Pulse width Modulation Command Systems Used for the Optimization of Three Phase Inverters

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***Abstract*—This paper deals with a novel pulse width modulation (PWM) switching strategy for a voltage source inverter through carrier modification. The proposed discontinuous sine carrier PWM (DPWM1) method, which uses two modified sine waves, has a better spectral quality and a higher fundamental component. This improved waveform has been derived from the original sine PWM technique through the addition of the 17-percent third-harmonic component to the original sine reference.**

Index Terms—PWM converter, digital control, microcontroller, simulation, harmonic distortion

I. INTRODUCTION

In recent years, a variety of power electronics equipment with voltage-fed pulse width modulation inverters (VSI-PWM) [1,10] used widely in industrial applications and power network systems have caused significant inherent problems, such as generation of reactive current and power, as well as higher harmonic distortion in the power sources.

The selection of the best PWM technique for most applications is uncertain, which can lead to less than optimum results. A critical evaluation of the aforementioned PWM techniques on the basis of applications is provided, thereby giving the framework and guidelines for the selection of the best technique for each area of application [3, 4].

These PWM strategies are based upon the computation of these moments according to the desired output voltage and they need digital control systems or microcontroller systems [2]. The determination of the switching moments of the semiconductor device from the inverter is important, and it can modify substantially the functioning of the entire electrical system.

Thus, this paper analyses and compares the output results of a three-phase inverter using PWM technique modulation, with continuous functioning (CPWM) and discontinuous functioning (DPWM1). The DPWM1 strategy enhances the fundamental output voltage, particularly at lower modulation index ranges, while keeping the total harmonic distortion (THD) lower, without involving changes in the device switching losses. The detailed comparison of the harmonic content and fundamental component of the modulation index and the results obtained for the PWM (CPWM) are also presented.

The performance of each these control methods (CPWM, DPWM) [5, 6, 7, 9] is usually judged based on the following parameters: a) total harmonic distortion (THD) of the voltage and current at the output of the inverter, b) switching losses within the inverter, c) peak-to-peak ripple in the load current, and d) maximum inverter output voltage for a given DC rail voltage.

II. PWM MODULATION STRATEGY USED FOR INVERTERS COMMAND

Fig.1 shows the three phase power inverters with variable inductance of the output load, and Figure 2 shows the generation of the command signals for the transistors within the three-phase inverter using the PWM technique command with continuous functioning (sinusoidal PWM, CPWM).

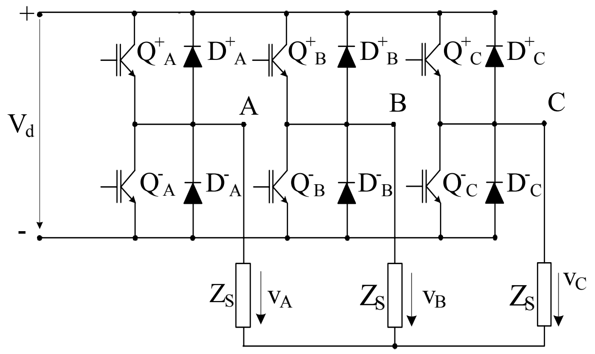


Figure 1. Three-phase inverter.

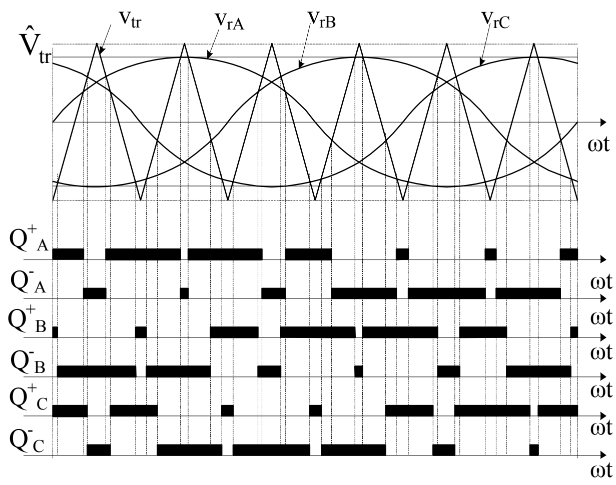


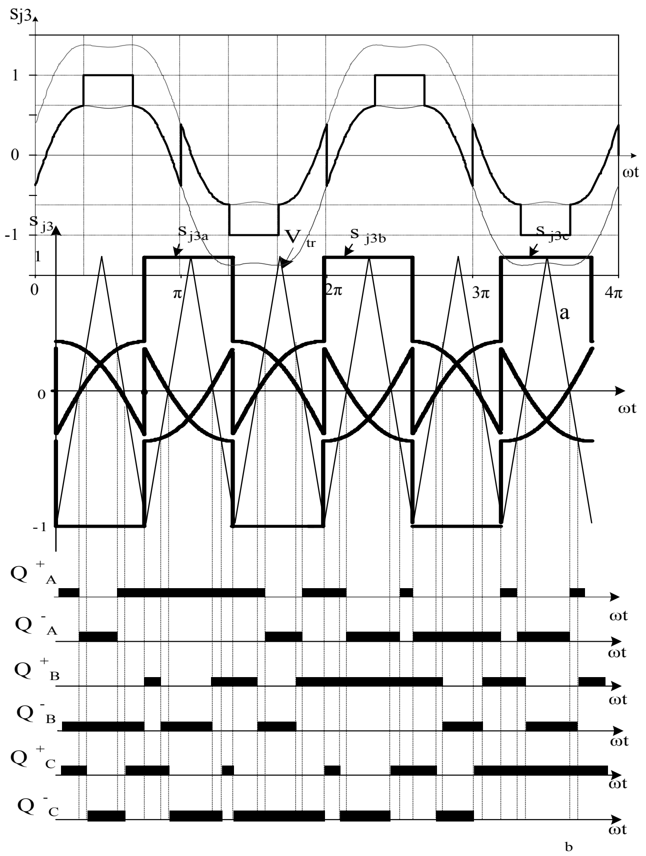
Figure 2. Generation of the command signals, (sinusoidal PWM).

Figure 3a shows the modulator signal sj3. The signal sj3 is a normalized signal ($\hat{V}_{tr}$ - amplitude triangular signal), described in relation (1). Figure 3b shows the generation of the command signals for the transistors within the three phase inverter using PWM technique command with discontinuous functioning (DPWM1).

$$s_{j3} = \begin{cases} m_a(\sin\omega_m t + 0.16\sin 3\omega_m t) - \dfrac{m_a}{3}; & 0 \le \omega_m t \le \dfrac{\pi}{3} \\ 1; & \dfrac{\pi}{3} \le \omega_m t \le \dfrac{2\pi}{3} \\ m_a(\sin\omega_m t + 0.16\sin 3\omega_m t) - \dfrac{m_a}{3}; & \dfrac{2\pi}{3} \le \omega_m t \le \pi \\ m_a(\sin\omega_m t + 0.16\sin 3\omega_m t) + \dfrac{m_a}{3}; & \pi \le \omega_m t \le \dfrac{4\pi}{3} \\ -1; & \dfrac{2\pi}{3} \le \omega_m t \le \dfrac{5\pi}{3} \\ m_a(\sin\omega_m t + 0.16\sin 3\omega_m t) + \dfrac{m_a}{3}; & \dfrac{5\pi}{3} \le \omega_m t \le 2\pi \end{cases} \quad (1)$$

Here, m_a is the amplitude modulation ratio and s_{j3} is the modulator signal.

Figure 3. a.) Modulator signal s_{j3}, b) Generation of command signals using DPWM1 command.



For the generation of the command signals, three modulation signals are used, described by the following relations:

$$s_{j3a} = s_{j3}\angle 0\,,\; s_{j3b} = s_{j3}\angle\frac{2\pi}{3}\,,\; s_{j3_c} = s_{j3}\angle\frac{4\pi}{3}\,, \quad (2)$$

Comparing DPWM1 command with CPWM command, DPWM1 allows an important reduction of the power losses within the power inverter, because the total number of the switching of the transistor for a semi-period is lower than for the CPWM command. Analyzing the signal waveforms presented in Figure 3, we can notice that only two out of the three pairs of switching transistors continually change their switching states, thus determining a certain behavior within a semi-period of the modulated signal, when one arm is OFF and the other in ON. In these conditions, the power losses are smaller with approximately 30%.

III. SIMULATION OF THE THREE-PHASE INVERTER

For the simulation of the power inverter a three phase load was used, containing three resistors (R=10Ω) and four parametric inductances (10mH, 15mH, 20mH and 25mH respectively). The frequency commutation is f_c=5kHz, the frequency modulation is f_p = 50Hz, the frequency modulation ratio is $m_f = f_c/f_p$=100, the power supply voltage V_{dc} = 310V.

Figure 4 shows the most important waveforms obtained after the simulation of the three-phase inverter, using sinusoidal PWM (CPWM).

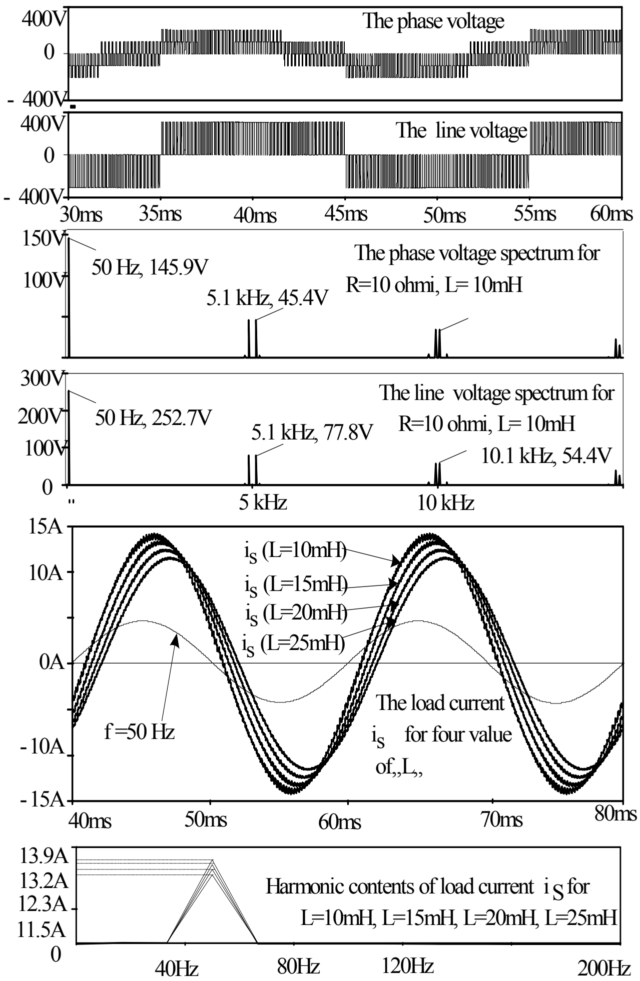


Figure 4. Waveforms and spectral diagrams of the phase voltage and line to line voltage; waveforms and spectral diagrams of the load current - for CPWM command.

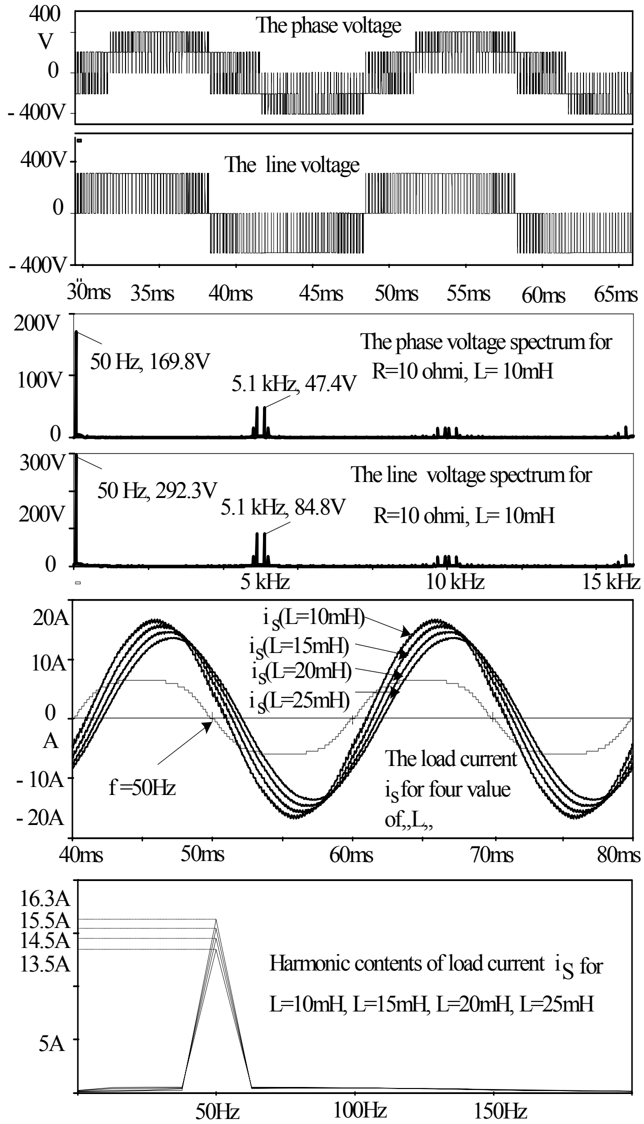


Figure 5. Waveforms and spectral diagrams of the phase voltage and line to line voltage; waveforms and spectral diagrams of the load current - for DPWM1 command.

Figure 5 shows the most important waveforms obtained after simulation, of the three-phase inverter, using DPWM1.

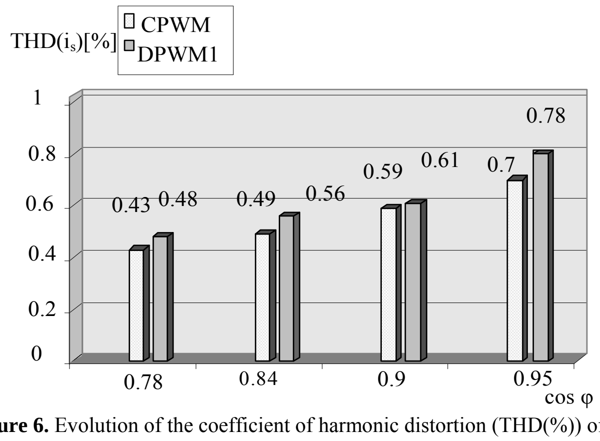


Figure 6. Evolution of the coefficient of harmonic distortion (THD(%)) of the load current is , depending on cosφ.

Taking into consideration the results after the simulation of the three-phase inverter, Figure 6 shows the evolution of the distortion harmonic coefficient (THD(%)) of the load current i_s , depending on cosφ and Figure 7 shows the evolution of the efficiency η(%) depending on cosφ.

$$\cos\varphi = \cos\left(arctg\,\frac{\omega L}{R}\right) \tag{3}$$

where L-R is inductive load.

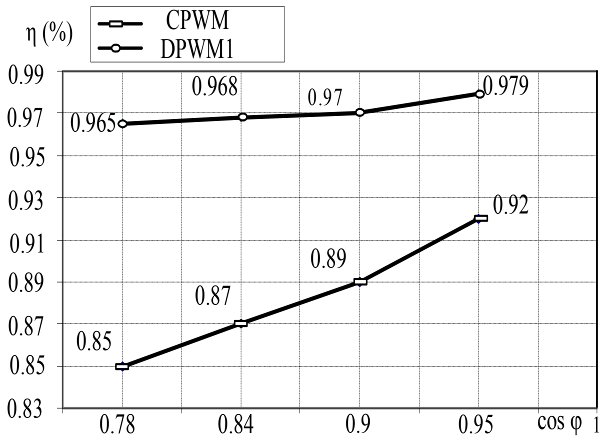
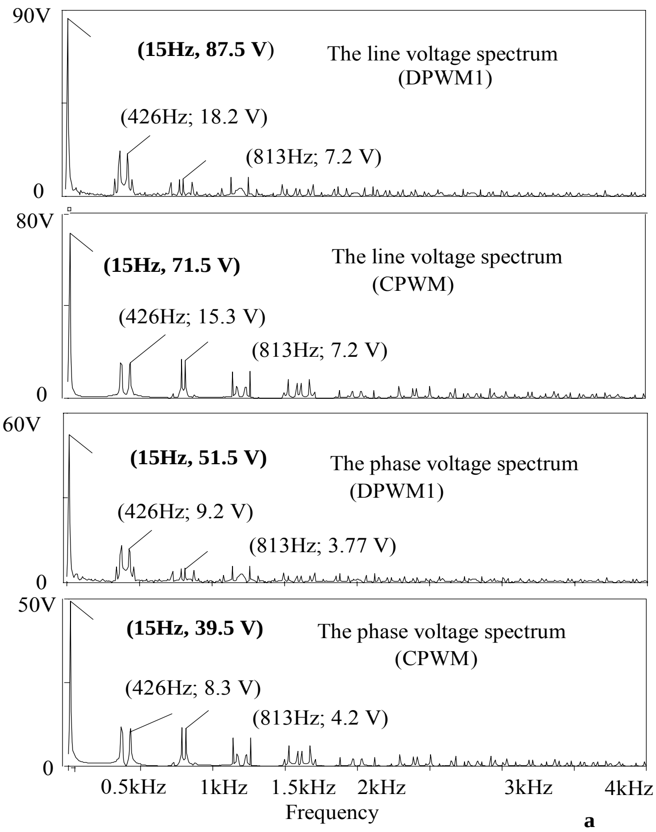


Figure 7. Variation of the efficiency of the three-phase inverter η (%) depending on cosφ.

The behavior of the three-phase inverter could be analyzed on spectral diagrams at low frequency for synchronous $m_f \in N$ and asynchronous $m_f \in R$ modulations[11]. Figure 8 shows the spectral diagrams of the line-to-line voltage and of the phase voltage of the inverter, using DPWM1 and CPWM command for the switching frequency f_c = 400Hz and, consequently, a) frequency of the modulating signal has the value 15Hz, b) frequency of the modulating signal has the value 50Hz.



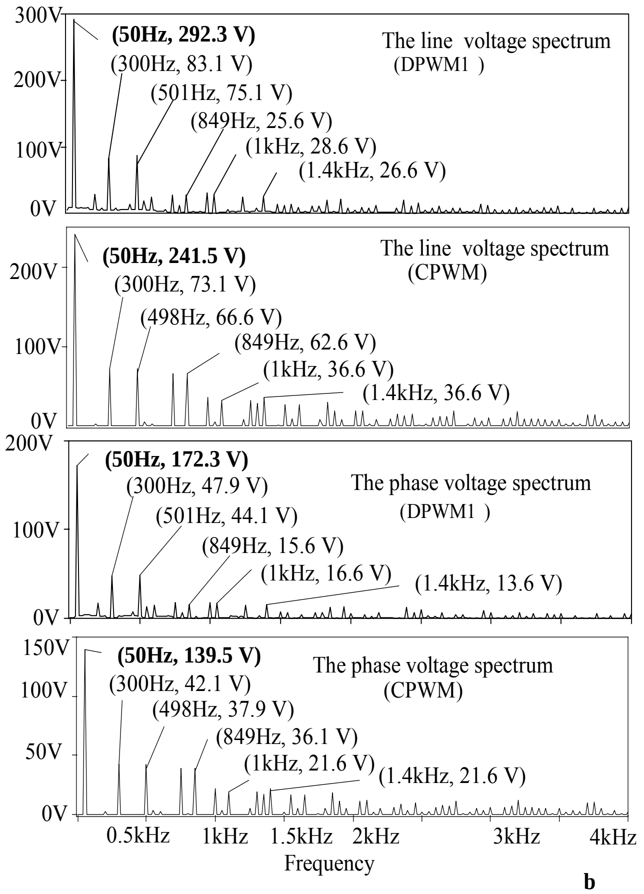


Figure 8. Spectral diagram of the phase and line-to-line voltage of the three-phase inverter, commanded with the frequency f_c=400Hz: a) DPWM1 and CPWM with frequency of the modulating signal 15Hz, b) DPWM1 and CPWM with frequency of the modulating signal 50Hz.

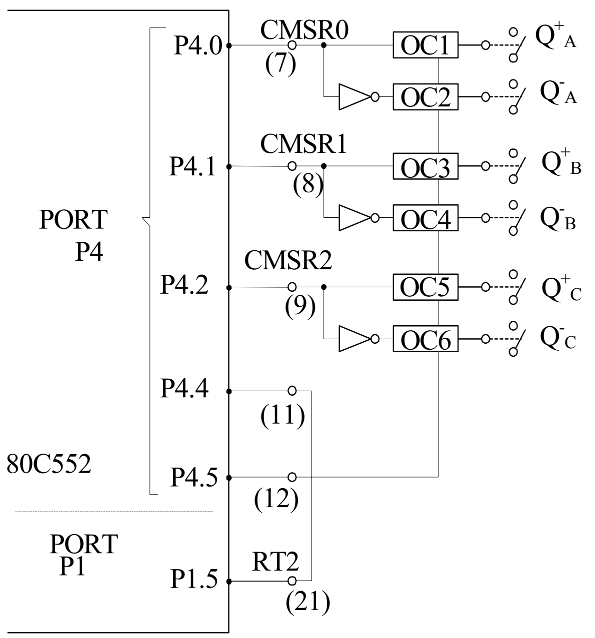


Figure 9. Control circuit of the three-phase power inverter with 80C552 microcontroller.

IV. PWM IMPLEMENTATION STRATEGY USING MICROCONTROLLERS

Using PWM modulation strategies implemented on a microcontroller for the command of three phase inverters leads to simpler hardware, to many possibilities of creating new command and control functions, allows the control of multiple switching devices [12], etc. In this case, signal generation using 80C552 microcontroller, was possible taking into account the fact that in a 10ms interval there are around 100 pulses, the number of pulses depending on the frequency modulation index $m=f_c/f_s$=5kHz/50Hz. The duration of these pulses must have quantified values because they depend on the microcontroller system clock frequency. The clock frequency of the system is 12MHz and the execution time of one instruction cycle is 1 microsecond. This one microsecond is the quantified time unit in our PWM control system. In order to be used in the 80C552 microcontroller system [13], theoretical commutation moments are rounded up, a rule imposed by the one microsecond quantification value.

Figure 9 shows the control circuit of the three-phase power inverter with 80C552 microcontroller. As we can see in the last figure, the hardware part contains only three signal inverters (I1, I2 and I3) and one connection between P4.4 pin and P1.5 (RT2), which has an alternative external reset function for the T2 timer. This connection allows the PWM signal generation using T2 timer by recalling the same function at every 20000 microseconds. The three inverters (I1, I2 and I3) are used to create the control signal for Q^-_A, Q^-_B and Q^-_C transistors, while P4.0 directly controls the Q^+_A transistor, P4.1 controls the Q^+_B transistor and P4.2 controls the Q^+_C transistor. The pin of port P4.5 has the function to strobe six optocouplers (OC1, …, OC6), used for galvanic insulation between the microcontroller system and the three phase power inverter.

The switch state of Q^+_A, Q^+_B and Q^+_C is directly controlled by P4 output port through "set" and "reset" bits of T2 timer. The switch state of Q^-_A, Q^-_B and Q^-_C is obtained by inverting control signals of Q^+_A, Q^+_B and Q^+_C using the three inverters I1, I2 and I3. In Table I, "S" is the "set" operation of the T2 timer, carried out by means of comparison registers, and "R" is the "reset" operation.

TABLE I. SWITCHING OF POWER DEVICES IN THE THREE-PHASE INVERTER FOR SINUSOIDAL PWM MODULATION

No. crt.	Theoretic (μs)	Quantified (μs)	Cumulated (μs)	Q^+_A	Q^-_A	Q^+_B	Q^-_B	Q^+_C	Q^-_C
				S	R	S	R	S	R
1	22.3	22	22			R	S		
2	160.4	160	182			S	R		
3	22.3	22	204			R	S		
4	154.7	155	359					R	S
5	10.8	11	370	R	S				
6	17.4	17	387	S	R				
7	21.5	22	409					S	R
8	148.5	149	558			S	R		
9	13.1	13	571			R	S		
10	141.9	142	713					R	S
.									
318	154.7	155	19998			S	R		

TABLE II. SWITCHING OF POWER DEVICES IN THE THREE-PHASE INVERTER FOR DPWM MODULATION STRATEGY

Nr. crt.	Theoretic (μs)	Quantified (μs)	Cumulated (μs)	Q^+_A	Q^-_A	Q^+_B	Q^-_B	Q^+_C	Q^-_C
				S	R	S	R	S	R
1	2.91	3	3	R		R		R	
2	50.9	51	54					S	
3	95.4	95	149	S					
4	48	48	197	R					
5	5.9	6	203					R	
6	45.2	45	248					S	
7	106.7	107	355	S					
8	41.8	42	397	R					
9	6.82	7	404					R	
10	39.4	39	443					S	
.									

The quantification of time intervals (one microsecond quantification time) leads to a specific cumulative error, namely a 19998 microseconds period instead of 20000 microseconds (corresponding to the 50hz frequency. The relative error is of 0.01% of the output frequency and is negligible.

During the functioning of the three phase voltage system, intersections occur between the three waveforms at every 60 electrical degrees, that is at every 3333,(3) microseconds. The quantification of time intervals leads to a value of 3333 microseconds, which also determines the cumulative error mentioned above. In the light of this observation, the evolution in time during a full period of a phase is divided in 6 distinct intervals. This is emphasized in Table I, which shows points in time of 3333, 6666, 9999, 13332, 16665 and 19998 microseconds. In these moments, certain modifications in the command order occur.

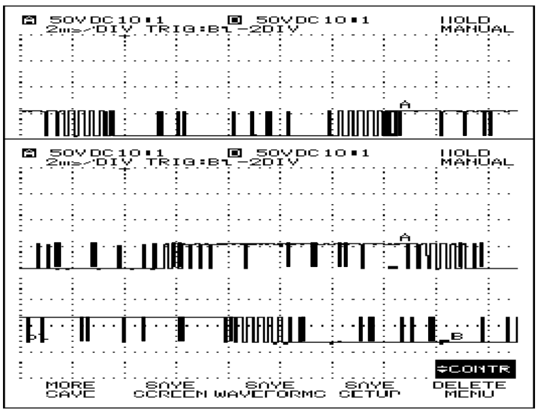
Table I indicates the first 10 states of the duration of impulses, obtained theoretically, but also quantified. In a machine cycle of one microsecond, time intervals shorter than 500 nanoseconds will be omitted in the switching strategy (they are rounded to 0). Table I also presents the time moments when the switches are turned on, obtained by cumulating the quantified time intervals.

The data in Table I show that the power devices need to perform 318 commands during the 19998 microseconds of a period of the three-phase signal obtained by the PWM technique with a 5kHz modulation frequency. This emphasizes the fact that the time for the command of the power devices is reduced (at every 63 microseconds, on the average). On the other hand, the distribution of these intervals of time is not uniform, which is specific to the sinusoidal PWM technique. Therefore, within a period, there are time intervals when the time moments corresponding to the commands from T2 timer are very close, which raises difficult time management problems for the microcontroller. This will essentially reflect upon the general strategy concerning the software approach of the problem. The comments referring to Table I are also valid for Table II

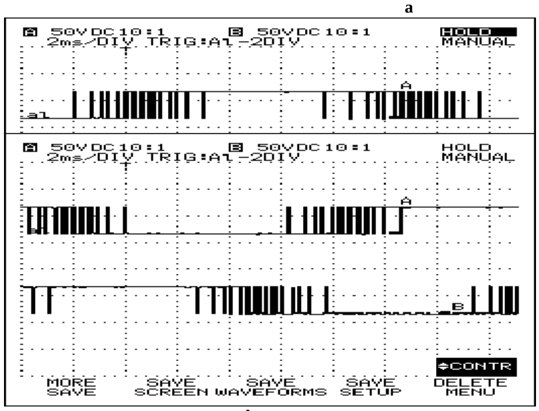
Because of the difficulties related to the working time, the analysis carried out showed that it is no longer possible to use indexed addresses in order to extract time moments that are necessary for the command of the inverter power devices from the data table. The instructions for extracting data from the tables by means of the DPTR indexed addresses need more time than it is allowed for the command of the inverter in certain time intervals within a period of the sinusoidal signal. The solution is to load immediately the data that indicate the command moments of the switches. Thus, the program working speed is increased, which allows the full control of the moments imposed by the sinusoidal PWM modulation with a 5 KHz frequency. This higher speed is obtained by a significant increase of the length of the command program resulting from the immediate data loading. It is not a major disadvantage, as the command program can be loaded in the program memory of the development system with 80C552 microcontroller. This allows the simple development, checking and debugging of the software part of the three-phase inverter.

The command program of the inverter will be performed in loops [8]. A loop will be 19998 microseconds long. At the end of this interval, the resetting of the T2 timer is commanded by setting the P4.4 pin of port P4 connected to pin P1.5 of port P1, which has the RT2 alternative function (reset timer T2). The state instruction of the P4.4 pin is followed by a long unconditional leap to the program area corresponding to the beginning of a period of the three-phase inverter.

Figure 10 presents, within a period (20 ms), the oscilloscope waveforms of the signal at the output of the 80C552 microcontroller for the command of switches Q^+_A, Q^+_B and Q^+_C.



a



b

Figure 10. Oscilloscope waveforms of the command signals for Q^+_A, Q^+_B and Q^+_C a) CPWM modulation b) DPWM1 modulation.

V. CONCLUSION

These PWM strategies can be designed to minimize harmonic losses, reduce torque pulsation, speed ripple, etc. The comparative analysis of the results obtained by simulation offers the possibility of using optimum selection criteria for the modulating waveform in order to obtain high efficiency for the inverter.

Results from an experimental microprocessor controlled PWM inverter drive are presented to demonstrate and confirm efficient DPWM1 control strategies.

REFERENCES

[1] S.R. Bowes, P.R. Clark,''Transputer-Based Harmonic-Elimination PWM Control of Inverter Drivers'' IEEE Trans. on IAS , vol.28, No.2, pp. 72-80,1992.

[2] S.R Bowes, P.R. Clark, ''Simple Miroprocessor Implementation of New Regular-Sampled Harmonic Elimination PWM Tehniques,'' IEEE Trans. on IAS , vol.28, No.1, pp. 89-95,1992.

[3] P.G. Handley, J.T.Boys, "Practical Real-time PMW Modulators," vol 139 ,no2 ,pp 96-102, March 1992

[4] J. Holtz, W. Lotzkat, Khambadkone A.,''On Continouse Control of PWM Inverters In the Overmodulation Range Including the Six – Step Mode,''IECON 18th Ann. Conf. IEEE Ind. Elect. Doc., San Diego/Ca, pp 307-312, 1992.

[5] A. M. Hava, R. J. Kerkeman, and T.A.Lipo. ''A High Performance Generalized Discontinous PWM Algorithm''.In IEEE-APEC Conf. Records., pp.886-894, Atlanta, Giorgia, 1997.

[6] A. M. Hava, R. J. Kerkeman, and T.A.Lipo. ''Simple Analytical and Graphical Tools For Carrieri Based PWM Methods''.In IEEE-PESC Conf. Records., pp.1462-1471, St. Louis, Missouri, 1997

[7] A. M. Hava, R. J. Kerkeman, and T.A.Lipo. ''Dinamic Overmodulation Characteristics Of Triangle Intersection PWM Meyhods''.In IEEE Industrial Application Soc. Conf. Records., pp.1520-1528, New Orleans, Louisiana, 1997

[8] S. Jeevananthan, R. Nandhakumar, P. Dananjayan. ''Invertid Sine Carrier for Fundamentak Fortification in PWM Inverters and FPGA Based Implementation'' Serbian Journal of Electrical Engineering, vol.4., no.2, pp. 171-187, November 2007.

[9] B.Justus Rabi, '' Minimization of Harmonics in PWM Inverters Based on Genetic Algorithms'', Journal of Applied Sciences 6(9), 2056-2059, ISSN 1812-5654, 2006.

[10] O. Ursaru, C. Aghion, L. Vornicu, "Angular PWM Modulation (PWMA)," Trans& Motauto'05+, Twelfth International Scientific-Tehnical Conference on Transport, Technologies and Military and Military-Educational Problems, vol. 3, pp. 131-134, 23-25 November 2005, Veliko-Tarnovo, Bulgaria

[11] V. Maier, S.G. Pavel, C.D. Maier, I. Birou, "Conect Application of the Discrete Fourier Transform in Harmonics" Advances in Electrical and Computer Engineering, vol.8, no.1, pp. 26-31, 2008.

[12] ***80C51Family Architecture, Philips Semiconductors, Sunnyvale, California, U.S.A, March 1995.

[13] ***80C51Family Derivatives. 8XC552/562 overviewe, Philips Semiconductors, Sunnyvale, California, U.S.A, August 1996.