MEDWELL PUBLISHING
International Journal of Electrical and Power Engineering 3 (2): 94-98, 2009
ISSN: 1990-7958

A Novel Online Dual Slope Delta Modulated PWM Inverter

[1,2]Ramdan Razali, [2]Zulkeflee Khalidan, [2]M. Badaruddin and [2]M.S. Najib
[1]Faculty of Engineering and Technology, University of Multimedia, Melaka, Malaysia
[2]Faculty of Electrical and Electronic Engineering, University of Malaysia Pahang, Pahang, Malaysia

Abstract: This study attempts to identify the modulation parameters of a Delta modulator. A novel technique of implementing the Delta modulator by a microcomputer Delta Modulators can be significantly reduced by allowing online parameter variation and synchronous operation, which can be varied during constant and variable frequency operation of the three-phase Voltage Source Inverter (VSI) so as to improve the performance in terms of harmonic content and fundamental voltage availability. Test results show that dual-slope and dual slope-variable window width operations provide considerably higher fundamental voltage while maintaining the spectra of dominant harmonics to occur at higher frequency range.

Key words: Delta modulator, harmonic content, jundamental voltage, spectra, parameter, VSI

INTRODUCTION

Microcomputer based PWM schemes for the power electronic converters have been growing in recent years. A carefully designed microcomputer based PWM controller provides simplification in hardware and improvement in performance. The hardware simplification adds to the reliability. Modern PWM inverters are continually seeking improvement of performance and reliability with reduction of control and power conversion cost. The microcomputer based PWM controller constitutes a compatible link between the controller and the inverter and can be integrated in the hardware and software of the same microcomputer. In conventional hardware modulator, the PWM waveforms are generated by comparing the sine reference wave with the triangular carrier wave by the natural sampling process. As the linear PWM region is exceeded into the transition region, the harmonic quality of the waves deteriorates significantly with the introduction of the lower order harmonics (Ziogas and Phoivos, 1981). Further, the dropping of pulses near the middle of the wave causes a current surge problem (Ali *et al*., 1988). In a microcomputer-based modulator, the wave can be constructed more accurately in the transition region controlling the harmonics and voltage jump and the non-linearity problem can be easily overcome. However, precise PWM wave generation in real time, as required by the drive system, remains a challenge because of the time critical performance requirement of the microcomputers (Ali *et al*., 1988).

In this study, a Novel method of implementing the delta modulator to control VSI by a microcomputer was proposed. It uses an algebraic equation to generate the PWM pulses to control the inverter. It is also proposed to carry out experiments to verify the theoretical results on formulation of a simple algebraic equation. The advantage of changing slope of the carrier wave and window width of the modulator in software control can be extended to the variable frequency operation of the inverter.

THEORETICAL BACKGROUND

One of the PWM schemes proposed for the control of inverters supplying ac drives is the Delta Modulation (Ziogas and Phoivos, 1981; El-kholy *et al*., 2007; Rashid, 1995; Bose, 2005; Rahman *et al*., 1987). It has the inherent features like automatic voltage/ frequency (v/f) control and reduction of number of switching per cycle during high frequency operation. However, the modulator has the disadvantages such as low voltage utilization of its dc voltage, non-synchronous operation and pulse-dropping phenomenon. In this study, improvement of DM scheme for inverter control has been investigated. The investigation is based on the previously reported equation on calculating the switching points of the Rectangular Wave Delta Modulation (RWDM) (Rahman *et al*., 1987).

The analysis of modulated waves requires the knowledge of switching point calculation. Formulation of an easy algebraic equation that can be solved almost

Corresponding Author: Ramdan Razali, Faculty of Engineering and Technology, University of Multimedia, Melaka, Malaysia

instantaneously would enable one to implement the modulation by microcomputer.

$$t_i = \frac{2\Delta V + St_{i-1}}{S} + \frac{V_R \sin\omega_R t_{i-1} - V_R \sin\omega_R t_i}{(-1)^i s} \quad (1)$$

where:

- ΔV = Half the window width.
- S = Slope of the triangular estimated wave considered to be equal.
- t_i = First pulse terminating point .
- ω_R = The frequency of the input sine wave in rad/sec.
- $V_R \sin\omega_R t$ = Reference sine wave.

Equation 1 is the previously reported equation of the RWDM (Fig. 1). It is a transcendental equation, having term t_i on both sides, which is not suitable for online microcomputer implementation (Rahman *et al*., 1987). In the next study a modification of Eq. 1 to make it a simple algebraic equation is derived. Also, the present study considers the slopes of rising and falling sides of the estimated wave to be unequal so as to have the additional means of the voltage control.

The derivation of a simple algebraic equation which may allow one to find switching points of RWDMed wave as shown in Fig. 2a and b.

Hence, the rising edge slope S_R can be related to above points as:

$$S_R = \frac{2\Delta V + V_m(\sin\omega t_i - \sin\omega t_{i-1})}{t_i - t_{i-1}} \quad (2)$$

which can be written as:

$$S_R(t_i - t_{i-1}) = 2\Delta V + V_m(\sin\omega t_i - \sin\omega t_{i-1}) \quad (3)$$

In Fig. 3 it is illustrated that $V_m(\sin\omega t_i - \sin\omega t_{i-1})$ is the vertical distance $V_m \sin\omega t$ given by the slope of sine wave at t_{i-1} multiplied by $(t_i - t_{i-1})$. Replacing $V_m(\sin\omega t_i - \sin\omega t_{i-1})$ by $\omega V_m \cos\omega(t_{i-1})[t_i - t_{i-1}]$ in Eq. 3 one obtains

$$t_i = \frac{2\Delta V}{S_R - \omega V_m \cos\omega t_{i-1}} + t_{i-1} \quad (4)$$

which is the desired algebraic eq. for the rising slope S_R. Once the value of the point t_{i-1}, is known the value of t_i can easily found by using Eq. 4.

For the falling slope, following the same arguments and steps and using Fig. 3, one obtains the expression of switching point t_i in term of t_{i-1} as:

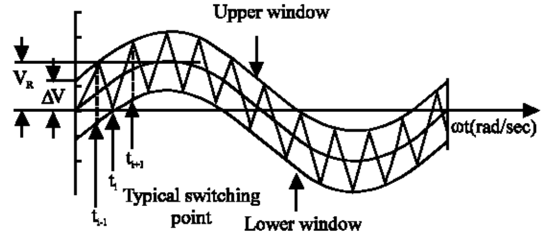

Fig. 1: Waveform of RWDM

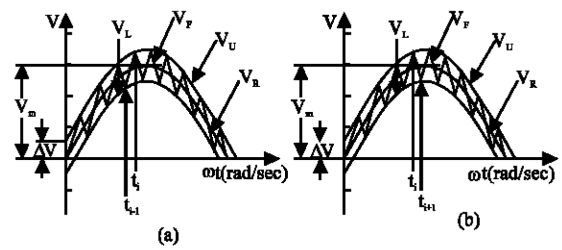

Fig. 2: Waveform of delta modulator for rising slope (a) and falling slope (b) of the carrier wave

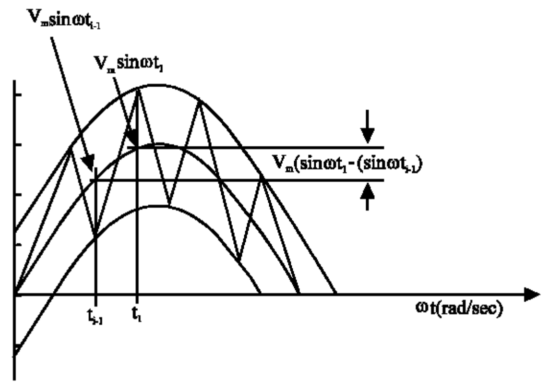

Fig. 3: Calculation of rising slope

$$t_i = \frac{2\Delta V}{S_F + \omega V_m \cos\omega t_{i-1}} + t_{i-1} \quad (5)$$

In general, the switching point t_i can be expressed in term of t_{i-1} as:

$$t_i = t_{i-1} + \frac{2\Delta V}{S + (-1)^i \omega V_m \cos\omega t_{i-1}} \quad (6)$$

where:

- S = S_R or S_F depending on i = odd or even (in normal modulation $S_R = S_F$).
- ΔV = Window width.
- V_m = Maximum value of the reference sine wave.
- ω = $2\pi f_m$, where f_m is the frequency of the reference sine wave.

Equation 6 is an algebraic equation, which can be used advantageously to analyze and implement DM. The first point of switching is 0, hence by setting modulation parameters as necessary, it is easy to find the switching points of RWDM for a cycle of the modulation wave.

Harmonic analysis of delta modulated waveform: The switching points of the modulated wave allow one to write the Fourier series of the modulated wave as follows:

$$a_n = \frac{2V_{dc}}{n\pi}\sum_{i=1,2,...}^{N_p}(-1)^{i+1}(\sin n\delta_i - \sin n\delta_{i-1}) \quad (7)$$

$$b_n = \frac{2V_{dc}}{n\pi}\sum_{i=1,2,...}^{N_p}(-1)^{i+1}(\cos n\delta_i - \cos n\delta_{i-1}) \quad (8)$$

where:

N_p = Number of pulses over a cycle.
$\delta_i = \omega t_i$ = $2\pi f_m t_i$ is the i th pulse position in radian.
V_{dc} = The dc supply voltage of the inverter.
n = Order of the harmonics.
a_n and b_n = nth order Fourier coefficients.

The fundamental voltage of the modulated wave can be obtained from Eq. 7 and 8 as:

$$a_1 = \frac{2V_s}{\pi}\sum_{i=1,2....}^{N_p}(-1)^{i+1}(\sin\delta_i - \sin\delta_{i-1}) \quad (9)$$

$$b_1 = \frac{2V_s}{\pi}\sum_{i=1,2....}^{N_p}(-1)^{i+1}(\cos\delta_i - \cos\delta_{i-1}) \quad (10)$$

and

$$V_1 = \sqrt{\alpha_1^2 + b_1^2} \quad (11)$$

where, V_1 is the fundamental voltage. Eq. 7-11 have been programmed using MATLAB software so that analysis can be carried out to study the harmonic behavior.

IMPLEMENTATION

A block diagram of online dual-slope Delta Modulated PWM VSI as shown in Fig. 4, designed and fabricated was run online successfully. Eq. 6 is programmed to calculate the dual slope Delta PWM (DPWM) switching pulses for online microcomputer controlled of a three-phase MOSFETs VSI operation. The proposed online strategy uses an Intel Pentium 100 Mhz,

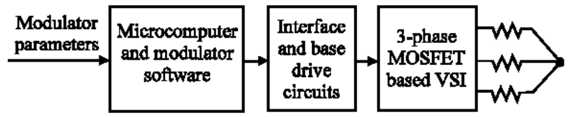

Fig. 4: Block diagram of delta modulated PWM VSI

supported by 16 MB of Random Access Memory (RAM) and its general facility of the printer port to generate required switching pulses. The modulation parameters i.e. S_R, S_F V_m dv and fm can be changed from keyboard command 'online' without the interruption of the supply to the load. The method is fast and accurate and as a result meets the steady state and the transient performance requirement of the load. The softwareimplementationof themodulatorconsists ofthe following sets of routines:

- Sampling and calculation of switching points.
- Reading of keyboard's port.
- Generating of six real time DPWM controller pulses with 60 degrees shifted from one another and outputting them through 2-7 pin of parallel port.

RESULTS

The typical DPWM pulses at 2 and 3 pin under different parameters setting are shown in Fig. 5 and 6, shows oscillograms of line to line and line to neutral voltages across the resistive load and their respective spectrums when the inverter is controlled by DPWM switching (gating) pulses as shown in Fig. 5. The spectrums are obtained by FFT analysis by MATLAB software on data of experimental waveforms. Table 1-3 are some of typical results when inverter is operated under different setting of modulators' parameters.

It is observed, in the waveform and the spectrum that the third harmonic and its multiples appear in the line to line voltages and their respective spectrum. This is expected because of three level switching giving the inverter line to line voltage the shape of square wave superimposed on the modulated wave. The third harmonics and their multiples are cancelled in the line to neutral voltage in Y-connected load.

In Table 1, it has been observed that keeping falling slope of the carrier wave constant (in this case, 4000 V/s), if the rising slope is varied (in this case 4000-2500 V/s), the output voltage of the inverter increases even at the fixed frequency (50 Hz) operation. The spectrums of line line and line to neutral voltage of Table 1 showed an

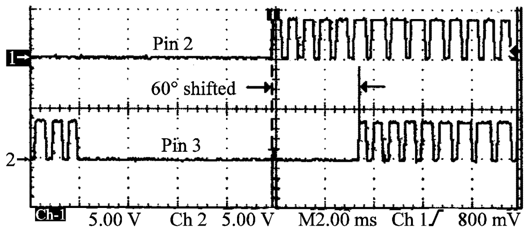

Fig. 5: Computer Generated DPWM at pin 2 and pin 3 of parallel port. The modulators' parameters are V_m = 6.0 V, f_m = 50 Hz, $S_F = S_R$ = 4000 V/s a nd dv = 0.6 V

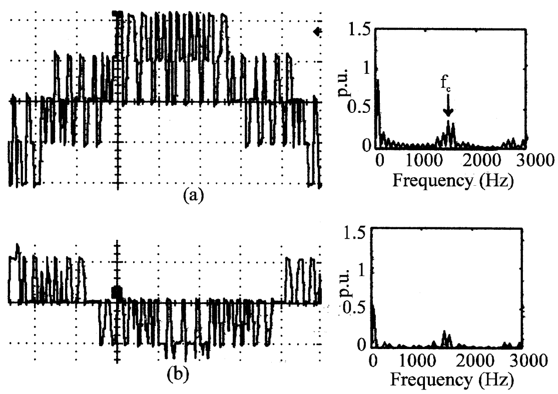

Fig. 6: (a) Line to line (b) line to neutral and their voltage spectrums of 3-phase VSI operation under DPWM controlled pulses

Table 1: Dual-slope operation of the delta modulator

Modulator parameters					Output voltages (p.u.)		
f_m Hz	S_F V/s	S_R V/s	V_m V	dv V	L-L	L-N	f_cHz
50	4000	4000	6	0.6	0.88	0.50	1500
50	4000	3250	6	0.6	0.96	0.56	1300
50	4000	2500	6	0.6	1.07	0.63	1000

Table 2: Dual-slope and dual slope-variable window width operation of the delta modulator

Modulator parameters					Output voltages (p.u.)		
f_mHz	S_F V/s	S_R V/s	V_m V	dv V	L-L	L-N	f_cHz
50	4000	4000	6	0.6	0.88	0.50	1500
50	4000	3250	6	0.5	0.96	0.58	1700
50	4000	2500	6	0.4	1.15	0.64	>3000

Table 3: Dual-slope, dual slope-variable window width and variable frequency operation of the delta modulator

Modulator parameters					Output voltages (p.u)		
f_m Hz	S_F V/s	S_R V/s	V_m V	dv V	L-L	L-N	f_c Hz
50	4000	3000	6	0.6	1.00	0.60	1200
70	4500	3000	6	0.35	1.14	0.67	2100
90	5000	2500	6	0.3	1.25	0.73	>3000

increase from 0.88-1.07 and 0.5-0.63 p.u., respectively. Result shows a higher fundamental voltage achieved compare to Sinusoidal PWM (SPWM) (0.87 p.u.), Modified SPWM (1.00 p.u.) and Harmonic Injection SPWM (1.00 p.u.) (Chaudhari and Fernandes, 1999). This observation is also in line with our prediction that dual slope operation of the modulator would allow one to vary the inverter output voltage smoothly.

Table 2 represents the results of investigation on controlling the inverter by changing both slopes, S_R and S_F, of the carrier wave and the window width of the modulator at fixed frequency operation. It is evident from the output voltages of the table that dual-slope operation still allows the fundamental voltage of the inverter to be changed as desired. At the same time the change in the window width allows the carrier frequency to occur in the higher range. This shows that software controlled of modulator's parameter can advantageously be used for the fundamental voltage of the inverter and yet maintaining the harmonic spectrum at higher frequency.

Typical results of such an operation are shown in Table 3. It is clear that with the frequency of the window width is changed, the fundamental voltage of the inverter line to line increases. The carrier frequency occurs in the same range.

CONCLUSION

In this study, the simple algebraic equation to determine the switchover points with desired DM parameters was formulated. A truly online dual slope DPWM generation based on the equation for the control of three-phase VSI successfully implemented. A practical MOSFET VSI has been designed, fabricated and tested successfully with considerably higher dc voltage utilization. The online generated DPWM pulses are automatically synchronized which removed the problem of non-synchronous operation. Experiments, carried out by online microcomputer operation, show that dual slope and dual slope-variable window width operation result in improved performance.

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