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Simulation and experimental tests of a real-time DPWM technique for the control of VSI-IM Drive

Simulation et tests expérimentaux en temps réel de la technique DPWM pour commander un onduleur de tension alimentant un moteur à induction

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ملخص

في هذه المقالة، يتم عرض النتائج التجريبية والمحاكاة لمصدر الجهد العاكس ثلاثي الطور (3P-VSI) الذي تتحكم به تقنية تعديل عرض النبضة المتقطع (DPWM). ويقترح هذا الأسلوب للتغلب على عيوب تقنية تعديل عرض النبضة الشعاعي (SVPWM) أساسا العالية التردد و الزيادة في فقدان التحول للعاكس. هذه الإستراتيجية في التحكم هي تقنية بسيطة وسهلة لتوليد نفس الرسم البياني للنبض الشعاعي (SVPWM) مع أقل الخسائر في التحويل و نقص في معامل التشوه الكلي (THD). الدافع الرئيسي من هذا العمل هو أن تقنية DPWM لم تحلل على نطاق واسع وعميق، ويمكن تقديمها كبديل جدي لتقنيات أخرى .وأظهرت نتائج هذه التقنية DPWM، انه تم تخفيض الخسائر في التحويل و معامل التشوه الكلي .وعلاوة على ذلك، تم مناقشة و تحليل تطبيقات هذه التقنية في وحدة تحكم (DS1104) dSPACE.

الكلمات المفتاحية : تعديل متقطع - العاكس بتعديل عرض النبض - تعديل عرض النبض المتقطع - التشوه التوافقي الكلي - الخسائر في التحويل

Résumé

Dans cet article, les résultats expérimentaux et de simulation de l'onduleur triphasé de tension (3P-VSI) commandé par la technique de modulation de largeur d'impulsion discontinue appelée DPWM-3 correspondant à quatre saturations de 30° sont présentés. Cette technique est proposée pour remédier aux inconvénients de la technique de la modulation vectorielle (SVPWM) principalement la fréquence de modulation élevée et une augmentation des pertes de commutation de l'onduleur. Cette stratégie de commande est une simple technique et facile à générer le même schéma de commutation de la MLI vectorielle (SVPWM) avec moins des pertes de commutation et un taux de distorsion harmonique (THD) réduit. La principale motivation du présent travail est que la DPWM n'est pas largement et profondément étudié et peut présenter comme une alternative sérieuse à d'autres techniques. Les résultats obtenus ont montré que les pertes de commutation et le taux d'harmonique sont réduits. En outre, l'implémentation de cette technique dans un contrôleur (DS1104) dSPACE est discutée et analysée.

Mots-clés : *modulation discontinus, onduleur à MLI, DPWM, Harmoniques, les pertes de commutation*

Abstract

In the present paper experimental and simulation results of three phase voltage source inverter (3P-VSI) controlled by the strategy called discontinuous pulse width modulation technique (DPWM_3) corresponding to four saturation of 30° are presented. This technique is proposed to overcome the disadvantages of the space vector pulse width modulation (SVPWM) mainly high modulation frequency and increased inverter switching losses. This control strategy is a simple and an easy technique generating the same switching pattern as space vector modulation with less switching losses and reduced total harmonic distortion. The main motivation of the present paper is that the DPWM is not largely and deeply investigated and can present a serious alternative to other PWM techniques. The obtained results have showed that with DPWM technique, switching losses and total harmonic distortion (THD) are reduced. Furthermore, the implementations of this technique in a dSPACE (DS1104) controller is discussed and analyzed.

Keywords: *Discontinuous modulation - PWM Inverter – DPWM – Harmonics - switching losses*

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1. INTRODUCTION

The main disadvantage of the PWM voltage source inverter is the non-sinusoidal currents and voltages produced at its output, affecting greatly the motor (harmonic currents and pulsating torques). Many works have investigated the methods to overcome this issue by introducing several control techniques such as sinusoidal pulse width modulation SPWM [1], space vector pulse width modulation SVPWM [2] and recently discontinuous pulse width modulation DPWM. The purpose of these PWMs is to achieve minimum switching losses, less total harmonic distortion (THD), reduced torque fluctuation and short time response to speed regulation [3-7].
The use of PWM inverters in variable speed AC drives [8-13] is mainly due to development in both fast switching power semiconductors and microprocessors technology. An alternative modulation technique known as discontinuous PWM (DPWM) is becoming very popular and important PWM technique for three phase voltage source inverter controlling AC motors especially induction motor. With this technique, the output voltage can reach the desired high values and it can be realized digitally. Therefore, it can be implemented easily in a DSP or a microcontroller [2]. In the literature several papers have studied different PWM techniques to compare their performances [14-18] in order to choose the best inverter control technique.

In the present work, the proposed discontinuous PWM technique for the control of three-phase voltage source inverter fed induction motor was simulated in the Matlab/Simulink environment and tested experimentally in a dSPACE board. In addition, testing this technique in open loop V/f control of three phase induction motor supplied by voltage source inverter has showed that this technique have many advantages over other techniques. As a result, the numbers of commutations and the switching losses are reduced and consequently the electromagnetic torque ripples are minimized and the speed becomes stable rapidly for DPWM which means better speed regulation. This paper is a contribution to the discontinuous pulse width modulation using the zero sequence signals to achieve less switching losses and reduced torque ripples. This work includes the description of DPWM modulations theories and the implementation of the proposed scheme experimentally using a dSPACE DS1104 board. The obtained results are analyzed and compared to the results of SVPWM.

2. THEORY OF DPWM TECHNIQUE

The basic principle of this technique is to saturate the reference for 120° of a period of 360°, keeping one of the three legs of the inverter without commutation. Therefore a switching discontinuity is obtained during this period of time. This will reduce considerably the number of commutations therefore the switching losses will be reduced as for each
120 ° there is a leg without commutation [19].
There are numerous strategies of discontinuous PWM based on the choice of the saturation position of the corresponding modulating at +1 is OFF upper state or at -1 is OFF at lower state.

- *Only one saturation of 120°:* this corresponds to the strategies denoted by **DPWMMIN** in the literature (modulating saturation at -1 during 120°) or **DPWMMAX** (saturation at +1 during 120°).
- *Two saturations of 60°:* this corresponds to the strategies **DPWM0**, **DPWM1** and **DPWM2**. It will be observed that it is possible to provide other intermediate placements of saturations to favor certain operating points.
- *Four saturation of 30°:* this corresponds to the strategy called **DPWM3**.

It can be noted from the curves presented in figure 1 that each modulating is saturated for 60°, i.e. each half period at different angles in relation to the initial sinusoidal reference. The values of these angles are as follows:

$\varphi = -\pi/6$ pour DPWM0
$\varphi = 0$ pour DPWM1
$\varphi = \pi/6$ pour DPWM2

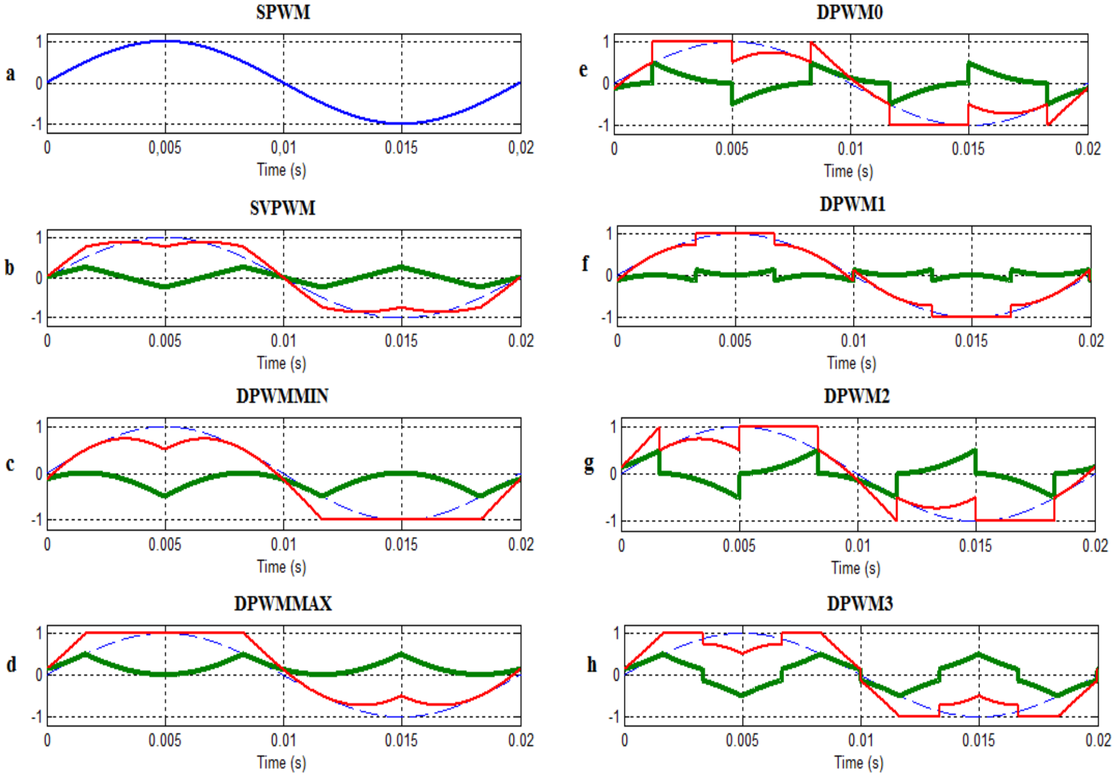

Figure.1. The reference waveforms V_r, V_r^* and the zero-sequence components U_0 injected width different strategies

Modulation index: the modulation index M is defined by the relation between the magnitude of the reference vector and the fundamental peak voltage of a square wave ($2*V_{dc}/\pi$).
Calculation principle of these PWM strategies is based on the injection of the zero sequence components U_0 in reference waveforms (V_{aref}, V_{bref} and V_{cref}), [20-21]. With:

$$V_{max} = Max\left(V_{aref}, V_{bref}, V_{cref}\right) \qquad (1)$$

$$V_{min} = Min\left(V_{aref}, V_{bref}, V_{cref}\right) \qquad (2)$$

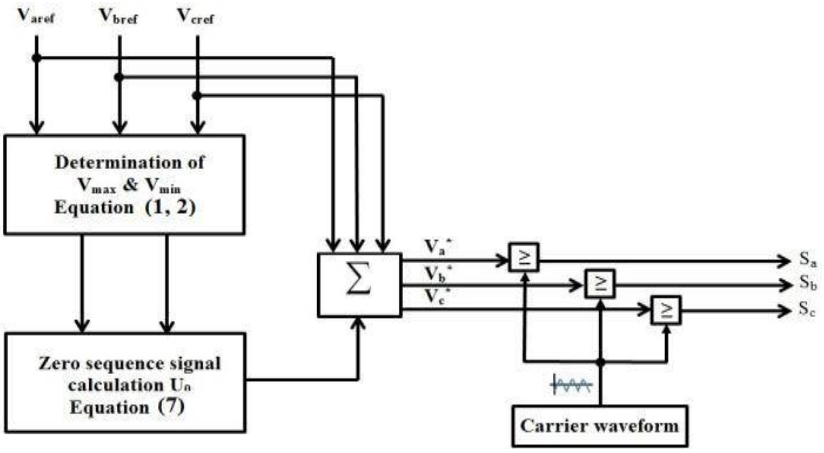

Figure.2. Triangle intersection technique based PWM employing the zero-sequence injection principle

As stated previously, the main idea is to keep the state of an arm of the inverter unchanged during each switching period.

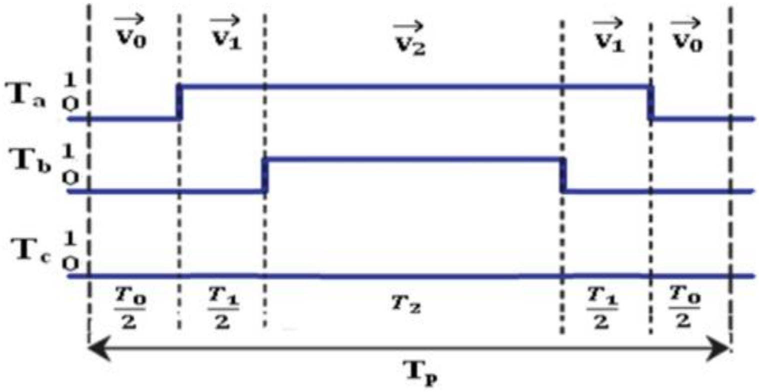

Figure.3. Chronogram of pulses based on two phase PWM (DPWM)

From the previous chronogram it can be noted that the difference between DPWM and SVPWM is in the distribution factor K. In SVPWM technique the periods of use of zero vectors T_0 and T_7 are equal, therefore a factor corresponding to a distribution of these periods is defined as follows:

$$K = \frac{T_7}{(T_0+T_7)} \qquad (3)$$

In this case K=0.5 for SVPWM technique, and always this factor is in the interval $0 \leq K \leq 1$.
According to this factor many strategies can be determined:

a) With K =0.5, this factor results in the technical SVPWM, because the time of use of the zero vector T_z is also distributed at the beginning and at the end of the timing (T_0=T_7). So the zero sequence components is given by figure 1(b).

$$U_0 = -(V_{max} + V_{min})/2 \qquad (4)$$

b) With K = 0, in this case, T7 =0 and T0=Tz, one of the pole voltage is connected to the negative DC-bus clamping the pole voltage during 120° while the other two phases modulate. So the zero sequence components is given by figure 1(c).

$$U_0 = -(V_{min} + E/2) \qquad (5)$$

c) With K= 1, in this case, T0 =0 and T7=Tz, one of the pole voltage is connected to the positive DC-bus clamping the pole voltage during 120° while the other two phases modulate. So the zero sequence components is given by figure 1(d) :

$$U_0 = -(V_{max} - E/2) \qquad (6)$$

d) With k = 0 →1, there are four possibilities as shown in figure 1(e: h) and are referred as discontinuous pulse width modulation (DPWM0, DPWM1, DPWM2 and DPWM3).
A general relation that enables constructing the zero-sequence component, U_0, as a function of K, V_{max} and V_{min} inside each sector is given by the equation expressed as follows [22-23]:

$$U_0 = -\left(KV_{max} + (1-K)V_{min} + (1-2K)\frac{E}{2}\right) \qquad (7)$$

In this work four saturation of 30° corresponding to the strategy called DPWM_3 is used because it has reduced commutations compared to the other strategies.

3. COMPUTER SIMULATIONS

In order to confirm and compare the developed algorithms computer simulations were conducted on a two level inverter feeding induction motor.
Motor parameters are given in Table 1. The tests are carried out for two modulation index M= 0.9 and M = 1.2, and a commutation frequency is 6 KHz.
Only the obtained waveforms of DPWM_3 are presented in figure 4 and figure 5 for modulation index M= 0.9 and M =1.2 (presenting an over modulation) respectively.

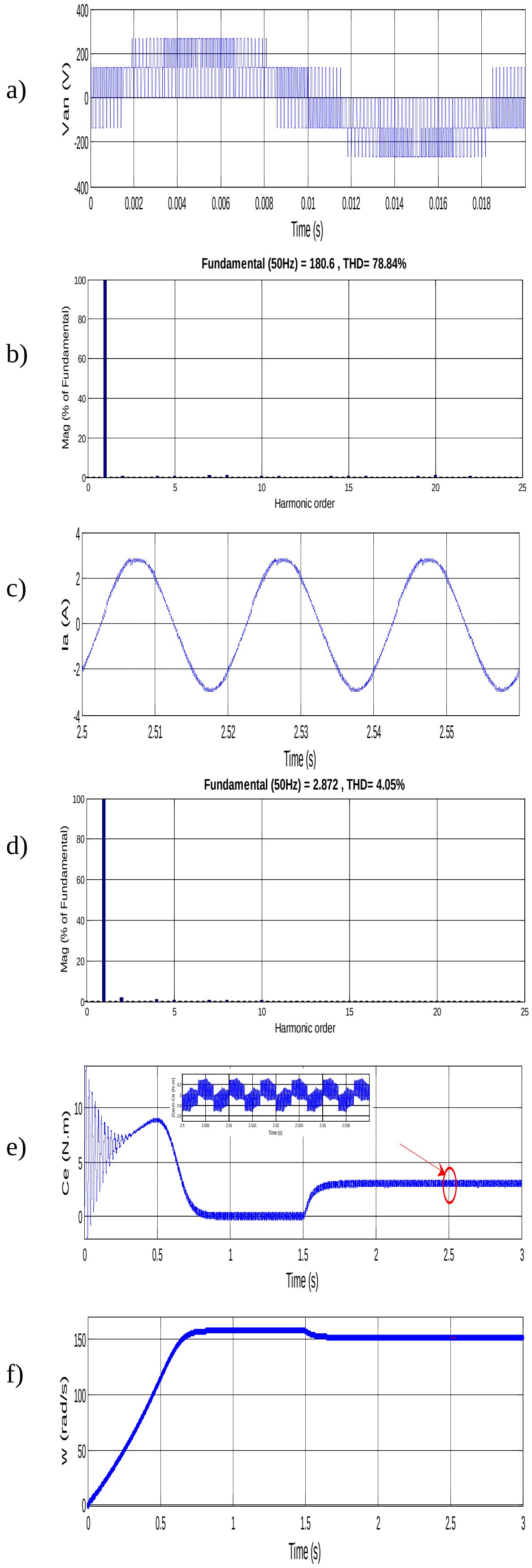

Figure.4. Discontinuous Pulse Width Modulation (DPWM_3), **M = 0.9**, a) Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%), e) Torque ripples (N.m) and f) Motor speed (rad/s)

Tab. 1 Induction motor parameters

MOTOR PARAMETERS	P=1.5 Kw, V_{ab}= 380 V, f=50 Hz, I_n= 3.6 A and n=1400 tr.mn^{-1}.R_s=4.85Ω, R_r=3.085 Ω, L_s= L_r=0.274H, M=0.258 H, f=0.00114Nm.rad^{-1}.s^{-1}, J=0.031 Kgm^2 and T_r=3N.m

Whereas the waveforms of SVPWM are not presented, the results of this strategy are summarized in Table 2 and Table 3 for comparison.

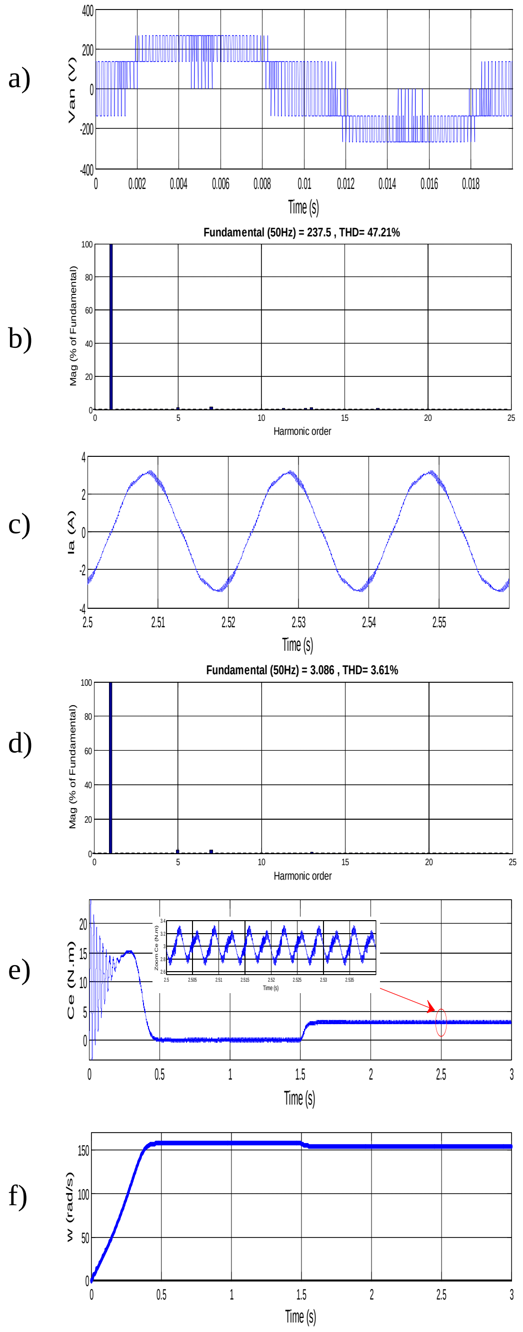

Figure.5. Discontinuous Pulse Width Modulation (DPWM_3), **M = 1.2**, a)Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%), e) Torque ripples (N.m) and f) Motor speed (rad/s)

4. IMPLEMENTATION AND EXPERIMENTS

The experimental setup shown in figure 6 is designed to validate the results obtained by computer simulation and evaluate the performances of DPWM_3. The real-time implementation of this strategy is carried out on the dSPACE DS1104. The experimental setup is composed from the following devices:

- IGBTs voltage source inverter commercialized by SEMIKRON with a DC source of 400 V,
- A 1.5 KW induction motor,
- Powder brake used as load,
- A dSPACE 1104 card (controller Board) was integrated in a PC enabling to generate the required pulses to control the inverter switches,
- Current and voltage sensors.
- Harmonics analyzer (QualiStar C.A 8335)

The visualization of system waveforms is realized through CONTROL DESK software, enabling to control the signals from Simulink dSPACE schemes.
The modulation frequency is 6 KHz and the torque applied to the motor shaft is 3 N.m.

Figure.6. Experimental test rig

The waveforms obtained by experimental tests are presented in figure 7 and figure 8 for a modulation index M=0.9 and M=1.2 (over modulation) respectively.

5. RESULTS AND DISCUSSIONS

The obtained waveforms when DPWM_3 is applied are presented in figure 4 and figure 5 for modulation indexes M=0.9, and M =1.2 (over modulation) respectively. The simulation results of SVPWM and DPWM are summarized in the table 2.

Tab. 2 Simulation Results

Techniques	**M=0.9**			**M=1.2**		
	THD_U (%)	**THD_I (%)**	**P**	**THD_U (%)**	**THD_I (%)**	**P**
SVPWM	**76.70**	**02.23**	**120**	**46.45**	**04.00**	**57**
DPWM_3	**78.84**	**04.05**	**78**	**47.21**	**03.61**	**53**

Width, P: is the Number of commutation in 1 cycle

The waveforms present the details of simulated and measured waveforms of the line to neutral voltage V_{an}(V) Fig.4(a) and Fig.5(a), the voltage frequency spectrum THD (%) Fig.4(b) and Fig.5(b), phase current I_a(A) Fig.4(c) and Fig.5(c), current frequency spectrum THD (%) Fig.4(d) and Fig.5(d), torque ripples

(N.m) Fig.4(e) and Fig.5(e), and motor speed curve Fig.4(f) and Fig.5(f) respectively. These waveforms are presented for evaluation and comparison.

It can be observed from the line to neutral voltage waveforms that the number of commutations is higher (120 commutations in one cycle) when SVPWM is used but the number of commutations is considerably reduced (78 commutations in one cycle) when DPWM_3 is used. Voltage waveform THD voltage total harmonic distortion is 76.70 % and 78.84 % for SVPWM and DPWM_3 respectively.

It can be noticed that the voltage THD of DPWM_3 is higher than voltage THD of SVPWM. Current total harmonic distortion (THD_I) is 2.23% and 4.05% for SVPWM and DPWM_3 respectively. Current harmonic distortion is higher when DPWM_3 is used.

Torque fluctuations are more pronounced when DPWM is used whereas speed curves are the same showing acceptable speed regulation for both strategies as presented.

The simulation results of SVPWM and DPWM are summarized in the table 2 for a modulation index M=1.2, representing the over-modulation.

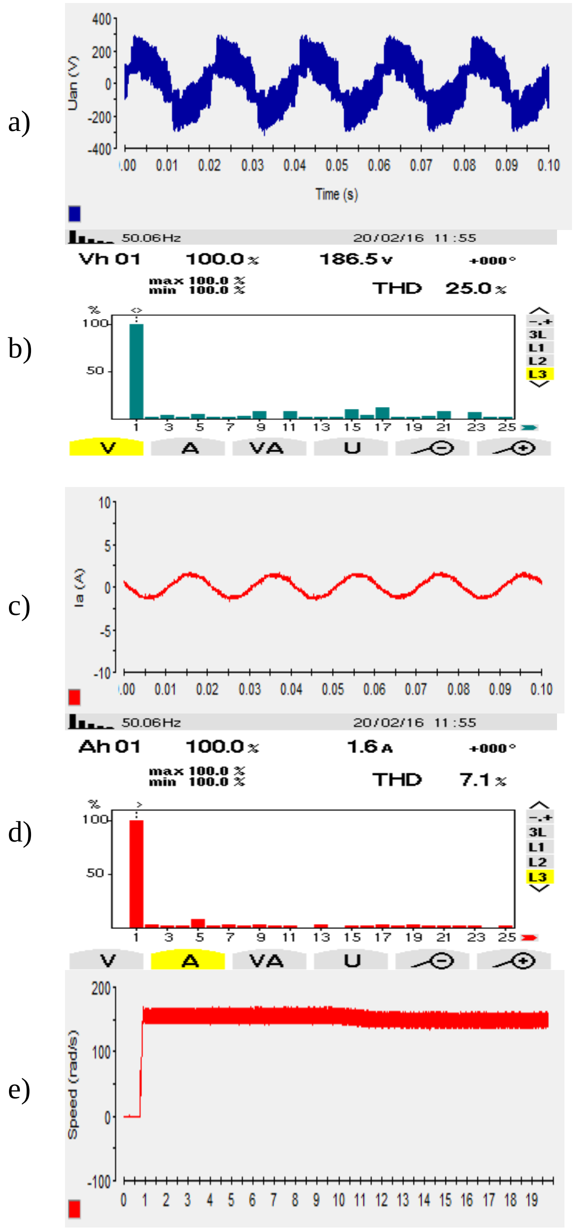

Figure.7. Discontinuous Pulse Width Modulation DPWM_3, **M = 0.9**, a)Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%) and e) Motor speed (rad/s)

It can be observed from the line to neutral voltage waveforms that the number of commutations is higher (57 commutation in one cycle) when SVPWM is used than the number of commutations (53 commutations in one cycle) when DPWM_3 is used. THD_v (voltage total harmonic distortion)) is 46.45 % and 47.21 % for SVPWM and DPWM_3 respectively. It can be noticed that the voltage THD of DPWM_3 is slightly higher than voltage THD of SVPWM. Current total harmonic distortion (THD_I) is 4.00% and 3.61% for SVPWM and DPWM_3 respectively. Current harmonic distortion is lower when DPWM_3 is used. Torque fluctuations are less when DPWM_3 is used as illustrated whereas speed curve is smooth when DPWM is used as illustrated

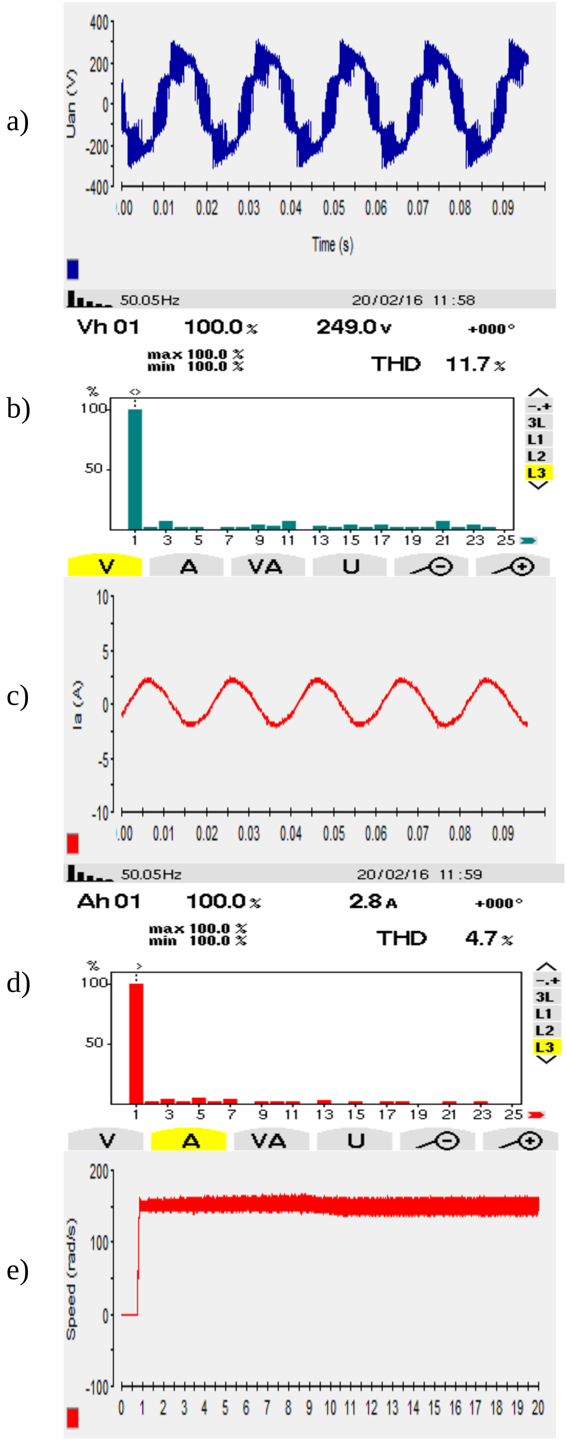

Figure.8. Discontinuous Pulse Width Modulation DPWM_3, **M = 1.2**, a)Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%) and e) Motor speed (rad/s)

In Figure 5(f) showing a better speed regulation when discrete pulse width modulation is employed.

- According to switching losses, it can be remarked that DPWM_3 have reduced switching compared to SVPWM, thus a reduction by 1/3 of switching losses is obtained. Torque fluctuations are more when DPWM but speed curves are the same showing acceptable speed regulation for both strategies.
- With modulation indexes superior to 1 (over-modulation with M=1.2):
- DPWM_3 has a better current spectrum quality (THD_I=03.61%) compared to other techniques (SVPWM, THD_I=4.00%),
- The switching losses, are also reduced when DPWM_3 is used compared to SVPWM.
- Torque fluctuations are less and speed curve is smooth when DPWM_3 is used showing a better speed regulation.

Only the obtained waveforms of DPWM_3 are presented in figure 7 (a)-(e) and figure 8 (a)-(e) for modulation indexes M= 0.9 and M =1.2 respectively. Whereas the waveforms of SVPWM are not presented, the results of this strategy are summarized in Table 3 for comparison.

Tab. 3Experimental results

Techniques	**M**	**THD_U (%)**	**THD_I (%)**
SVPWM	0.9	27.10	03.70
	1.2	11.00	04.90
DPWM_3	0.9	25.00	07.10
	1.2	11.70	04.70

The voltage total harmonic distortion THD (voltage total harmonic distortion) is 11.00 % and 11.70 % for SVPWM and DPWM_3 respectively. It can be noticed that the voltage THD of DPWM_3 is higher than the voltage THD of SVPWM. Current total harmonic distortion (THD_I) is 4.90% and 4.70% for SVPWM and DPWM_3 respectively. Current harmonic distortion is lower when DPWM_3 is used. The speed curve is smooth when DPWM is used as illustrated in Fig.8(e), showing a better speed regulation for DPWM_3.
With modulation indexes equal to 0.9 (M=0.9):

- It can be observed that SVPWM has a higher voltage THD (THD_U=27.00%) regarding DPWM_3 (THD_U=25%) but a relatively lower current THD_I=3.70% compared to DPWM_3 (THD_I = 7.10%)
- With modulation index superior to 1 (over modulation M=1.2):
- DPWM_3 has a better current spectrum quality (THD_I=4.70%) compared to SVPWM, THD_I=4.90%).
- The switching losses, are reduced when DPWM_3 is used compared to SVPWM
- Speed curve is smooth when DPWM_3 is applied showing a better speed regulation.

The experimental results are in good agreement with the simulation results in harmonics and switching losses reductions as stated and noticed previously therefore less torque fluctuations can be obtained when DPWM-3 is used.

6. CONCLUSION

The evaluation of DPWM_3 performances as two level voltage source inverter control technique is conducted and compared to SVPWM technique. The implementation of this technique is carried out by simulation in Matlab environment and real time implementation in dSPACE DS1104 experimental platform. It has been demonstrated that DPWM_3 technique has better performances over SVPWM in switching losses (reduced number of commutations) especially for over modulation achieving at the same time an acceptable level of harmonic distortion. Therefore, DPWM_3 technique is more appropriate to AC variable speed drives and system controllers with a high switching frequency. In the future works, real time implementation of DPWM_3 technique to control a three phase multilevel inverter will be conducted.

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