A PWM Strategy for the Modular Structured Multilevel Inverter Suitable for Digital Implementation

CIEP 2002
Guadalajara, MEXICO
October 20-24

Aziz, J.A, Salam, Z.
Department of Energy Conversion,
Faculty of Electrical Engineering,
Universiti Teknologi Malaysia,
81310 Skudai, Johor Bahru,
Malaysia

Abstract – A single carrier PWM strategy for a modular structured multilevel voltage source inverter is discussed in this paper. Using symmetric regular sampling technique, a multilevel modulation strategy is established to define the switching angles of the inverter switches. Mathematical equations for the PWM scheme suitable for digital implementation are derived. Finally simulation and hardware results are presented.

I. INTRODUCTION

It is well established that multilevel voltage source inverters (VSI) offer several advantages compared to their conventional two-level counterparts. A large body of literature over the past decade has testified its viability especially for high power application [1-4]. By synthesizing the ac output terminal voltage from several levels of dc voltages, staircase output waveform can be produced. This allows for higher output voltage and simultaneously lowers the switches voltage stress. Multilevel inverter has become an effective and practical solution for reducing switching losses in high power application. Furthermore, it is known to have better harmonic profile and thus the requirement of output filter is reduced. With these merits, multilevel VSIs have recently become very popular in renewable energy sources applications [5,6].

Generally the development of multilevel inverter system can be broadly divided into the two issues namely, power circuit topology and switching strategy. For circuit topology, three main types have been frequently cited in literature: (1) diode-clamped multilevel inverters (DCMI), (2) flying capacitor multilevel inverters (FCMI) and (3) modular structured multilevel inverters (MSMI). Abovementioned topologies have their specific advantages and disadvantages as detailed elsewhere [2]. The selection of an appropriate topology depends on a particular application and the nature of the dc supply that feed the inverter.

The second aspect that defines the inverter performance is the switching strategy. This is closely related to the harmonic profile of the inverter output waveform. The simplest scheme is the square wave, which has the poorest harmonic performance. This is followed by quasi-square wave, which offers a marginal improvement compared to the square wave inverter. The most popular switching technique is the Pulse Width Modulation (PWM), which is currently being implemented in majority of the VSIs.

Historically, the development of PWM switching strategy was prompted by the natural sampled sinusoidal PWM technique introduced by Schonung and Stemmler in 1964 [6]. This analog technique is based on the physical comparison between a carrier signal and a pure sinusoidal modulating signal. Its digital version, i.e. the regular-sampling PWM was introduced by Bowes in 1975 [7]. It has simplified the PWM generation tremendously and has become the impetus for the proliferation of several important digital PWM techniques until the present day. Several currently popular PWM schemes are the selective harmonic elimination PWM (SHEPWM) [8] optimized PWM [9] and more recently the space vector PWM (SVPWM) [10].

Abovementioned modulation techniques were originally applied to the two-level inverter. However, it was discovered that by making some modifications they could also be suitably used for multilevel inverter. For multilevel sinusoidal PWM in particular, different methods of carrier arrangement namely as phase opposition disposition (POD), phase disposition (DP) and alternatively in phase opposition disposition (APOD) [11] have been suggested. All of these techniques employ multiple carriers with a single modulating waveform. In this report, a new PWM switching strategy for multilevel inverter is proposed. It is based on a SPWM with a single carrier and multiple modulating signals.

II. MODULAR STRUCTURED MULTILEVEL INVERTER

The modular structured multilevel inverter (MSMI), as shown in Fig. 1, is unique when compared to other types of multilevel VSIs such as the diode-clamped (DCMI) and flying-capacitor (FCMI) inverters, in sense that it consists of several modules that require separate dc sources [1-3]. This feature is well suited for various renewable energy sources such as fuel cell, photovoltaic, and biomass, etc where the required dc sources are readily available.

This work is sponsored by the Malaysian Ministry of Science, Technology and Environment under Grant No. IRPA 72342

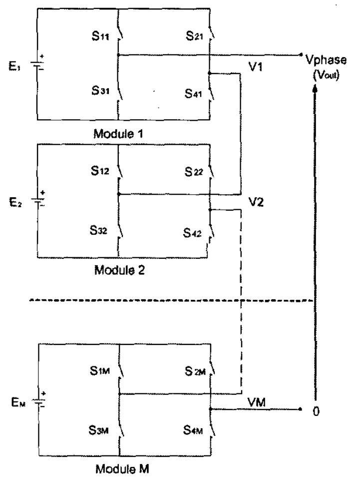


Fig. 1: Single-phase structure of a MSMI.

The output voltage of an MSMI is equal to the summation of the output voltage of the respective modules that are connected in series. The number of module (M), which is equal to the number of dc sources required, depends on the number of levels (N) of the MSMI. Given that the relationship between N and M for MSMI is described in equation (1), i.e.

$$M=\frac{N-1}{2} \qquad (1)$$

For example, for an output voltage consisting of five levels which include +2E, +E, 0, -E, and –2E, the number of modules needed is 2. Table 1 shows the selected switching configuration for a modular structured five-level inverter.

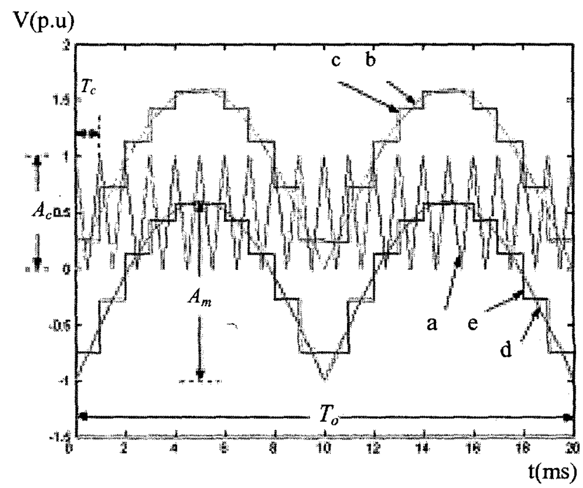
TABLE 1
INVERTER SWITCHES STATE FOR MODULAR STRUCTURED FIVE-LEVEL INVERTER

Load Voltage	+2E	+E	0	0*	-E	-2E
S_{11}	ON	ON	ON	OFF	OFF	OFF
S_{21}	OFF	OFF	ON	OFF	ON	ON
S_{31}	OFF	OFF	OFF	ON	ON	ON
S_{41}	ON	ON	OFF	ON	OFF	OFF
S_{12}	ON	ON	ON	OFF	OFF	OFF
S_{22}	OFF	ON	ON	OFF	OFF	ON
S_{32}	OFF	OFF	OFF	ON	ON	ON
S_{42}	ON	OFF	OFF	ON	ON	OFF

III. THE PROPOSED MODULATION SCHEME

The proposed modulation scheme for the MSMI is based on the classical unipolar PWM switching technique [1]. The main idea behind this method is to compare several modified sinusoidal modulation signals $s(t)$ with a single triangular carrier signal $c(t)$ as shown in Figure 3.1. These modified modulation signals have the same frequency (f_o) and amplitude (A_m). Since the modulation is symmetric, the sinusoidal modulation signals are sampled by the triangular carrier signal once in every carrier cycle. The carrier signal is a train of triangular waveform with frequency f_c and amplitude A_c

Intersection between the sampled modulation signals and the carrier signal defines the switching instant of the PWM pulses. In order to ensure quarter wave symmetry PWM output waveform, the starting point of the modulation signals ought to be phase shifted by one period of the carrier wave. Furthermore the modulation ratio must be even number. The number of modulation signals needed is equal to the number of modules (M) in the MSMI.



Legend
a. Carrier signal $c(t)$
b. Absolute sinusoidal modulation signal $m_1(t)$
c. Modified sinusoidal modulation signal $s_1(t)$ of $m_1(t)$
d. Shifted absolute sinusoidal modulation signal $m_2(t)$
e. Modified sinusoidal modulation signal $s_2(t)$ of $m_2(t)$

Fig. 2: The modified sinusoidal modulation signals and a single carrier signal.

For an N-level inverter, the amplitude modulation index, m_a is defined as:

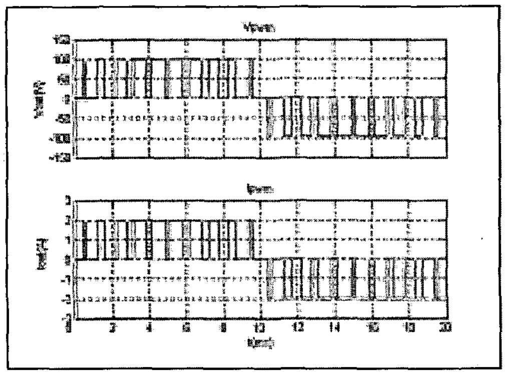
$$m_a=\frac{A_m}{\frac{(N-1)}{2}A_c} \qquad (2)$$

Therefore if A_c defined at a fixed p.u (1p.u), then m_i ranges between 0 and 1, while A_m ranges between 0 and M. The definition of the modulation ratio m_f for multilevel inverter is similar with a conventional two-level output inverter, i.e.

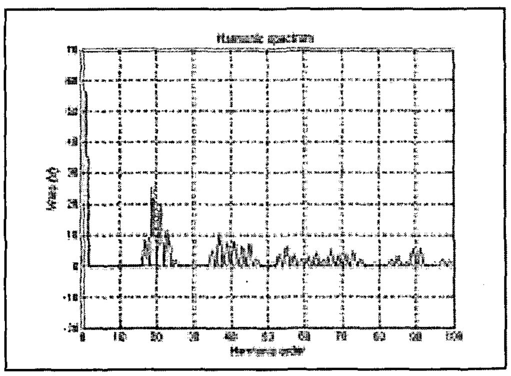
$$m_f = \frac{f_c}{f_o} \qquad (3)$$

VI. Simulation of Inverter System

To obtain an insight on the proposed modulation scheme, a MATLAB simulation was carried out. The 5-level MSMI system is simulated using SIMULINK, which is a simulation interface provided by MATLAB. It is assumed that the dc voltage input to each module is E = 100V, the output voltage fundamental frequency f_o = 50Hz and the carrier frequency, f_c = 1kHz (m_f = 20). While the inverter load is a pure resistive loading unit. Fig. 3 and 4 shows the output voltage, current voltage and frequency spectrum of 5-level MSM VSI for m_a = 0.4 and m_a = 0.8 respectively.

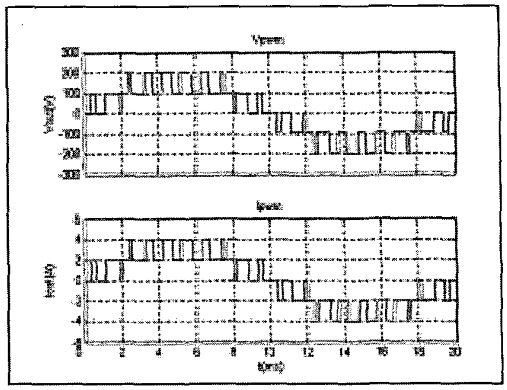


(a)

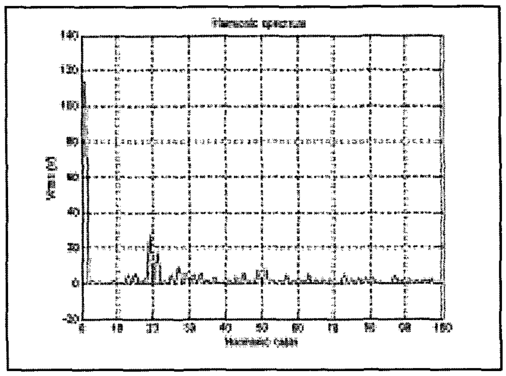


(b)

Fig. 3: MATLAB simulation for a 5-level inverter using the proposed PWM technique (a) output voltage and current, (b) frequency spectrum for m_a = 0.4 and m_f = 20.



(a)



(b)

Fig. 4: MATLAB simulation for a 5-level inverter using the proposed PWM technique (a) output voltage, (b) frequency spectrum for m_a = 0.8 and m_f = 20.

V. Derivation of Switching Angles

It is desirable to obtain mathematical expressions that define the switching instants for the inverter switches. From the simulation carried out, it was found that simple equations could be developed from the proposed modulation scheme. The equations could be use to generate the PWM pulses on-line using digital technique.

The idea of mathematical derivation is to determine the point of intersection between single carrier and the sampled modulation signals. Referring to Fig. 2, the single carrier and two set of sampled modulation signals in generating five-level inverter output voltage for m_a = 0.8, m_f = 20. Due to symmetrical nature of the proposed PWM scheme, the intersection between the positive slope carrier $c_k^+(t)$ and the modulating signals is not required in the derivation. It can be deduced from the rising edge equation. While, the straight-line equation for the carrier wave is denoted by $c_k^-(t)$ for the negative slope. It can be expressed as:

$$c_k^{'}(t)=\left(\frac{-A_c}{\frac{T_c}{2}}\right)\alpha_k+hA_c \qquad k=1,2,3.... \text{ and } h=1,3,5.... \tag{4}$$

The modulation signals can be described as

$$s_{1k}(t)=A_m\sin\left[\omega(i)+\frac{\pi}{m_f}\right];\quad s_{2k}(t)=A_m\sin\left[\omega(i)+\frac{\pi}{m_f}\right]-A_c \tag{5}$$

$i=0,1,2,3....\rightarrow$ when intersect with $c_k^{'}(t)$

Where the angular frequency ω, in (5) is

$$\omega = 2\pi f_o \times \frac{T_o}{m_f}=\frac{2\pi}{m_f}$$

After some mathematical manipulation and simplification, the switching instant for *kth* pulse of N-level can be written as:

$$\alpha_{kM}=\frac{T_c}{2}\left[(h+\mathrm{M}-1)-\frac{A_m}{A_c}\sin\left(\omega(k-1)+\frac{\pi}{m_f}\right)\right]$$
$$=\frac{T_c}{2}\left[(2k+\mathrm{M}-2)-\frac{A_m}{A_c}\sin\left(\omega(k-1)+\frac{\pi}{m_f}\right)\right] \tag{6}$$

Where M = 1,2,3...and relationship between M and N for modular structured multilevel inverter is expressed by (1). Equation (6) is used to generate the PWM pulses using a microcontroller. The main advantage of (6) is that it avoids the problem of "level jumping" as described in [4].

VI. HARDWARE IMPLEMENTATION

A five-level MSI was prototyped to verify the equation and proposed method. Fig. 5 shows the flow chart of a low power test-rig, constructed to test the modular structured 5-level inverter. Generation gate pulses are done by a C167, the 16-bit microcontroller from Siemens. To implement the MSI with the selected switches configuration in table 1, the only additional hardware needed is a 14-pin ex-or IC before the pulses generated from microcontroller go through the gate-drive.

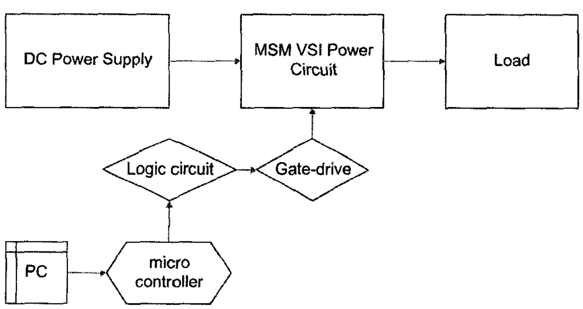
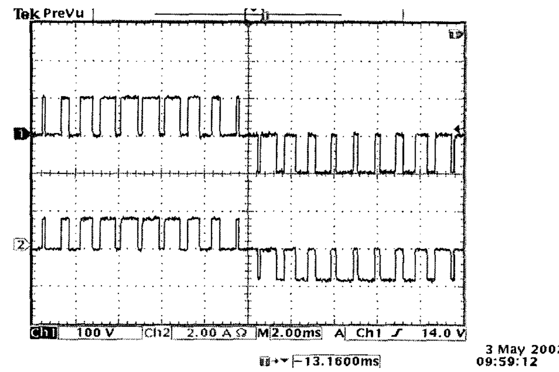
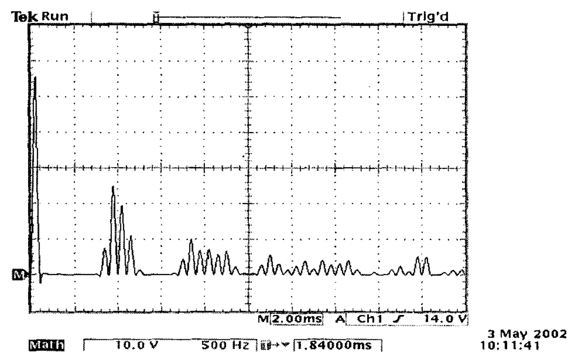


Fig. 5: Flowchart of test-rig to implement the MSM VSI

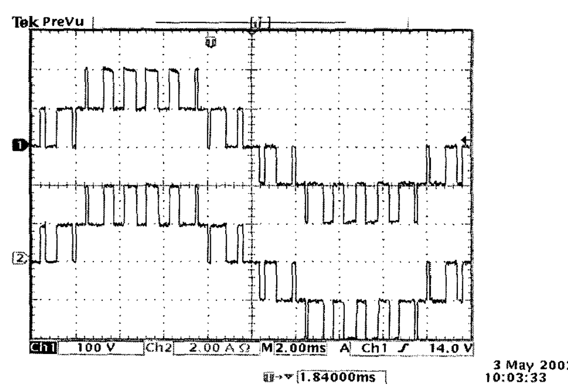


(a)

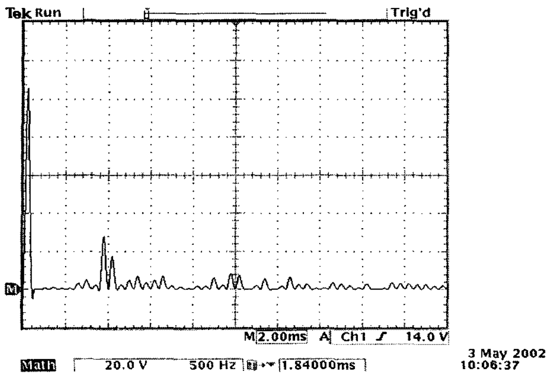


(b)

Fig. 6: Practical result of five-level MSI for $m_a = 0.4$; $m_f = 20$. (a) Top trace: Output voltage. Vertical scale 100V/div. Bottom trace: Output current. Vertical scale 2A/div. Horizontal scale 2ms/div. (b) Frequency spectrum. Vertical scale 10V/div. Horizontal scale 500Hz/div.



(a)



(b)

Fig. 7: Practical result of five-level MSI for $m_a = 0.8$; $m_f = 20$. (a) Top trace: Output voltage. Vertical scale 100V/div. Bottom trace: Output current. Vertical scale 2A/div. Horizontal scale 2ms/div. (b) Frequency spectrum. Vertical scale 20V/div. Horizontal scale 500Hz/div.

Figures 6 and 7 show the practical result for MSM VSI when $m_a = 0.4$ and $m_a = 0.8$ at $m_f = 20$. The figure shows that the practical result obtained from test-rig is in good agreement with the simulation result, which is shown in Fig. 3 and 4. It was found that only odd harmonic order is exists for the modulation scheme since the modulation ratio m_f is limited to even number. The positions of the harmonics depend on the modulation ratio. All the harmonics are shifted to high frequencies when the modulation ratio increased. The amplitude of each harmonic is depends on the modulation index, whereby the better harmonic performance can be obtained when modulation index get closer to 1.0. It also found that for the same modulation index, the harmonics amplitude of five-level inverter is half compared to three-level inverter.

VII. Conclusion

A single carrier multilevel modulation strategy based on the unipolar regular sampled PWM technique has been proposed for a MSMI. The scheme uses a single carrier with multiple modulating waveforms. The mathematical formulation to obtain the switching angles has been outlined. Using the derived equation, experimental results obtained give a good agreement with the simulation result. When m_a is less than 0.5 the inverter give 3 level output voltage, but when it greater than 0.5 the inverter will give five level output voltage. The frequency spectrum obtained from simulation and experimental shows that the switching strategy produces better harmonics than the conventional two-level inverter. It also found that the "level jumping" problem as described in earlier literature is absent.

References

[1] Ahmad Azli N. et al. "Regular Sampled PWM Switching Strategies for A Modular Structured Multilevel VSI", *Journal of Technology 1998*, Universiti Teknologi Malaysia, 1998. pp 1-8.

[2] Lai J.S and Peng F.Z. "Multilevel Converters – A New Breed of Power Converters", *Industry Applications Conf. 1995*. Thirtieth IAS Annual Meeting, IAS '95., Conference Record of the 1995 IEEE , Vol. 3 , 1995 pp: 2348 –2356.

[3] Agelidis V.G et al. "A Multilevel PWM Inverter Topology for Photovoltaic Applications", *Proc. of the IEEE Symposium on Industrial Electronic*, 1997 (ISIE '97), vol 2, pp. 589-594.

[4] A. Dell'Aquila et al. "Novel Multilevel PWM Inverter Implementation", *International Conf. on Industrial Electronics, Control and Instrumentation, 1997. IECON 97. 23rd,* Vol: 2 , pp. 710 – 715, 1997.

[5] Hinga P.K et al., "A New PWM Inverter for Photovoltaic Power Generation System", *Power Electronic Specialist Conf., (PESC '94) Record, 25th Annual IEEE*, pp. 391-395 vol 1: 1994.

[6] A. Schonung and H. Stemmler, "Static Frequency Changers with Subharmonic Control in Conjunction with Reversible Variable Speed AC Drives", *Brown Boveri Rev.*, 1964, pp. 555-557.

[7] Sydney R. Bowes, "New sinusoidal pulsewidth-modulated inverter", *Proceeding of IEE*, vol 122, no. 11, pp. 1279-1284, 1975.

[8] Enjeti P.N., Ziogas P.D and Lindsay J.F, "Programmed PWM Techniques to Eliminate Harmonics: A Critical Evaluation", *IEEE Trans. Industry Applications,* vol. 26 no. 2, pp. 302-316, 1990.

[9] S.R. Bowes and A. Midoun, "Microprocessor Implementation of New Optimal PWM Switching Strategies", *Electric Power Applications, IEE Proc. B* [see also IEE Proceedings-Electric Power Applications], Volume: 135, Issue :5, Sept.1988, Page(s): 269-280

[10] Boys, J.T.; Handley, P.G., "Harmonic analysis of space vector modulated PWM waveforms", *Electric Power Applications, IEE Proc. B* [see also IEE Proceedings-Electric Power Applications], Volume: 137 Issue: 4 , July 1990 Page(s): 197 –204

[11] Carrara G. et al., "A New Multilevel PWM Method; A Theoretical Analysis", *Power Electronics Specialist Conf, 1990. PESC '90 Record., 21st Annual IEEE*, pp 363-371.