<0.952$) and mode 2 ($0.952<m<1.0$). Figure 2(b) shows a reference vector for the mode 1 and the lower and upper trajectory limits for this operation region. Figure 2(c) is the equivalent figure for mode 2.

Equation (1) gives the effective times of inverter switching states in undermodulation region.

$$t_a = 2.\frac{\sqrt{3}.T_S}{4.V_{dc}}.V^*.\sin(\pi/3 - \alpha^*)$$

$$t_b = 2.\frac{\sqrt{3}.T_S}{4.V_{dc}}.V^*.\sin\alpha^* \qquad (1)$$

$$t_0 = \frac{T_S}{2} - (t_a + t_b)$$

where

t_a, t_b, t_0 - effective time for the lagging, leading and zero switching vectors respectively;

$T_s = 1/f_s$ - sampling time (f_s - switching frequency);

V^* - command vector;

V_{dc} – DC link voltage

α^*- angle of V^* in a 60° sector.

For overmodulation modes I e II, the equations (1) remain true, however it is necessary to compensate the output fundamental voltage losses through amplitude and/or angle modification [1]. In overmodulation mode I, the amplitude is modified from V* to V_m, and in overmodulation mode II,

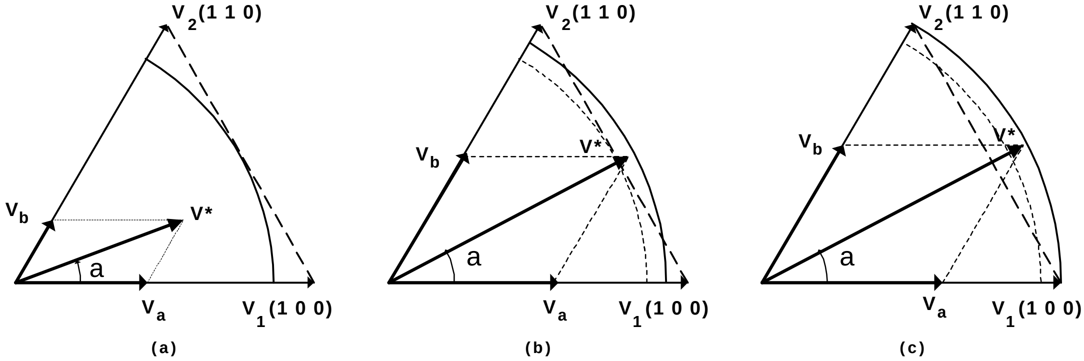


Fig. 2 – SVPWM operation regions (a) undermodulation (b) overmodulation I (c) overmodulation II

besides the amplitude modification, the angle is also modified from * to $_{m}$.

Figure 3(a) shows the flowchart for the conventional SVPWM algorithm. It is possible to see the steps of the algorithm, which are: sector identification; calculation of *; calculation of the modulation index; calculation of t_a, t_b, and t_c; and calculation of $T_{A\text{-}ON}$, $T_{B\text{-}ON}$, and $T_{C\text{-}ON}$ depending on the sector location. It is important to observe that there are three different algorithms to calculate t_a, t_b and t_c in order to cover the whole operation range, i. e., undermodulation, overmodulation mode I, and overmodulation mode II. Therefore this algorithm is very time consuming because: i) the equations to calculate the effective times depend on the operation region; ii) the switching times are calculate using the effective time and the sector information; and iii) the method used to identify the sector where the reference vector lies is very complex.

III – SIMPLIFIED ULTRA FAST SVM ALGORITHM

The simplified algorithm proposed in this work proposed algorithm is based on the approach proposed in [6].The main points proposed in [6] are:

- Calculate the turn-on and turn-off times directly, instead of calculate the effective times and identify the sector to build them up;
- Explore the decoupling between the angle and amplitude of the command voltage vector in the calculation of turn-on and turn-off times;
- Extrapolate the undermodulation region to go into the o overmodulation region (saturation function);

The first step toward the simplification of the SVPWM algorithm is given by using the d-q components. This strategy simplifies the calculation of the sin(*) e sin(pi/3 - *) terms, avoiding the use of a look-up table. The calculations of the switching times become simpler, and are given by equation. (2).

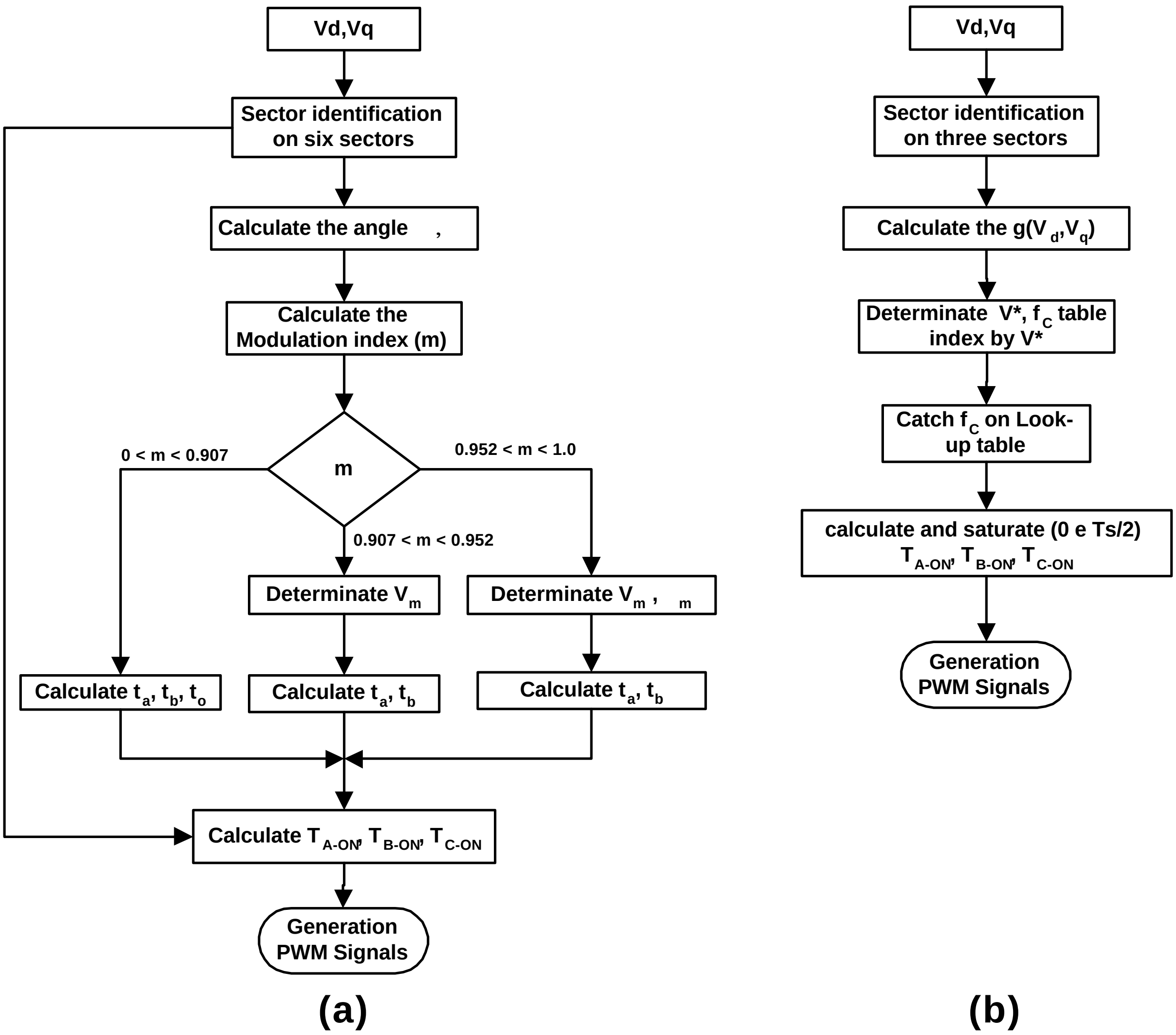


Fig. 3 – Flowchart of (a) conventional algorithm (b) simplified algorithm

$$T_{A\ ON=}\begin{cases}\frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\left(V_d+\frac{V_q}{\sqrt{3}}\right)\right) & S=1,4\\ \frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}[\ 2.V_d]\right) & S=2,5\\ \frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\left(V_d\quad\frac{V_q}{\sqrt{3}}\right)\right) & S=3,6\end{cases}\quad (2.a)$$

$$T_{B\ ON=}\begin{cases}\frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\left[V_d+\sqrt{3}.V_q\right]\right) & S=1,4\\ \frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\frac{2.V_q}{\sqrt{3}}\right) & S=2,5\\ \frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\left(V_d+\frac{V_q}{\sqrt{3}}\right)\right) & S=3,6\end{cases}\quad (2.b)$$

$$T_{C\ ON=}\begin{cases}\frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\left(V_d\quad\frac{V_q}{\sqrt{3}}\right)\right) & S=1,4\\ \frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\frac{2.V_q}{\sqrt{3}}\right) & S=2,5\\ \frac{T_S}{4}\left(1+f_C\frac{3}{2V_{dc}}\left[V_d\quad\sqrt{3}.V_q\right]\right) & S=3,6\end{cases}\quad (2.c)$$

Therefore, equation (2.a) can be rewritten as shown in equation 3.

$$T_{A\ on}=\frac{T_S}{4}\left(1+f_C.g(V_d,V_q)\right)\qquad(3)$$

For operation in the linear region, f_c is unity, and the function $g(V_d,V_q)$ is, in fact, the normalized switching time. However, for operation in the overmodulation region, f_c is no longer unity, and assumes values to do the angle and amplitude compensation. The compensation factor f_c was obtained based in [6], and can stored in a small look-up table. Figure 4 shows the f_c as function of modulation index.

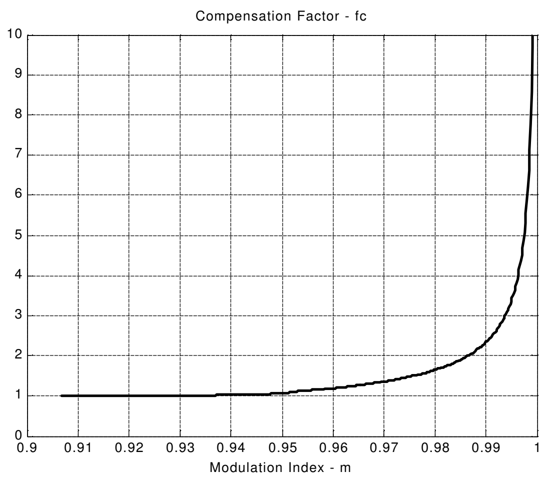


Fig 4. – Compensation factor.

III.1 – Simplification of the strategy for Sector Identification

The simplification of strategy for sector identification is also a key point of the ultra fast SVPWM simplified algorithm. Basically, the proposed approach is an improvement of the strategy shown in [7]. The sector is determined by Boolean logical operations of the sign bit of three functions of the reference vectors dq components, as given in equation (4).

$$\begin{aligned}A&=Sign(\ V_d)\\ B&=Sign(\sqrt{3}V_d+V_q)\\ C&=Sign(\ \sqrt{3}V_d+V_q)\end{aligned}\qquad(4)$$

The sector identification given in [7] is done using equation 5.

$$N=A+2.B+4.C\qquad(5)$$

The simplification uses the similarities between the sectors 1 and 4, 2 and 5, and 3 and 6. This reduces the total number of sectors from 6 to 3, and therefore only 2 conditional expressions (*if*) are required for calculation of $g(V_d,V_q)$, instead of 6 as proposed in [7]. Figure 5 shows the idea behind the sector identification. On the other hand the sector identification using the proposed approach is done using equation 6.

$$N^*=(A\ xor\ \mathrm{B})+2.(\mathrm{B}\ xor\ \mathrm{C})\qquad(6)$$

The sign function is implemented through a AND logical operation. And the sum operation is implemented with a bit shift and an OR logical operation.

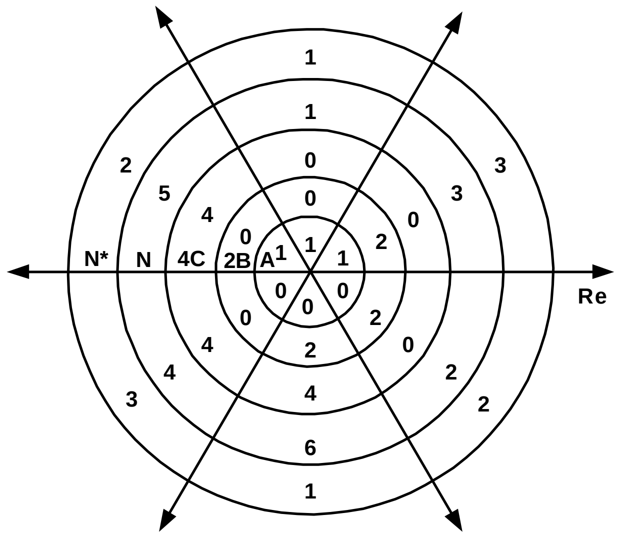


Fig.5 – Simplification of sector identification.

III.2 – Saturation Function

The last stage before gates switching signals generation is the saturation of the switching times in 0 or Ts/2. However, different from the approach proposed in [6], here the saturation is done to the function $(1+f_C.g(V_d,V_q))$ either in 0 or 2. Therefore, since the multiplication by Ts/4 is made after the saturation, the switching frequency can be easily changed in the source codes, only by changing the switching period T_S.

Figure 3(b) shows the flowchart for the simplified algorithm proposed in this work. This algorithm is much simpler and consumes much less computation time because: i) it is based on the switching time rather than the effective time, i.e., it calculates the switching times directly; ii) the overmodulation mode 1 and 2 regions are obtained through a extrapolation of the undermodulation region; iii) uses a small look-up table for correction of amplitude factor on overmodulation region; and iv) the sector identification algorithm is much simpler.

V – SIMULATION AND EXPERIMENTAL RESULTS

In order to validate the proposed simplified algorithm, a V/Hz controlled induction motor drive with 20 kHz switching frequency was simulated and implemented.

V.1 – Simulation Results

A model of the V/Hz induction motor drive using the proposed algorithm was done using MATLAB/Simulink. The drive parameters are given in table 1. Figure 6 shows the phase currents for the drive in different operation frequencies. Figure 6(a) shows the drive operating in the linear region at 50 Hz (m = 0.833). Figure 6(b) shows the drive operating in the overmodulation mode 1 region at 56 Hz (m=0,933).Finally, figure 6(c) shows the drive operating in the overmodulation mode 2 at 59 Hz (m=0,983).

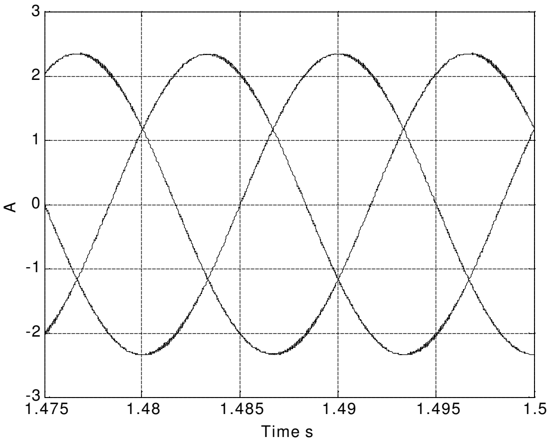
TABLE I : Drive system parameters

DC link voltage (V_{dc})	300 V
Sampling time (T_s)	50 S (f_S = 20 kHz)
Induction motor	1 Hp, 230 V, 4-pole
	frequency range: 0 – 60 Hz
	Power factor (full load): 85%
	Efficiency: (full load): 85%
	Stator resistance (Rs): 4.850
	Rotor resistance (Rr): 5.386
	Stator leak. inductance (Lls): 18.48 mH
	Rotor leak. inductance (Llr): 20.53 mH
	Magnetizing inductance (Lm): 225 mH
	Rotor Inertia (J): 0.01155 Kg.m^2
	Fan Load [T_L= r^2]: k= $1.65x^{-5}$

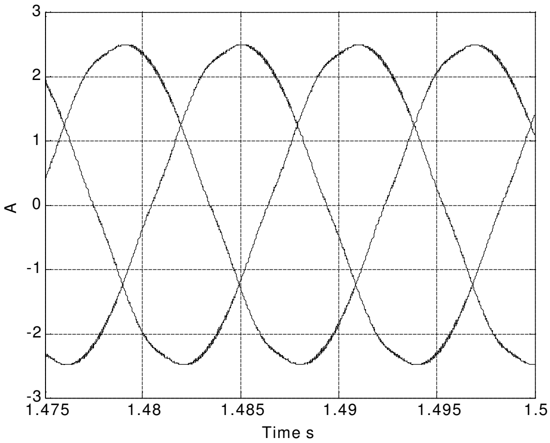
V.2 – Experimental Results

The same drive system used for simulation was implemented. The voltage-fed inverter was built using 6 IGBTs IRGPC50UD (600 V, 27 A) and a three-phase bridge driver IR2130 (2,5 S dead-time). The proposed simplified SVPWM as well as the open-loop V/Hz control was developed using a 16 bits fixed point DSP TMS320F240. This DSP has a 50 s instruction processing time. The SVPWM sampling time was 50 S (1/20kHz). The switching signals were generated through the six full compare unit of the DSP. The look-up table compensation factor (f_C) is composed by 256 elements. This number of elements was enough to assure the DSP precision.

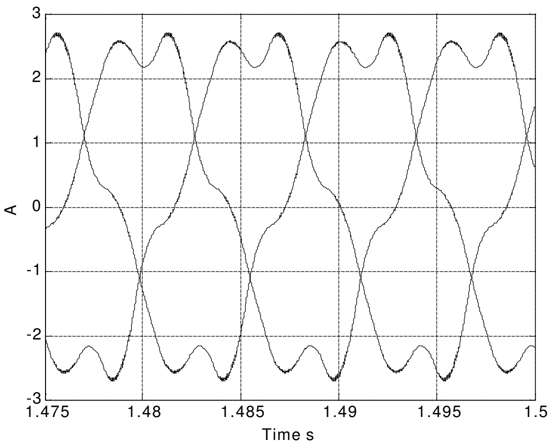
The execution time of the simplified SVPWM algorithm took only 110 machine cycles (5,5 S). The whole algorithm, which includes open loop V/Hz control and the simplified SVPWM, took 217 machine cycles (10.85 S).



(a)



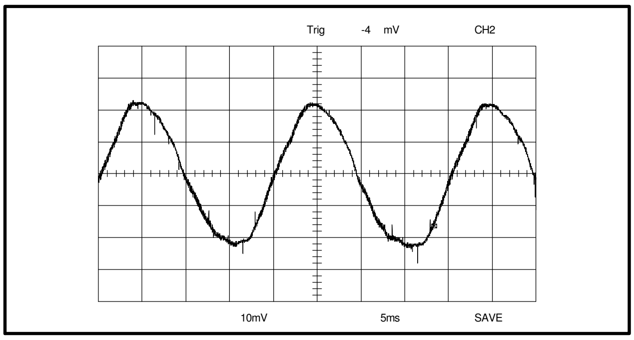
(b)



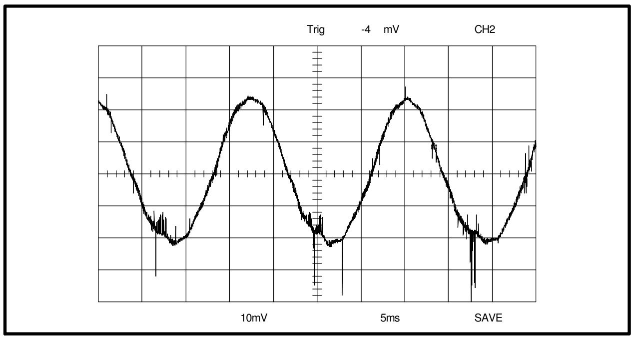
(c)

Fig. 6 – Simulation results:
(a) phase current – 50 Hz, m = 0.833;
(b) phase current – 56 Hz, m = 0.933;
(c) phase current – 59 Hz ,m = 0.983.

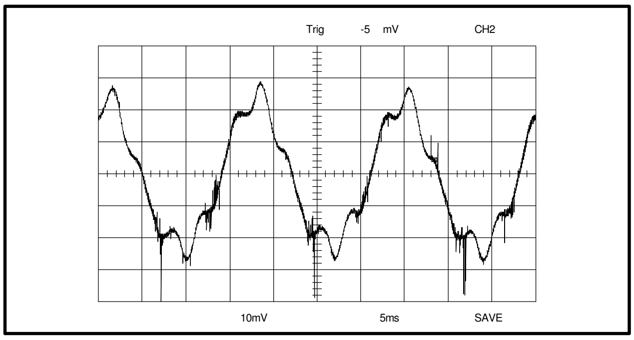
Figure 7, for comparison propose, shows the phase currents for the drive in the same operation points as those shown in the simulation results. Figure 7(a) shows the drive operating in the linear region at 50 Hz (*m* = 0.833). Figure 7(b) shows the drive operating in the overmodulation mode 1 region at 56 Hz (*m*=0,933).Finally, figure 7(c) shows the drive operating in the overmodulation mode 2 at 59 Hz (*m*=0,983). The experimental results are similar to the simulation results, which validate the approach.



(a)



(b)



(c)

Fig. 7 – Experimental results:
(a) phase current – 50 Hz, m = 0.833;
(b) phase current – 56 Hz, m = 0.933;
(c) phase current – 59 Hz, m = 0.983;
Scales: 5ms/div, 1A/div

VI - CONCLUSIONS

This paper proposes a new ultra fast simplified SVPWM algorithm. The simplification of the SVPWM algorithm is achieved by exploring i) the decoupling between the angle and amplitude of the command voltage vector in the final result of the algorithm; ii) the extrapolation of the undermodulation strategy to go into the overmodulation region; iii) the reduction of the number of equation to calculate the switching times; and iv) the simplification of the sector identification strategy.

The results simulation and experimental results show that the simplified algorithm works very well in under and overmodulation regions at a much less computation cost compared to conventional algorithm. Regarding the execution time, the performance of the proposed approach is excellent. The execution time of the simplified algorithm is close to the conventional algorithm, however the simplified operates in the under and overmodulation region, while the conventional operates only in the undermodulation. The execution time of the SVM algorithm takes 110 machine cycles (5.5 s when using TMS320F240).

Although the results were given to open loop V/Hz control induction motor drive, the same algorithm is also suitable for vector control induction motor drive.

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