Comparison of Output Current Harmonics of Voltage Source Inverter used Different PWM Control Techniques

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Abstract: Induction motor driver circuits are harmonic sources because of their semiconductor switching power components. Harmonics are provided by inverter, are inevitable, so optimization of these is made. For this purpose, more fast and had less switching losses ones of used semiconductor power switching components are preferred, also PWM (Pulse Width Modulation) techniques used in inverter are developed. In this paper, Sinus PWM (SPWM), Square Wave PWM, Carrier Based SVPWM and Space Vector PWM (SVPWM) techniques are implemented using dsPIC30F2010 micro controller which is one of DSP (Digital Signal Processor) controllers developed for motor control. Output current harmonics of open loop voltage source inverter for different PWM techniques are measured by harmonic analyzer. Comparison of PWM techniques is made with obtained measurement results and it is shown that minimum current harmonic is produced by SVPWM technique with experimental results.

Key Words: Square Wave PWM, SPWM, Carrier Based SVPWM, SVPWM, Harmonic, DSP, VSI.

1 Introduction

Because of advances in solid state power devices and microprocessors, switching power converters are used in more and more modern motor drivers to convert and deliver the required energy to the motor [1]. Task of inverter is convert DC input voltage to AC voltage with desired magnitude and frequency. Output voltage regulation is made as constant or variable frequency. Variable output voltage can be obtained keeping constant inverter gain and adjusting DC input voltage. Another method, if DC input voltage is constant and not adjustable, variable output voltage can be obtained by adjusting of inverter gain, this is provided by PWM control of inverter [2].

PWM technique is based on comparison of carrier signal with control signal. Intersection points of signals shows commutation time of semiconductor power electronic switching components [3]. There are two PWM signals as symmetric and asymmetric. Pulses of symmetric PWM signal are always symmetric according to center of each PWM period. Pulses of asymmetric PWM signal are aligned with one side of PWM period. Symmetric PWM signals produce less output current and voltage harmonic [1]. Basic purpose of PWM technique is to reduce inverter output harmonic level, to increase voltage magnitude, to reduce switching losses [3]. The most important characteristic of PWM method is that as inverter input DC voltage is constant, inverter output voltage and frequency can be changed [4].

Existence of harmonics in energy system is understood from corruptions of current and voltage waveforms that have sinusoidal form. One of the known harmonic sources is inverter too. Effects of inverter output current harmonics cause that increment of voltage droop because of current harmonic components, overheating at induction motors because of occurred oscillations, faulty measurements and decrement of life of equipments which are connected to out of inverter. So decrement of harmonics is desired.

Inverter power devices are switched as on-off many times in half period to produce output voltage which has less harmonic. SPWM is used widespread from of old because of application easiness of PWM techniques. Fundamental output voltage magnitude of PWM techniques is provided by adjusting of modulation index. If modulation index is less than one, only side bands of fundamental wave frequency and carrier frequency harmonics appear. Another PWM modulation is based on space vector representation of reference and inverter voltages. Produced sinusoidal modulation at space vector representation has less inverter state variation and higher modulation index than three phases SPWM. Nowadays MOSFETs and IGBTs are used in inverters which have hundreds of kVA power range [5]. There is big interest in usage of microprocessor as controller at AC drivers and systems. It is considerably approached to production of sinusoidal voltages with adjustable magnitude. Different approaches can be used to formulation PWM switching strategies [6].

In this paper, inverter output current harmonics are investigated for different PWM techniques. Control of a voltage source inverter is made using dsPIC30F2010 micro controller which is one of DSP controllers developed for motor control. The motor that connected to inverter output is operated as no-loaded. Two separate softwares are performed for SVPWM and other carrier based PWM techniques at C programming language in MPLAB IDE. All PWM signals are consisted from 64 parts. PWM signals are obtained putting related signal data to sin table at software which developed for carrier based PWM signals. For different PWM techniques, inverter output current harmonic analysis is made changing modulation index and modulation ratio with harmonic analyzer. Output current of the system which controlled according to different PWM techniques and output current harmonics are investigated comparing each other. Experimental results proved that SVPWM technique has the least Total Harmonic Distortion (THD).

2. Various PWM Techniques

Square Wave PWM is obtained comparing triangular carrier signal with control signal shaped square wave as shown in Fig. 1.

$$m_f = \frac{f_c}{f_1} \quad (1)$$

At equation 1, m_f is modulation ratio, f_c is carrier frequency and f_1 is fundamental frequency.

Modulation ratio determines that square wave will consist of how many parts. As m_f is number of parts in square wave, output signal harmonics are found with equation 2.

$$k = m_f \pm 1 \quad (2)$$

When switching frequency increase, effects of output signal harmonics decrease, also output voltage decrease and so switching losses increase.

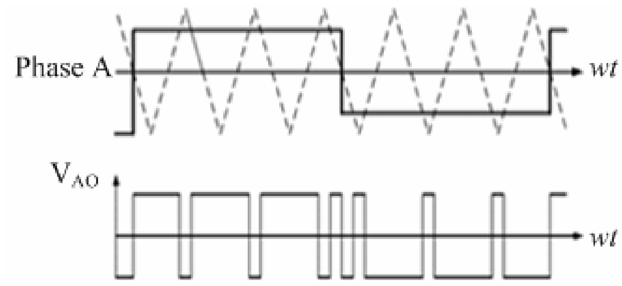

Fig. 1 Obtainment of square wave PWM [2].

As shown in Fig.2, SPWM is obtained comparing triangular carrier wave with control signal shaped sinus.

$$M = \frac{V_c}{V_t} \quad (3)$$

At equation 3, M is modulation index, V_c is control signal value and V_t is carrier signal value.

Output voltage magnitude increases with increasing of M modulation index. State of M>1 is called over modulation. In state of over modulation, effects of harmonics increase due to shape of output voltage wave approaches to square wave.

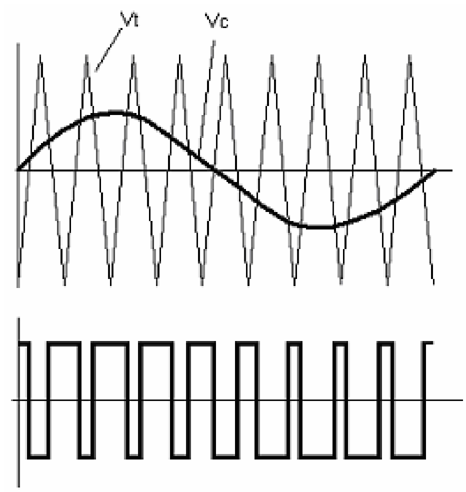

Fig. 2 Obtainment of SPWM.

First application of SVPWM is probably zero-sequence injection PWM method which is an analog application. After approximate ten years this modulator is appeared in literature with direct digital application. The method is called SVPWM because utilized direct digital application at space vector theory. SVPWM method has superior performance characteristics and is the most popular method [7]. One of the most important advantages of Space Vector Modulation (SVM) is that it is appropriate for DSP. Furthermore SVM presents usage of advanced DC bus voltage, decreasing commutation losses and lower THD. SVPWM has advantage of reduction of motor losses. This method directly controls phase to phase voltage of inverter and indirectly increases phase voltage [8].

Space vector concept is derived from rotating field of used AC machine in modulation of inverter output voltage. In this modulation technique, three phase quantities are transformed to their equivalent two phase quantities. As shown in Fig. 3, to use in inverter output module, reference vector magnitude is found from two phase component. Switching time of IGBTs is determined with aid of two active vector and one zero vector which are belong to sector including Vref vector [9].

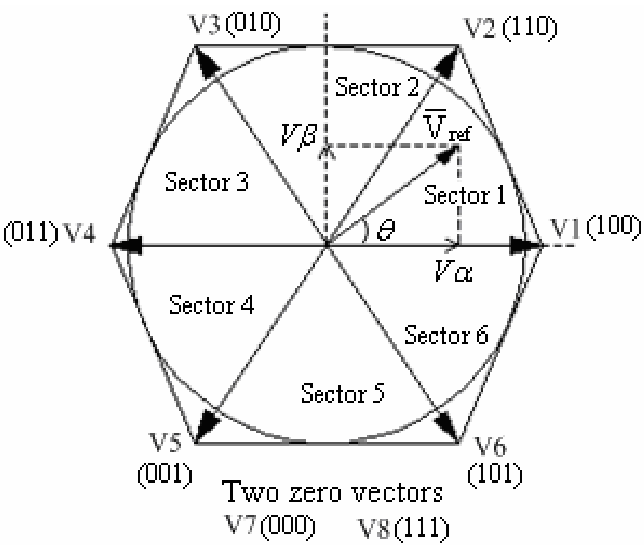

Fig. 3 Obtainment of SVPWM [9].

Carrier Based SVPWM is less complex and easier comprehensible than normal SVPWM; also application of it is simpler than conventional method. As shown in Fig. 4, it is obtained with comparing of triangular carrier signal with control signal which composed of injecting of third harmonic to fundamental sinus wave. It shows exactly same characteristics of SVPWM. In this method, mathematical computation concentration in SVPWM method is reduced.

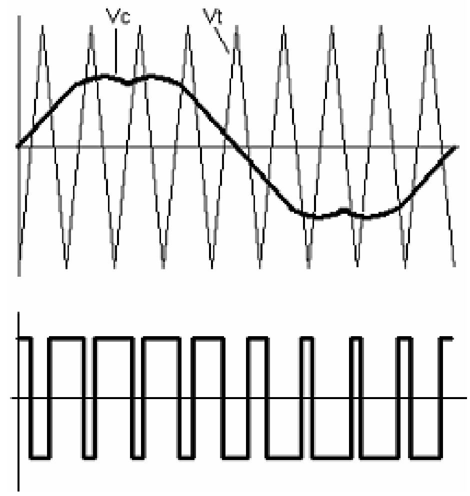

Fig. 4 Obtainment of carrier based SVPWM.

3. Experimental Study

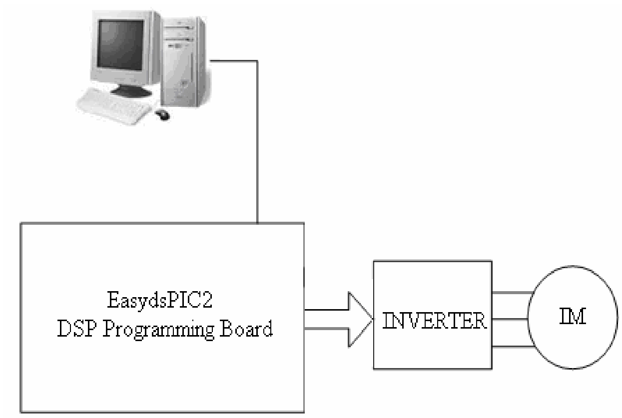

Fig. 5 Block diagram of application circuit.

Block diagram of application circuit is shown in Fig.5. EasydsPIC2 DSP board is used for both programming and control and it is connected to computer via USB.

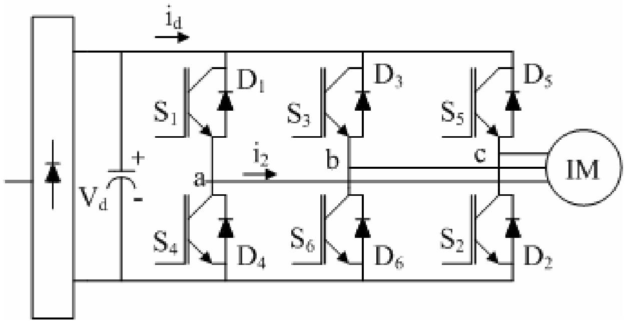

Fig. 6 Voltage Source Inverter.

As shown in Fig. 6, Voltage sources inverters takes DC voltage input side of it and gives AC voltage from output side of it. AC voltage and/or frequency can be constant or variable depending on application. There is constant voltage source at input of voltage source inverter. If voltage source is not constant, a big capacitor can be linked to input of voltage source inverter. Inverter output can be single phase or multi phase and can be square wave, sinus wave, PWM wave or half square wave. Voltage source inverters are used many applications as widespread [10].

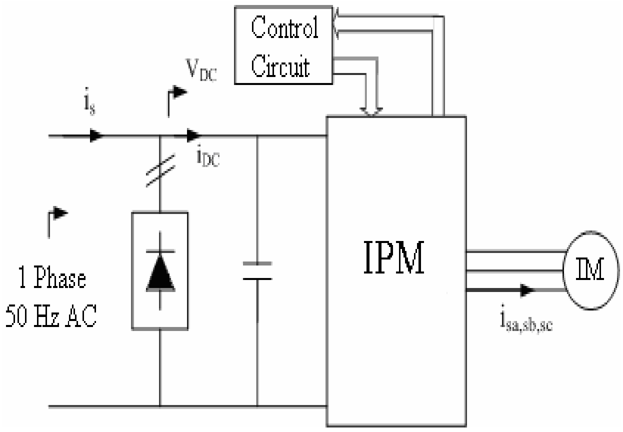

Fig. 7 Voltage source AC driver circuit principle scheme of induction motor [11].

IPM (Intelligent Power Module), which is shown in Fig. 7, is designed to protect self against to over current, short circuit and over heating. When these states occurred, in any case of control signal IPM stops and sends fault signal to out. It includes six IGBT semiconductor power switching elements. Totally four independent 15V voltage source is required to external feeding of IPM, one for each of three upper branches and only one for below branches. Control signal that produced with this aim is given to each IGBT in IPM such as HP4504 through optical driver. It can operate in high switching region such as 15 kHz with used IPM [11]. Label information of used induction motor is given Table 1.

Table 1. Label information of used induction motor

GAMAK					4404354284
3~ MOT	TYPE AGM71 2b				EFF
I.CL F	IP 55	B3	S1	CE	
V	Hz	A	kW	Cos φ	1/min
Δ 220	50	2,3	0,55	0,84	2780
Y 380		1,34			

3.1 Application of Various PWM Control Techniques

PWM technique is based on comparing of control signal with carrier signal. If control signal is bigger than carrier signal (Vc > Vt), output becomes +Vi or if control signal is smaller than carrier signal (Vc < Vt), output becomes –Vi. Intersection points of signal shows commutation time of semiconductor power electronic switches. There are a lot of different PWM techniques and they are called according to shape of their control signal. Basic aim in PWM technique is to reduce inverter output harmonic level, to increase voltage magnitude, to reduce switching losses as minimum [3].

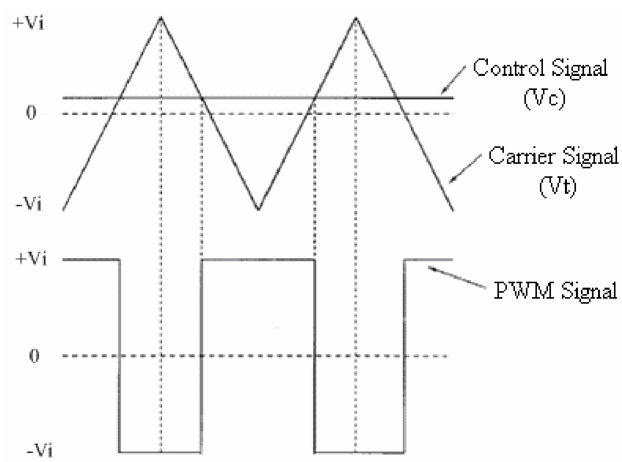

Fig. 8 Two levels carrier based PWM [3].

There are two operating mode in PWM technique. These are linear mode and nonlinear mode. In linear mode, magnitude of control signal is equal to or smaller than magnitude of carrier signals. Shape of a PWM that is in linear mode is shown in Fig.8. In nonlinear mode, magnitude of control signal is bigger than magnitude of carrier signal. Efficiency drops under %100 and over modulation occurs. Total harmonic distortion of output switching wave shapes increase [3].

Simplified block diagram of Motor Control PWM (MCPWM) module, which shows production of supplemental pulses of this technique for induction motor driver, is shown in Fig. 9 [12].

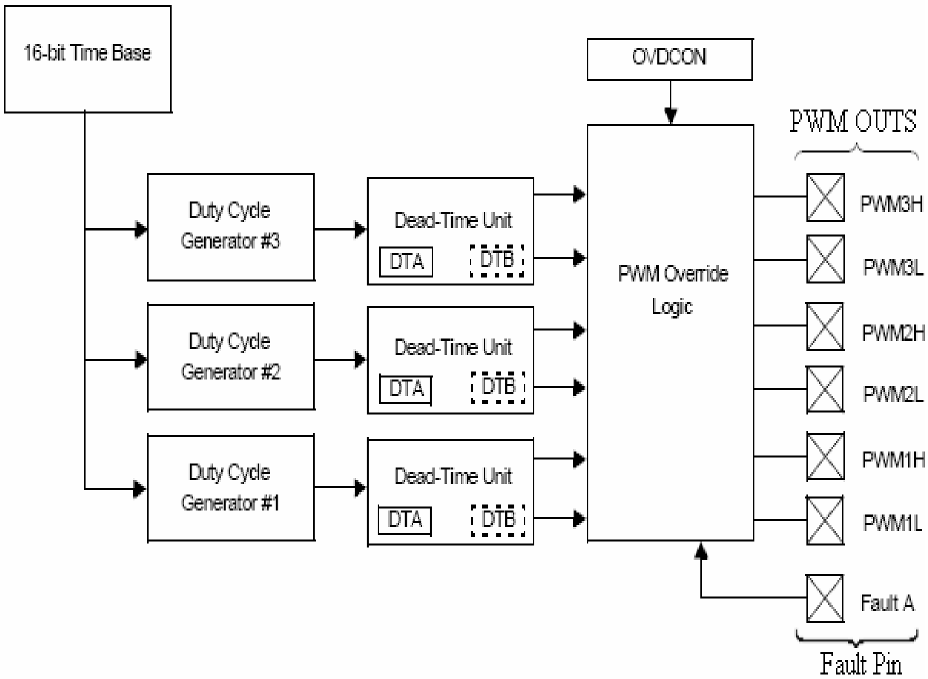

Fig. 9 Block diagram of MCPWM [12].

Duty cycle generators produce pulses that include previously programmed duty cycle knowledge. Dead time units slide pulses to prevent short circuit during driving of IGBTs in inverter. In inverter, six PWM outputs are connected to IGBTs individually. Purpose is to produce three phase sinus waves as 50 Hz and with 120° phase difference. Data is transferred to variables to obtain sinus at PWM outputs depending on table data that expressed sinus wave. Each data in table express data which will send to duty registers.

Required software for obtainment of PWM signals is developed with C programming language in MPLAB IDE environment. Hex file which obtained compiling this program is loaded to DSP microcontroller via mikroElektronika-dsPicFLASH program. Adjustment of parameters in software is made according to user guide of dsPIC30F2010 [13]. There are two basic types of software. One of these is for SVPWM, another is for SPWM. Instead of sinus table used in SPWM's software, other PWM signals are produced putting formed data for square wave PWM and carrier based SVPWM to table. dsPIC' s PWM motor control module can calculate S_2, S_4 and S_6 semiconductor power switching components' commutation times adding dead time to S_1, S_3 and S_5 semiconductor power switching components' commutation times. The software is developed using this feature of dsPIC's PWM control module.

Individual harmonic measurements are made at each PWM technique for different modulation index and modulation ratio. Comparison of PWM techniques is based on THD that is used to restrict inverter output current harmonics. THD_I value is expressed with equation 4.

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \qquad (4)$$

3.2 Experimental Results

Measurements related with induction motor no-load current harmonics, inverter output voltage and current waveforms are made for PWM techniques such as SPWM, Square Wave PWM, Carrier Based SVPWM and SVPWM according to different modulation index and modulation ratio by power analyzer. Experiments are made for 0,5 and 0,9 modulation indexes and as modulation index increase, output voltage increase and output current harmonics decrease. This is shown in Table 2.

Modulation index M is a value that changes in range 0.0-1.0. In state of M>1, over modulation occur. Output voltage increase and also output harmonics increase due to output signal approaches square wave. Harmonics aren't examined in over modulation state as purpose of this work is to reduce harmonic level to minimum.

Modulation ratio m_f is selected as 9, 100 and 175. As shown in measurement results, as modulation index increase, output waveform approaches sinus waveform and as current harmonics decrease, switching frequency increase so switching losses increase.

Table 2. Magnitudes of inverter output currents and THD_I values

	M =0,5 m_f= 9	M =0,9 m_f = 9	M =0,5 m_f = 100	M =0,9 m_f =100	M =0,5 m_f = 175	M =0,9 m_f =175
Square Wave PWM	Rms 398 mA THD_I =% 213	Rms 635 mA THD_I =% 170,3	Rms 216,8 mA THD_I =% 84,4	Rms 435 mA THD_I =% 83,2	Rms 213,1 mA THD_I =% 87,2	Rms 420 mA THD_I =% 84,9
SPWM	Rms 244,2 mA THD_I =% 148,3	Rms 372 mA THD_I =% 124,9	Rms 128,3 mA THD_I =% 3,7	Rms 232 mA THD_I =% 2,8	Rms 126,8 mA THD_I =% 3	Rms 232 mA THD_I =% 2,5
Carrier Based SVPWM	Rms 243 mA THD_I =% 144,7	Rms 346 mA THD_I =% 105,6	Rms 127,8 mA THD_I =% 2,7	Rms 232 mA THD_I =% 2,5	Rms 126,8 mA THD_I =% 2,6	Rms 231 mA THD_I =% 2,3
SVPWM	Rms 260,4 mA THD_I =% 143,6	Rms 369 mA THD_I =% 99,5	Rms 141 mA THD_I =% 2,7	Rms 262 mA THD_I =% 1,8	Rms 141,5 mA THD_I =% 2,5	Rms 258 mA THD_I =% 1,5

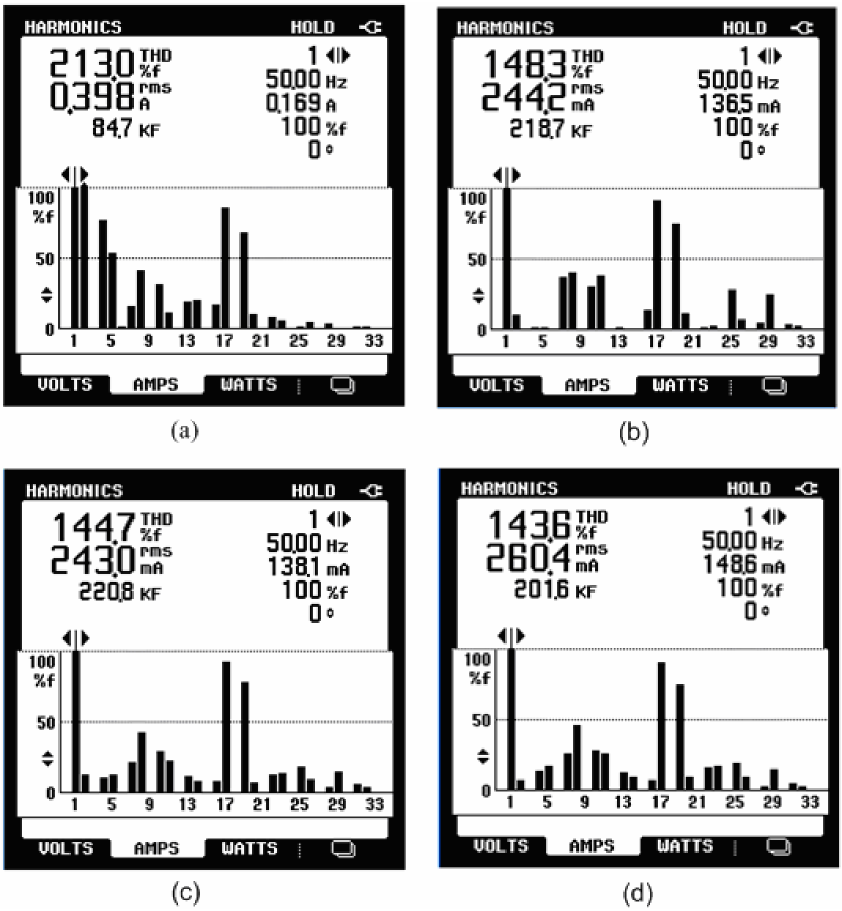

Fig. 10 Inverter output current harmonics spectrum for M=0,5, m_f =9 with square wave PWM (a), SPWM (b), carrier based SVPWM (c), SVPWM (d) techniques.

Fig. 10 and Fig. 11 show that harmonic spectrum decrease with output current magnitude in state of increment of modulation index and modulation ratio at same time.

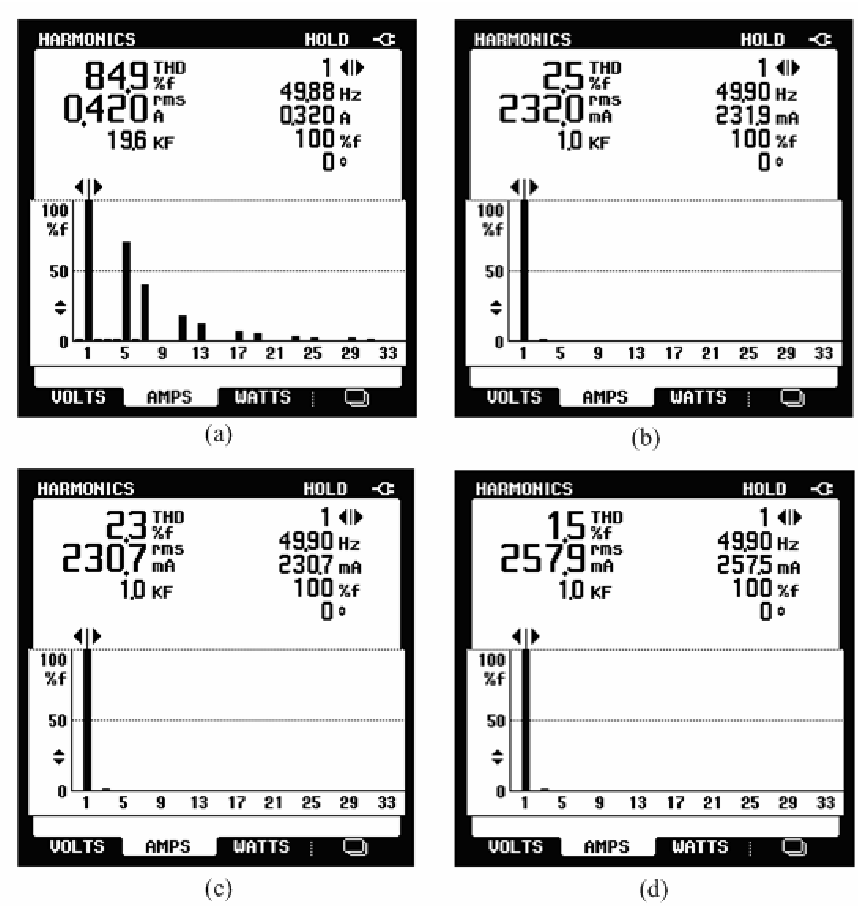

Fig. 11 Inverter output current harmonics spectrum for M=0,9, m_f =175 with square wave PWM (a), SPWM (b), carrier based SVPWM (c), SVPWM (d) techniques.

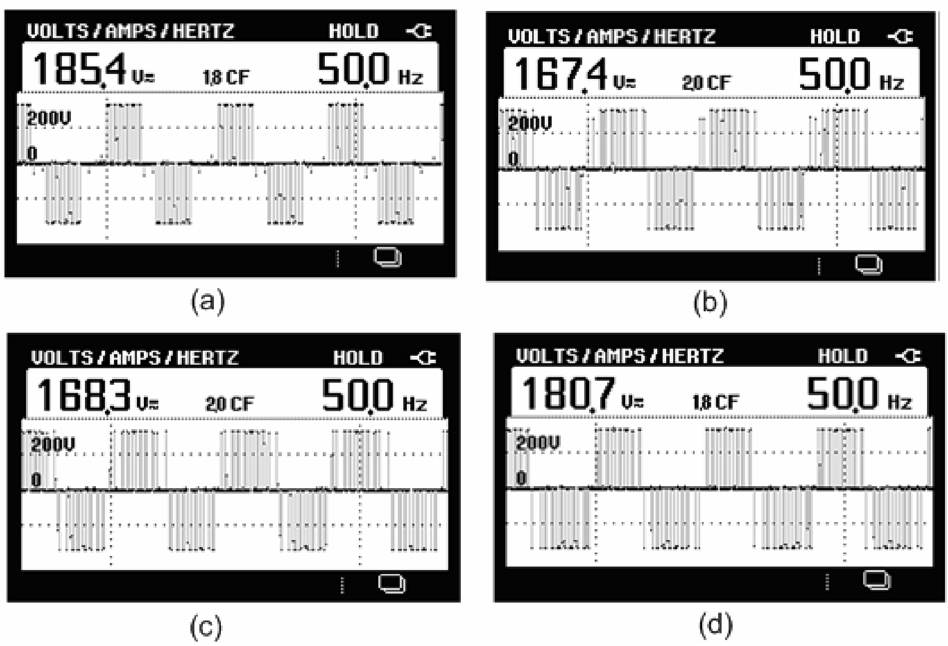

Fig. 12 Waveforms of inverter output voltage for M=0,5, m_f =9 with square wave PWM (a), SPWM (b), carrier based SVPWM (c), SVPWM (d) techniques.

As shown in Fig 12 and Fig 13, output voltage increase, when modulation index increase. Instead of square wave PWM has the highest output voltage among PWM techniques, as shown in Fig 13 it has the worst output voltage waveform. SVM technique has 15% more output voltage than conventional modulation [9]. So output voltage of SVPWM is higher than SPWM. This state is also seen from experimental results. At the same power, less current will be absorbed from inverter that used SVPWM due to SVPWM output voltage is higher than SPWM output voltage. This provides selection of used components for less currents and reduction of transmission losses. In all PWM techniques outside of square wave PWM, waveform of output voltage approaches to sinus by increasing modulation ratio.

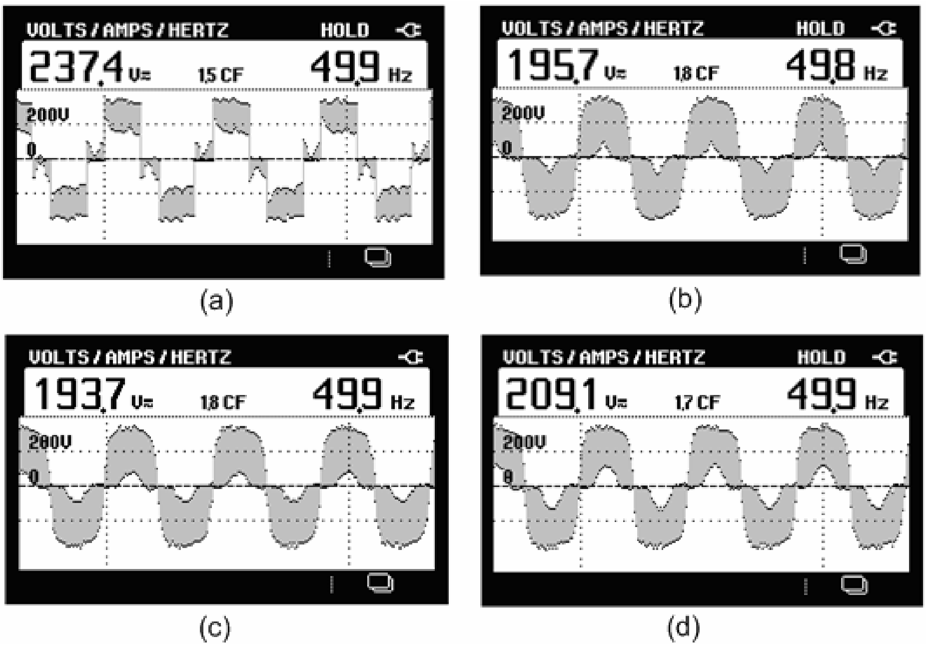

Fig. 13 Waveforms of inverter output voltage for M=0,9, m_f =175 with square wave PWM (a), SPWM (b), carrier based SVPWM (c), SVPWM (d) techniques.

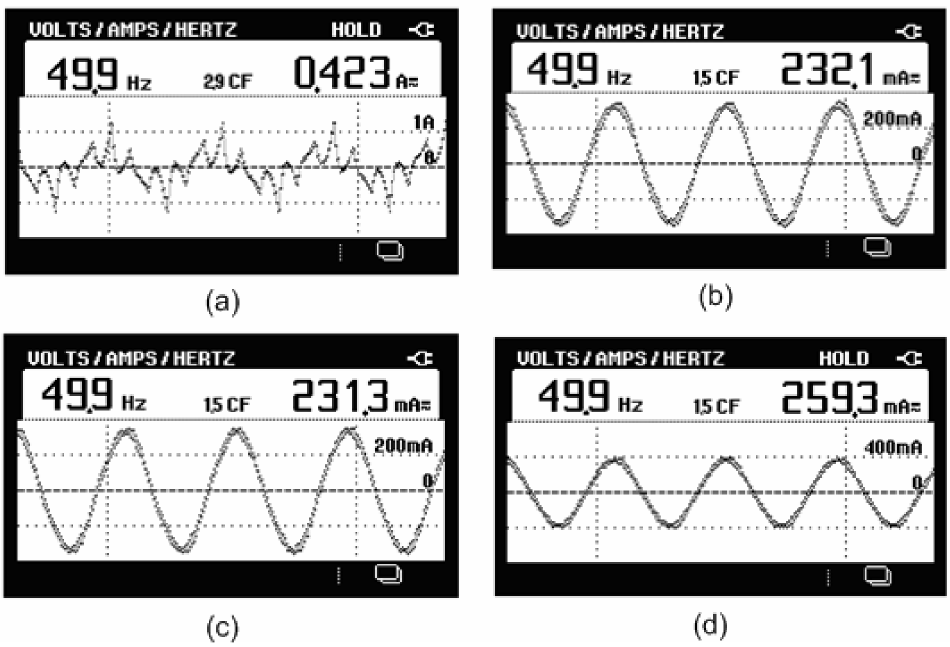

Fig. 14 Waveforms of inverter output current for M=0,9, m_f =175 with Square wave PWM (a), SPWM (b), carrier based SVPWM (c), SVPWM (d) techniques.

While in inverter that used SPWM, carrier based SVPWM and SVPWM techniques output current waveform is in sinus shape, output current waveform of inverter that used square wave PWM is far from sinus shape as shown in Fig. 14.

4. Conclusions

In this paper, current harmonics of no-loaded motor that connected to open loop voltage source inverter output are investigated for different PWM control techniques. As shown in experimental results, harmonic spectrum of SVPWM is the least instead of it has computation concentration. SVPWM technique has wide linear modulation ratio. Its commutation losses are less due to it prevents unnecessary switching. Total harmonic distortion is less. For same modulation index, output voltage of SVPWM is higher than output voltage of SPWM. Motor control system can be designed according to low current level for same power value because of increment at output current. This decrease in current causes decrease in transmission losses. Application of vectorial control is easier in SVPWM technique that has more advantage than other PWM techniques.

In future works, harmonics can be examined with more advanced PWM techniques in state of variable load. Optimum modulation index and modulation ratio can be found with Genetic Algorithms and Artificial Neural Networks.

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