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A Discontinuous PWM Techniques Evaluation by Analysis of Voltage and Current Waveforms

Fares Zaamouche#1, Salah Saad*2 and Larbi Hamiche*3

Mining Institute, Electromechanical Department, Larbi Tebessi University, Tebessa 12000, Algeria

1f.zaamouche@univ-tebessa.dz

* *Laboratory LSELM, Badji-Mokhtar University, BP 12, Annaba 23000, Algeria*

2saadsalah2006@yahoo.fr

3hamiche_larbi@yahoo.fr

***Abstract* – In this paper experimental and simulation results of three phase voltage source inverter (3P-VSI) controlled by a discontinuous pulse width modulation technique (DPWM) 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 are discussed and analyzed.**

***Keywords* – Discontinuous modulation, PWM Inverter, DPWM, Harmonics, switching losses**

I. 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 solve this problem 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 minimised 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 SVPWM and DPWM modulations theories and the implementation of the proposed scheme experimentally using a dSPACE DS1104 board. The obtained results are discussed and analyzed and compared.

II. INVERTER CONTROL TECHNIQUES

Recently, several pulse width modulation (PWM) techniques were developed, studied and applied to ac motors control. Two techniques were given a great deal of interest mainly, space vector modulation (SVPWM) and discontinuous pulse width modulation (DPWM).

A. Theory of SV-PWM technique

The SVM technique was firstly developed for space vector electrical machines control. Its principle is to rebuild the reference vector from different voltage vectors. Each vector corresponds to a combination of a three phase inverter switches states. The SVPWM technique processes the signals directly on the diphase frame of the Concordia transformer. Thus, the line to neutral voltages are represented in the (α, β) frame. From the combination of the three state variables, the inverter has eight switching states. It can generate eight different vectors of voltage output. These eight space vectors define the limits of the six sectors in the (α, β) and two of these vectors equal to zero. Theoretical developments of this technique are described and studied elsewhere [2-6].

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It can be observed that in this technique the periods of use of zero vectors T_0 et T_7 are equal, therefore a factor corresponding to a distribution of these periods is defined as follows:

$$K = \frac{T_7}{(T_0+T_7)} \tag{1}$$

In this case K=0.5 for SVPWM technique, and always this factor is in the interval $0 \leq K \leq 1$

B. 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 Fig.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

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:

$$V_{max} = Max(V_{aref}, V_{bref}, V_{cref}) \tag{2}$$

$$V_{min} = Min(V_{aref}, V_{bref}, V_{cref}) \tag{3}$$

According to the previous chronogram the difference between DPWM and SVPWM is in the distribution factor K, regarding 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

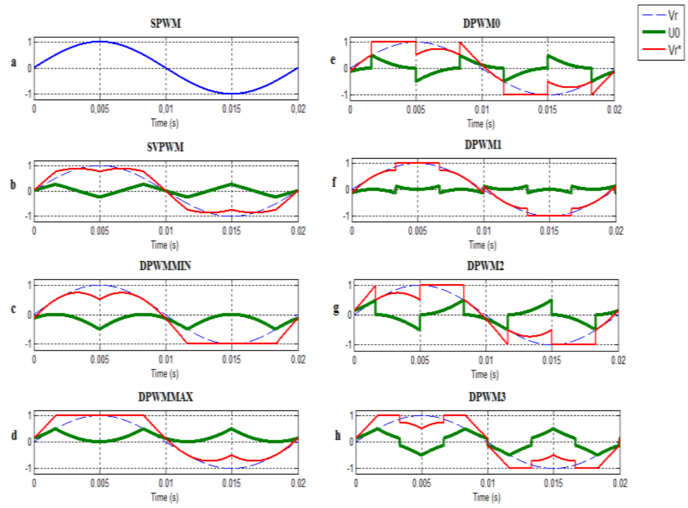

Fig.1. The reference waveforms V_r, V_r^* and the zero-sequence components U_0 injected width different strategies

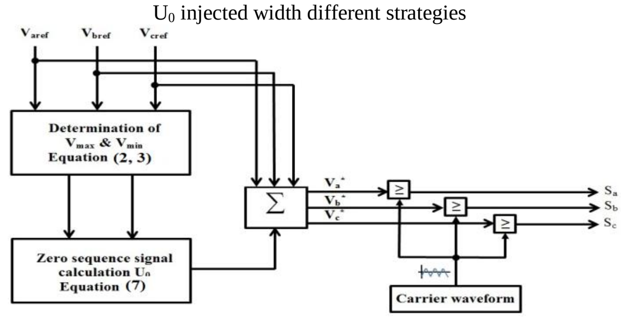

Fig.2. Triangle intersection technique based PWM employing the zero-sequence injection principle

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

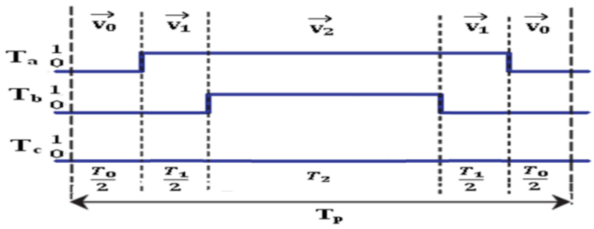

Fig.3. Chronogram of pulses based on two phase PWM (DPWM)

(T_0=T_7). So the zero sequence components is given by (Fig.1(b)).

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

b) With K = 0, in this case, T_7 =0 and T_0=T_z, 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 (Fig.1(c)).

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

c) With K= 1, in this case, T_0 =0 and T_7=T_z, 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 (see Fig.1(d))

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

d) With k = 0 →1, there are four possibilities as shown in Fig.1(e) and (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 [22-23]:

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

III. COMPUTER SIMULATION

In order to validate and compare the developed algorithms computer simulations were conducted on a two level inverter feeding induction motor.

Motor parameters are given in Table 2, the tests are carried out for two modulation index is M= 0.9 and M = 1.2, and a commutation frequency is 6 KHz.

TABLE II
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=0.00114$Nm.rad^{-1}.s^{-1}$, J=0.031 Kgm^2 and T_r=3N.m

The obtained waveforms are presented in Fig.4 and Fig.5 for modulation index M=0.9 and M =1.2 (presenting an over modulation) respectively.

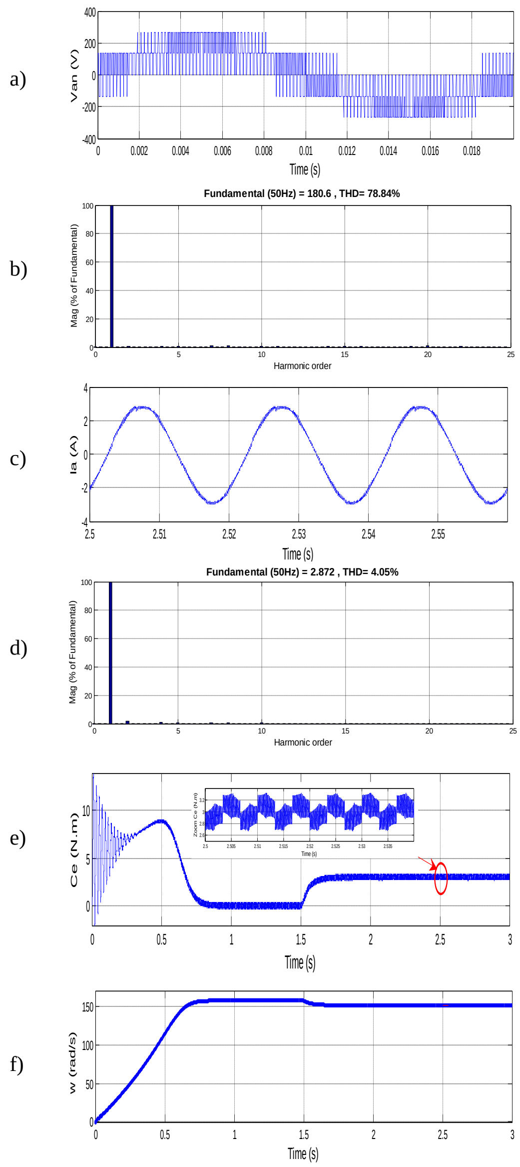

Fig.4. Discontinuous Pulse Width Modulation (DPWM_3), **M = 0.9**, a)Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%), e) Torque ripples (N.m) and f) Motor speed (rad/s)

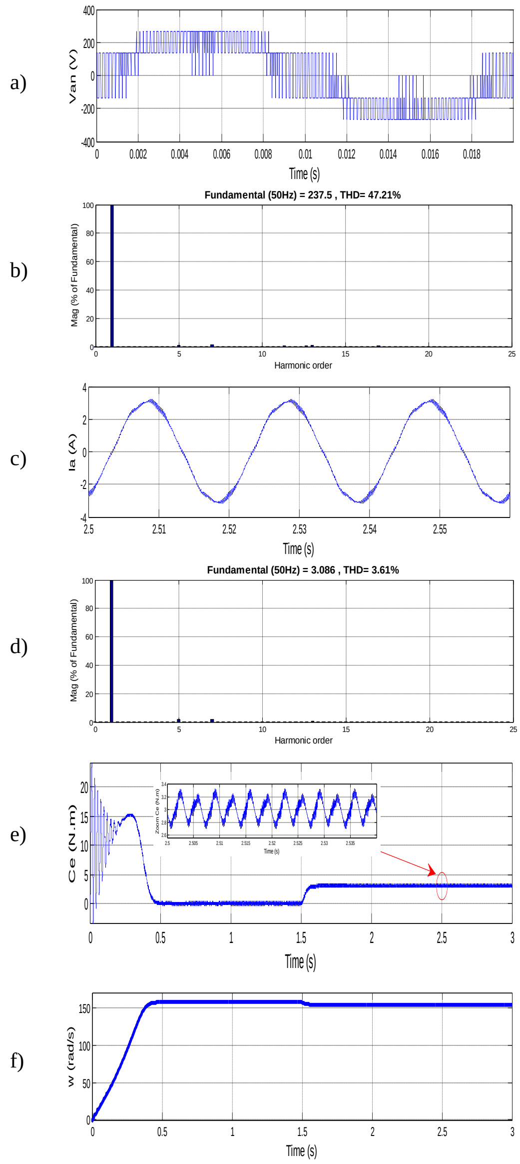

Fig.5. Discontinuous Pulse Width Modulation (DPWM_3), **M = 1.2**, , a)Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%), e) Torque ripples (N.m) and f) Motor speed (rad/s)

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IV. Implementation and Experiments

An experimental rig Fig.6 is designed to validate and confirm the results obtained by computer simulation and evaluate at the same time the performances of DPWM and SVPWM control techniques. The real-time applications on the dSPACE DS1104 are carried out using Real-Time Interface in MATLAB/Simulink environment. This test rig is composed from the following elements:

- 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.

Fig.6. the rig of the experimental set up used in this work. The modulation frequency is 6 KHz and the torque applied to the motor shaft is 3 N.m.

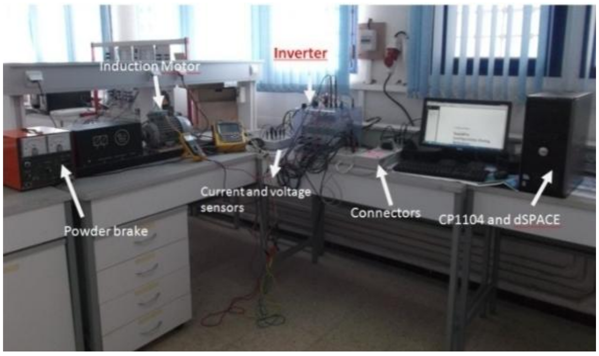

Fig.6. Experimental test rig

The waveforms obtained by experimental tests are presented in Fig.8 and Fig.9 for a modulation index M=0.9 and M=1.2 (over modulation) respectively.

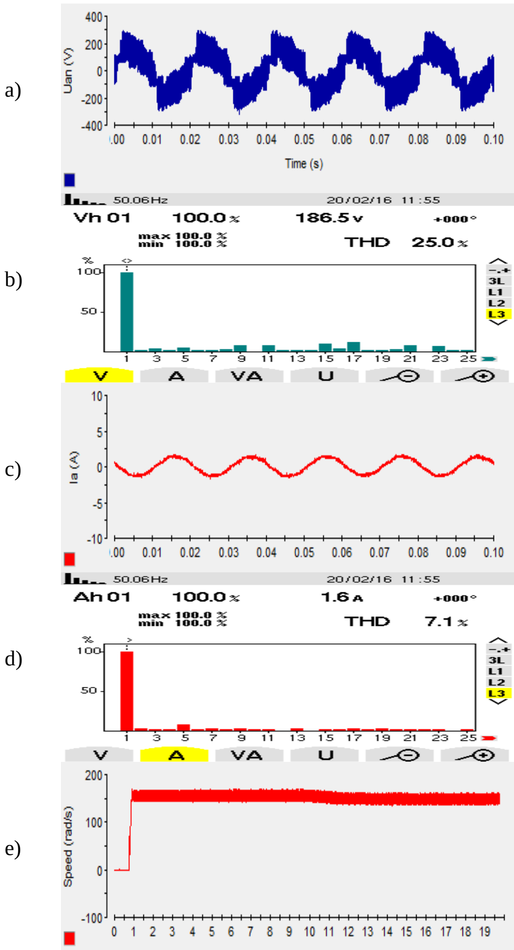

Fig.7. Discontinuous Pulse Width Modulation DPWM_3, **M = 0.9**, a)Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%) and e) Motor speed (rad/s)

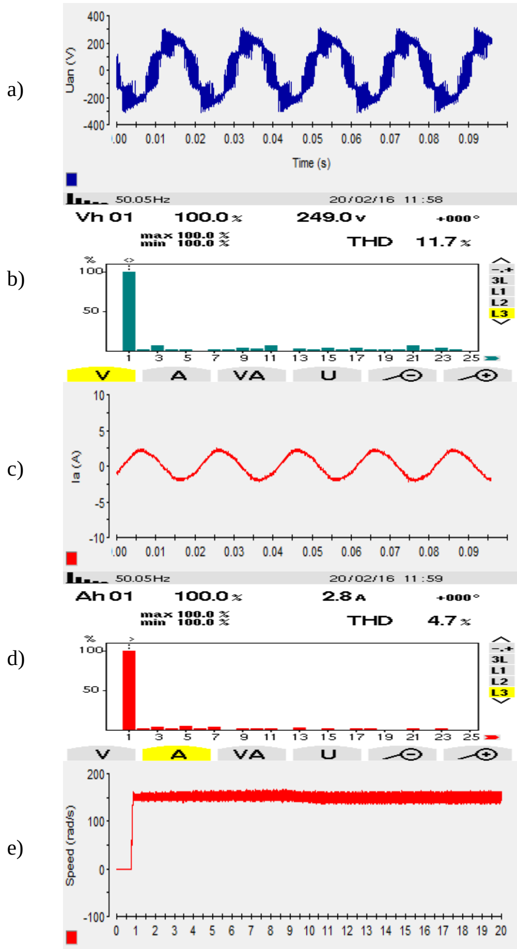

Fig.8. Discontinuous Pulse Width Modulation DPWM_3, **M = 1.2**, a)Line to neutral voltage V_{an}(v), b)Voltage frequency spectrum THD (%), c) Phase current I_a(A), d) Current frequency spectrum THD (%) and e) Motor speed (rad/s)

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V. RESULTS AND DISCUSSIONS

The simulation obtained waveforms when DPWM is applied are presented in Fig.4 and Fig.5 for modulation index M=0.9, and M =1.2 (over modulation) respectively. The following table summarizes the obtained simulation results.

TABLE III
SIMULATION RESULTS

Techniques	M=0.9			M=1.2		
	THD_U (%)	THD_I (%)	P	THD_U (%)	THD_I (%)	P
DPWM_MIN	77.38	03.13	79	48.35	04.49	51
DPWM_MAX	77.28	03.15	78	47.06	04.48	54
SVPWM	**76.70**	**02.23**	**120**	**46.45**	**04.00**	**57**
DPWM_1	77.60	04.29	81	48.81	03.78	53
DPWM_2	77.55	05.45	80	47.23	03.87	54
DPWM_3	**78.84**	**04.05**	**78**	**47.21**	**03.61**	**53**
DPWM_4	77.08	05.29	80	47.10	04.14	54

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 commutation in one cycle) than the number of commutations (78 commutations in one cycle) when DPWM_3 is used. THD of voltage total harmonic distortion is 76.70 % and 78.84 % (Fig.4.b) 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% (Fig.4.d) 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 as illustrated in Fig.5.e whereas speed curves are the same showing acceptable speed regulation for both strategies as presented in Fig.4.f.

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

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 % (Fig.5.b) 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% (Fig.5.d) 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 in Fig.5.e whereas speed curve is smooth when DPWM is used as illustrated in Fig.5.f. showing a better speed regulation when discrete pulse width modulation is employed.

- With modulation indexes less than 1(M=0.9):
  - It can be observed that SVPWM has a better spectrum quality (THD_U=76.70% and THD_I=2.23%) regarding other techniques (DPWM_3 (THD_U=78.84% and THD_I=4.05%),
  - 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.
- With modulation indexes less than 0.5 (under-modulation with M=0.5): it can be noted that the transient state period is very long.
  - Torque fluctuations are less and speed curve is smooth when DPWM is used showing a better speed regulation.

The obtained experimental waveforms when DPWM_3 is applied are presented in Fig.7 and Fig.8 for a modulation index M=0.9 M =1.2 (over modulation) respectively. The obtained experimental results are summarized in the table IV.

TABLE IV
EXPERIMENTAL 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 waveforms present measured waveforms of the line to neutral voltage V_{an}(V) Fig.7.a and Fig.8.a, the voltage frequency spectrum THD is equal to 27.1% and 25% Fig.7.b Whereas phase current I_a(A) presented in Fig.7.c giving a current frequency spectrum THD equal to 3.7% and 7.1%. The motor speed curves shown in Fig.7.e is smooth when DPWM is applied showing better speed regulation.

The experimental results of SVPWM and DPWM are shown in the table IV for a modulation index M=1.2, representing the over-modulation.

It can be observed from THD (voltage total harmonic distortion) is 11.00 % and 11.70 % (Fig.8.b) 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 4.90% and 4.70% (Fig.8.d) 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.

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- With modulation indexes less than 1(M=0.9):
  - It can be observed that SVPWM has a better voltage spectrum quality (THD_U=11.00%) regarding other techniques (DPWM_3 (THD_U=11.70%) but a relatively lower current THD_I=4.70% compared to SVPWM (THD_I = 4.90%)
- With modulation indexes superior to 1 (over modulation M=1.2):
  - DPWM_3 has a better current spectrum quality (THD_I=4.70%) compared to other techniques (SVPWM, THD_I=4.90%).
  - The switching losses, are reduced when DPWM_3 is used compared to SVPWM
- With modulation indexes less than 0.5 (under-modulation with M=0.5): it can be noted that the transient state period is very long.
  - Speed curve is smooth when DPWM 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.

VI. Conclusions

In this paper the evaluation of DPWM performances as inverter control technique is conducted and compared to SVPWM technique. The implementation of both techniques is carried out by simulation in Matlab environment and real time implementation in dSPACE DS1104 experimental platform. It has been demonstrated by both tests 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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