Optimal Pulsewidth Modulation (PWM) Online Control of a Modular Structured Multilevel Inverter (MSMI)

N. Ahmad Azli, *Student Member, IEEE* and A. H. Mohd Yatim, *Member, IEEE*

Abstract-- **An inverter topology for high power applications that seems to be gaining interest lately is the modular structured multilevel inverter (MSMI). The switching frequency constraint in a MSMI with high isolated DC voltages calls for a low switching frequency modulator such as the optimal PWM switching strategies. This paper presents a different approach in controlling a MSMI output voltage based on the optimal PWM switching strategies. For better output voltage magnitude control resolution, a curve fitting technique (CFT) for online computation of the optimal PWM switching angles is proposed. Focus is given on the CFT and the multilevel design aspect of the proposed control strategy for the MSMI. Simulation and experimental results of the MSMI operation are given to verify its performance.**

Index Terms—**Inverter, multilevel systems, optimal control**

I. Introduction

An inverter topology for high voltage high power applications that seems to be gaining interest lately is the multilevel inverter. The main feature of a multilevel inverter is its ability to reduce the voltage stress on each power device due to the utilization of multiple levels on the DC bus. This is especially important when a high DC bus voltage is imposed by an application. There are several types of multilevel inverters but the one considered in this paper is the modular structured multilevel inverter (MSMI). The structure of the MSMI is not only simple and modular but also requires the least number of components compared to other types of multilevel inverters. This in turn, provides the flexibility in extending the MSMI to higher number of levels without undue increase in circuit complexity as well as facilitates packaging [1]. It must be realized however that an important requirement of the MSMI in applications involving real power transfer is DC sources that are isolated from one another. Thus, the MSMI topology is very much suitable for high power AC power supply applications particularly in power conditioning systems for alternate/renewable sources of energy such as PV arrays and fuel cells due to the originally isolated DC voltages that are available from these sources. To make an impact in future energy supply, it is inevitable for these energy sources to produce high DC voltages. The potential of the MSMI in high power UPS systems is also promising as future designs see the prospect of acquiring DC sources from fuel cells instead of batteries due to the indefinitely operation feature of the latter.

N. Ahmad Azli is with the Electrical Engineering Faculty, Universiti Teknologi Malaysia, UTM Skudai 81310 Johor MALAYSIA (e-mail: naziha@ fke.utm.my).

A. H. Mohd Yatim is with the Electrical Engineering Faculty, Universiti Teknologi Malaysia, UTM Skudai 81310 Johor MALAYSIA (e-mail: halim@ ieee.org).

In traditional two-level output inverters, it is a well-known fact that optimal PWM switching strategies offer several distinct advantages over the sinusoidal subharmonic natural PWM strategy. In particular, for the same amount of reduction in lower order harmonics, the effective switching frequency of an inverter employing optimal PWM switching strategies is greatly reduced when compared to the one using the sinusoidal subharmonic natural PWM strategy [2]. Hence, with this modulation strategy, despite operating at a lower switching frequency, high quality output voltage can still be achieved. This feature of the optimal PWM switching strategies can be exploited by the MSMI topology with high isolated DC voltages where gate turn off thyristors (GTOs) are typically employed with switching frequencies that are limited to a few hundreds Hertz due to the considerable switching losses associated with them [3].

A study of optimal precalculated switching patterns for the control of a generalized multilevel inverter in view of elimination of selected harmonics has been presented in [4]. The switching angles solutions trajectories of the proposed optimal PWM switching strategies for the multilevel inverter in this study exhibit discontinuities that are related to a change in sequence of the levels that increase with the number of switching angles per quarter cycle (N) chosen. To facilitate interpolation of the optimal PWM switching angles solutions, the discontinuities in the switching angles solution trajectories are eliminated by choosing suboptimal solutions which are based on local instead of global minima with moderate increase in the harmonic residuals as the trade-off.

A different approach in controlling a MSMI output voltage particularly for high power AC power supply applications based on the optimal PWM switching strategies without any problems related to discontinuities in the switching angles solution trajectories is proposed in this paper. This in turn facilitates the development of equations based on a curve fitting technique (CFT) that can be used to calculate the optimal PWM switching angles online in real time for better resolution of the MSMI output voltage magnitude control. The next section describes the circuit

0-7803-7233-6/01/$10.00 ©2001 IEEE.

topology and basic operation of the MSMI. This is followed by detail descriptions on the proposed online optimal PWM multilevel control strategy that is based on a CFT and a multilevel control design. Section IV provides some simulation and experimental results to verify the performance of the MSMI based on the proposed control strategy. Section V concludes the paper.

II. THE MSMI

A. Structure and Basic Operating Principle

Fig.1 shows the single-phase structure of a MSMI. It consists of (nl − 1)/2 single-phase H-bridge inverters referred to as MSMI modules, that are connected in series to generate an nl level output phase voltage. The MSMI output phase voltage is equal to the summation of the output voltages of the respective modules that is

$$Vo=V\text{-}M1+V\text{-}M2+........+V\text{-}Mm \quad (1)$$

where,
V-M1 : output voltage of module 1
V-M2 : output voltage of module 2
V-Mm : output voltage of the m^{th} module

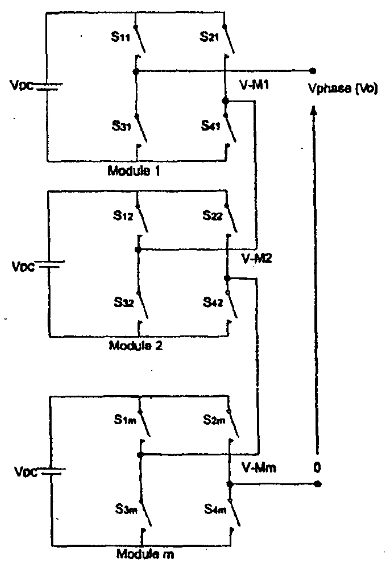


Fig. 1. Structure of a single-phase nl-level MSMI

Each MSMI module has its own DC source (V_{DC}) and consists of four power devices designated as S_{1m}, S_{2m}, S_{3m} and S_{4m} for the m^{th} module. Each MSMI module can generate a three-level output namely + V_{DC}, 0 and − V_{DC}. This is made possible by connecting the DC source sequentially to the AC side via the four power devices. Table I lists the output phase voltage with the corresponding switching states of power devices for a 5-level MSMI. For an output phase voltage consisting of 5 levels, which are $+2V_{DC}$, $+V_{DC}$, 0, $-V_{DC}$ and $-2V_{DC}$, the number of modules required in the MSMI is two.

Table I: Power devices switching states of a 5-level MSMI

Output voltages	S_{11} $(\overline{S_{31}})$	S_{21} $(\overline{S_{41}})$	S_{12} $(\overline{S_{32}})$	S_{22} $(\overline{S_{42}})$
+ 2E	**1**	**0**	**1**	**0**
+ E	1	0	0	0
+ E	**1**	**0**	**1**	**1**
+ E	0	0	1	0
+ E	1	1	1	0
0	0	0	0	0
0	**1**	**1**	**1**	**1**
0	1	0	0	1
0	0	1	1	0
0	0	0	1	1
0	1	1	0	0
- E	0	1	1	1
- E	**0**	**1**	**0**	**0**
- E	1	1	0	1
- E	0	0	0	1
- 2E	**0**	**1**	**0**	**1**

As depicted from Table I, sixteen legal configurations of power devices switching states and output phase voltage levels are available for a 5-level MSMI. From the sixteen configurations available, only five are needed for the MSMI operation. The availability of output phase voltage redundancies in a MSMI as indicated by Table I have shown to be advantageous in improving its performance [3],[5],[6]. This feature of the 5-level MSMI however is not taken into consideration in this paper; although it can be included in future work. Instead, only five power devices switching configurations as required for the MSMI operation are selected as shown boldfaced in Table I to allow for the implementation of a hybrid PWM switching arrangement [7]. This switching arrangement is introduced to enhance the ability of the proposed control strategy in complying with the limitations in the switching frequency of the power devices due to the high DC link voltages imposed on the MSMI.

B. The Hybrid PWM Switching Arrangement

Based on the hybrid PWM switching arrangement, any pair of the four power devices in each MSMI module is pulsewidth-modulated at a relatively high frequency while the other pair is commutated at a low output voltage fundamental frequency to reduce switching losses. In this paper, S_{1m} and S_{3m} are assigned the role of the slow switching power devices while S_{2m} and S_{4m} take the role of high switching power devices, where m = 1 and 2 respectively. Since the former are switched at a low frequency, their switching losses are greatly reduced.

III. ONLINE OPTIMAL PWM MULTILEVEL CONTROL STRATEGY

A. Online Optimal PWM Switching Strategies

In implementing the optimal PWM switching strategies for a 5-level MSMI, each module's output is represented by a generalized quarter-wave symmetric PWM waveform of a single-phase H bridge inverter based on the unipolar PWM switching scheme as shown in Fig. 2.

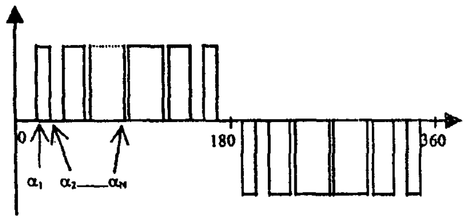


Fig. 2. A generalized quarter-wave symmetric PWM waveform.

Elimination of the lower order harmonics of the MSMI output voltage is considered as the performance criterion in the optimal PWM switching strategies. Owing to the symmetries in the generalized PWM waveform representing each module's output as shown in Fig. 2, only odd harmonics exist and their Fourier coefficients are given by [2]

$$a_n = \frac{4}{n\pi}\left[\sum_{k=1}^{N}(-1)^{k+1}\cos(n\,\alpha_k)\right] \tag{1}$$

$$b_n = 0 \tag{2}$$

where n is the harmonic order and α_k is the= k^{th} switching angle. Based on the chosen performance criteria, (1) can be solved for N variables α_1 to α_N by equating any N-1 harmonics to zero and assigning a specific value to the amplitude of the fundamental of module 1's output in per unit value (ap1-M1) and the amplitude of the fundamental of module 2's output in per unit value (ap1-M2). As N for the generalized PWM waveform representing each module's output are the same, (1) is solved once by equating any N-1 harmonics to zero and assigning values between 0 to 1 to ap1-M that is defined in general as the amplitude of the fundamental of each module's output in per unit value. As the non-linear equations for the switching angles in the optimal PWM switching strategies are transcendental in nature and incorporate periodic trigonometric terms, more than one set of solutions usually exist. A set of solutions for the switching angles satisfying the criterion

$$\alpha_1<\alpha_2<\alpha_3<\_\_\_\_\alpha_N<\pi/2 \tag{3}$$

have to be obtained for each increment in ap1-M to provide for output voltage control with simultaneous elimination of lower order harmonics for the MSMI. The non-linear equations to eliminate N-1 lower order harmonics such as 3,5,7 etc. are in the form of [2]

$$\begin{bmatrix} \cos\alpha_1 & -\cos\alpha_2 & \cdots\cdots\cdots(-1)^{N+1}\cos\alpha_N \\ \cos 3\alpha_1 & -\cos 3\alpha_2 & \cdots\cdots\cdots(-1)^{N+1}\cos 3\alpha_N \\ \vdots & & \\ \cos(x)\alpha_1 & -\cos(x)\alpha_2 & \cdots\cdots\cdots(-1)^{N+1}\cos(x)\alpha_N \end{bmatrix} = \begin{bmatrix} \frac{\pi(ap1-M)}{4} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{4}$$

where x = 2N − 1.The optimal PWM switching angles solutions are found by solving these non-linear equations using the routine C05NBF from the Numerical Algorithms Group (NAG) Foundation Library that are made accessible from MATLAB NAG Foundation Toolbox. With proper set up of the non-linear equations in the routine and initial starting values of the switching angles, a set of solutions can be obtained for varying ap1-M. Due to the constraint imposed on the switching frequency of the power devices in the MSMI, N is chosen to be 8. This value seems to constitute a sensible trade-off between the quality of the output voltage and the efficiency of the MSMI. With N = 8, seven lower order harmonics in each MSMI module's output voltage which are 3,5,7,9,11,13 and 15 are eliminated. Fig. 3 illustrates the respective switching angles solutions trajectories for N=8. It can be depicted from this figure that although the switching angles solutions trajectories may appear to be linear over a wide range of ap1-M, they are in fact non-linear in nature particularly at the upper and lower end of the solutions trajectories

To allow for online real time calculation of the optimal PWM switching angles for the MSMI, a curve fitting technique (CFT) is adopted due to the curvilinear or non-linear feature of the switching angles solutions trajectories. The CFT involves accurate representation of each of these trajectories, by equations in terms of ap1-M. MATLAB's curve fitting function based on polynomial regression is found to be an adequate tool to best approximates these trajectories. In this case, each trajectory is modeled by a polynomial equation in the form of

$$\alpha_k=a_0+a_1[(ap1\text{-}M)]+a_2[(ap1\text{-}M)^2]+\ldots..a_y[(ap1\text{-}M)^y] \tag{5}$$

where y is the polynomial order. The unknown coefficients (a_0, a_1, a_2 ….. a_y) are computed by doing a least square fit which minimizes the sum of squares of the deviations of the data which in this case is the values of α_k corresponding to each ap1-M. To further improve the accuracy of the equation and to reduce y, each switching angles solutions trajectory is represented by two equations with only one being utilized at a time depending on ap1. Results obtained from a comparison study between the actual optimal PWM switching angles solutions obtained from the numerical method routine and the solutions calculated using the equations based on (5) for all ap1-M show accuracies that range from about 99.7% to 100%.

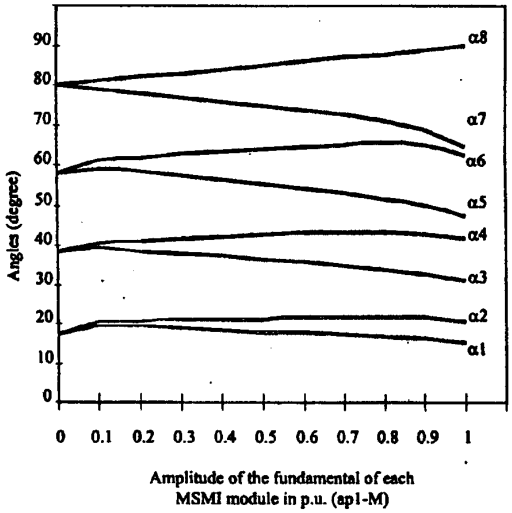


Fig. 3. Switching angles solutions trajectories for N=8

Based on the hybrid PWM switching arrangement, only two of each MSMI module's power devices are pulse width modulated at a higher switching frequency, which is given by [2]

$$f_{dsw} = (N + 1)\,f \qquad (6)$$

where f is the MSMI operating frequency. Thus for N = 8, the switching frequency of the two power devices as previously specified for each MSMI module is only 450 Hz, which conforms to the low switching frequency requirement for high DC side voltage application. The order of the first and second significant harmonic component in the MSMI output voltage is given by [2]

$$D_1 = 2N + 1 \qquad (7)$$

$$D_2 = 2N + 3 \qquad (8)$$

B. Multilevel Control Design

Each module of the MSMI is designed to eliminate a number of specified lower order harmonics with its output voltage fundamental peak value contributing to a certain percentage of the total MSMI output voltage fundamental peak value (V_{o1} (peak)). This means that variations in the amplitude of the fundamental of a 5-level MSMI output phase voltage in per unit value (ap1) actually represents the variations in ap1-M1 and ap1-M2. The multilevel control design aspect of the proposed online optimal PWM multilevel control strategy, which depends on the MSMI output phase voltage levels, determines the percentage of V_{o1}(peak) contributed by each module. In general, for each module employing the optimal PWM switching strategies, the maximum obtainable output voltage V-Mm (peak); is one per unit for a one per unit DC voltage supplied to it This means that if the DC voltage supplied to each module is V_{DC}, the maximum of its PWM output voltage is V_{DC} as well. Based on the online optimal PWM multilevel control strategy, while the lower order harmonics elimination is achieved, the 5-level MSMI output voltage may not exhibit a 5-level PWM waveform. This situation occurs when each module is designed to contribute the same percentage of V_{o1} (peak).

In a MSMI, the multilevel characteristic is in fact an advantage as it actually increases the effective switching frequency of the MSMI output phase voltage, which is also the switching frequency of the input to the controller, as nl increases. This implies that although the power devices switch at low switching frequencies, the switching frequency of the control input can be several times higher depending on nl and the multilevel control design of the MSMI. Thus, to maintain the multilevel characteristics of the MSMI, the multilevel control aspect of the proposed control strategy is designed as shown in Table II. In this multilevel control design, ap1-M1 is given the flexibility to vary between 0 and 1, while ap1-M2 is set to either be in full operation (ap1-M2 = 1) or not in operation at all (ap1-M2 = 0), depending on the required ap1. It can be seen in Table II that the MSMI operation depends mostly on module 1 except when ap1 is greater than 0.5 where by module 2 is also in operation. In other words, the MSMI output voltage exhibits a five-level PWM waveform only when ap1 is greater than 0.5 and less than 1. Otherwise, a three-level output voltage PWM waveform is generated. This way, although eight power devices are required in the 5-level MSMI topology, not all of them are fully utilized in the inverter operation.

Table II: The Proposed Multilevel Control Design for a 5-level MSMI

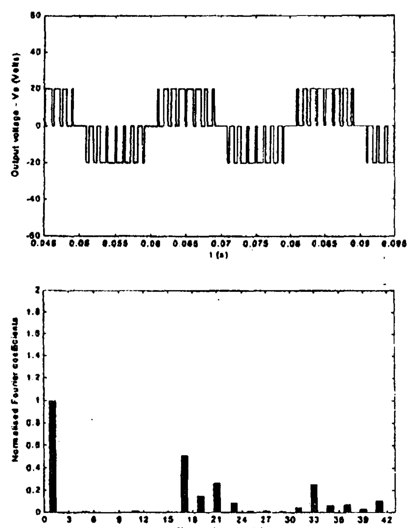
V_{o1} (peak) (V)	ap1	V_1-M1 (peak) (V)	ap1-M1	V_1-M2 (peak) (V)	ap1-M2
0	0	0	0	0	0
0.2 V_{DC}	0.1	0.2 V_{DC}	0.2	0	0
0.4 V_{DC}	0.2	0.4 V_{DC}	0.4	0	0
0.6 V_{DC}	0.3	0.6 V_{DC}	0.6	0	0
0.8 V_{DC}	0.4	0.8 V_{DC}	0.8	0	0
V_{DC}	0.5	V_{DC}	1	0	0
1.2 V_{DC}	0.6	0.2 V_{DC}	0.2	V_{DC}	1
1.4 V_{DC}	0.7	0.4 V_{DC}	0.4	V_{DC}	1
1.6 V_{DC}	0.8	0.6 V_{DC}	0.6	V_{DC}	1
1.8 V_{DC}	0.9	0.8 V_{DC}	0.8	V_{DC}	1
2 V_{DC}	1	V_{DC}	1	V_{DC}	1

The power devices in module 2, which are S_{22} and S_{42}, are allowed to "rest" when ap1 is less than or equal to 0.5 so that they are able to absorb higher switching losses when ap1 is greater than 0.5 where by ap1-M2 is set as 1. S_{12} and S_{32} on the other hand, are already set to switch at the output voltage fundamental frequency based on the hybrid PWM switching arrangement.

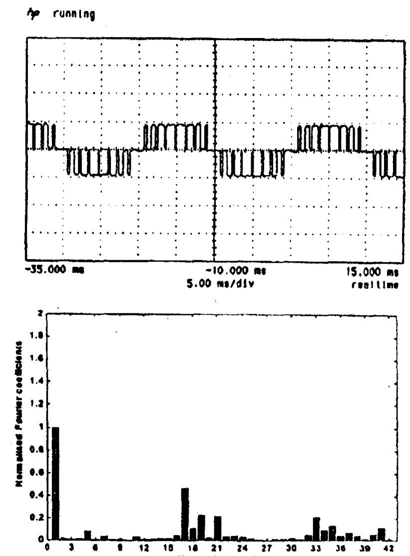
IV. SIMULATION AND EXPERIMENTAL RESULTS

To show the performance the MSMI based on the online optimal PWM multilevel control strategy, a simulation study is carried out using MATLAB's Simulink. A low power proof-of-concept prototype of the MSMI is also constructed with the online optimal PWM multilevel control strategy based on the CFT implemented using a DS1102 controller board. This controller board is based on a Texas Instruments TMS320C31 floating-point DSP, which builds the main processing unit, providing fast instruction cycle time for numeric intensive algorithm [8] The board interfaces to the host, which in this case is a personal computer, via a standard PC/AT interface bus. The DC voltage supplied to each MSMI module is set at V_{DC} = 20 V for both the simulation and experimental work. Using the DS1102 controller board to generate the MSMI gating signals, the lowest sampling time achievable by the DSP is 100 µsec, which corresponds to a 1.8° resolution for the switching angles. This results in some missing pulses particularly for lower ap1 values where by there exist pulse widths that are less than one sampling interval.

Fig. 4 and Fig. 5 show the PWM pattern and harmonic spectrum of the simulated and experimental MSMI output voltage for ap1 = 0.4 and 0.7 respectively that represent the tests on the capability of the CFT based equations to calculate the optimal PWM switching angles at the primary ap1-M values. Similar results are given by Fig. 6 for ap1 = 0.78 that represents the tests at the non-primary ap1-M values.

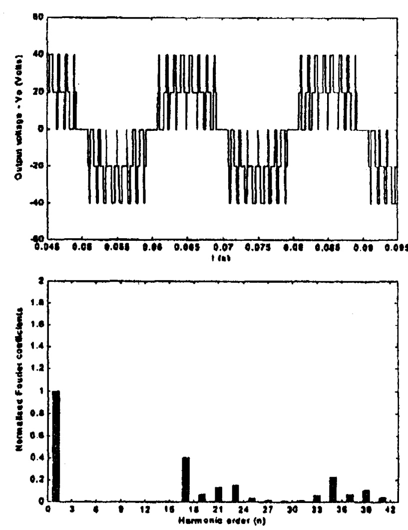


(a)

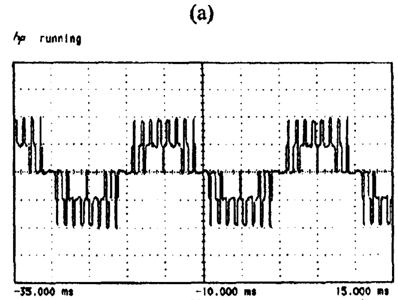


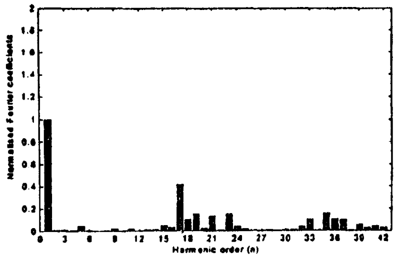
(b)

Fig. 4. PWM waveform and harmonic spectrum of the 5-level MSMI output voltage (V_o) for ap1 = 0.4 (a) simulation (b) experimental



(a)



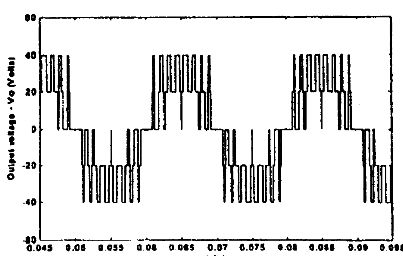


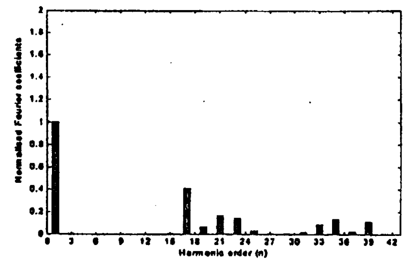
(b)

Fig. 5. PWM waveform and harmonic spectrum of the 5-level MSMI output voltage (V_o) for ap1 = 0.7 (a) simulation (b) experimental

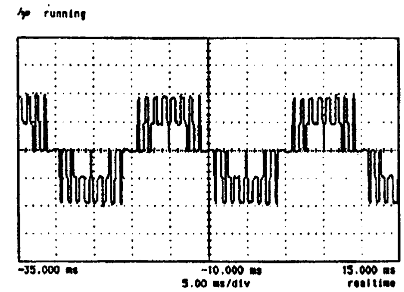
The PWM waveforms of the 5-level MSMI output voltages from both the simulation and experimental results for ap1 = 0.4 and ap1 = 0.7 show three-level waveforms and five-level waveforms respectively. These results reflect the multilevel control design aspect of the proposed optimal PWM multilevel control strategy as described earlier. From the simulation results of Fig. 4(a) and 5(a), it is evident that the lower order harmonics of the 5-level MSMI output voltage are eliminated with the first dominant harmonic being the 17^{th}, which is in accordance to the theoretical study. This confirms the ability of the equations obtained from the CFT to exactly calculate the optimal PWM switching angles at any of the primary ap1-M values The experimental results of Fig. 4(b) and Fig. 5(b) exhibit similarities to the simulation results although a combination of reduced and elimination of the lower order harmonics is noticed. Some even order harmonics are detected in both the harmonic spectrums of the 5-level MSMI output voltage particularly those above the first dominant harmonic. This is most probably due to the inadequacy in the timing resolution achievable by the DSP that affects the supposing quarter-wave symmetric properties of the MSMI output voltage waveform.

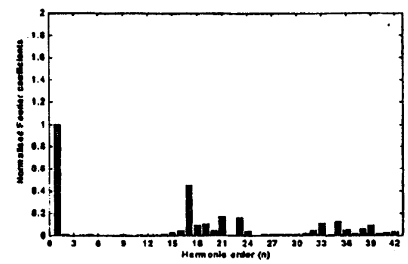
The results of Fig. 6 show that the equations based on the CFT are also capable of calculating the optimal PWM switching angles at other than the primary ap1-M values. This indicates that with the proposed online optimal PWM multilevel control strategy, better resolution in the control of the MSMI output voltage magnitude can be achieved.





(a)





(b)

Fig. 6. PWM waveform and harmonic spectrum of the 5-level MSMI output voltage (V_o) for ap1 = 0.78 (a) simulation (b) experimental

V. CONCLUSIONS

Optimal PWM online control of a 5-level MSMI output voltage has been presented. The proposed implementation of the optimal PWM switching strategies for a 5-level MSMI that considers each module's output in accomplishing lower order harmonics elimination in the MSMI output voltage is not only simple and straight forward but also involve less complexities in terms of solving for the optimal solutions using the numerical method. In addition, considering the MSMI circuit topology for AC power supply application, only one set of non-linear equations need to be solved involving only one inequality constraint. With the proposed control strategy for the 5-level MSMI, similar to its structure, control of its output voltage is also modular in nature as the switching angles solution trajectories for each module are essentially the same. The participation of each module in producing the optimised MSMI output voltage however is determined by the multilevel design aspect of the control strategy. The proposed multilevel control design has allowed the development of the online optimal PWM switching strategies based on the CFT for the 5-level MSMI. This in turn, contributes to better resolution of the magnitude control of the MSMI output voltage as well as better output voltage quality. Thus allowing it to be used as a basis for online optimal PWM control of a MSMI output voltage for high power AC power supply applications.

REFERENCES

[1] F. Z. Peng, J. Lai, J. W. McKeever and J. VanCoevering, "A multilevel voltage-source inverter with separate DC sources for static var generation," *IEEE Transactions on Industry Applications*, vol. 32, no. 5, pp. 1130-1138, 1996.

[2] P. N. Enjeti, P.D. Ziogas and J.F. Lindsay, "Programmed PWM techniques to eliminate harmonics: A critical evaluation," *IEEE Transactions on Industrial Applications*, vol. 26, no. 2, pp.302-316, 1990.

[3] M. Marchesoni "High-performance current control techniques for applications to multilevel high-power voltage source inverters," *IEEE Transactions on Power Electronics*, vol.7, no. 1, pp. 189-204, 1992.

[4] G. Carrara, D. Casini, S. Gardella and R. Salutari, "Optimal PWM for the control of multilevel voltage source inverter," *The European Power Electronics Association*, pp. 255-259, 1993.

[5] D. Casini and M. Marchesoni, "Sliding mode multilevel control for improved performances in power conditioning systems," *IEEE Transactions on Power Electronics*, vol.10, no. 4, pp. 453-463,1995.

[6] L. M. Tolbert, F. Z. Peng and T. G. Habetler, " Multilevel PWM methods at low modulation indices," *IEEE Transactions on Power Electronics*, vol. 15, no. 4, pp. 719 – 725, 2000.

[7] R. Lai and K. D. T. Ngo, "A PWM method for reduction of switching loss in a full-bridge inverter," *IEEE Transactions on Power Electronics*, vol. 10, no. 3, pp. 326-332, 1995.

[8] dSPACE Gmbh, "Floating-Point Controller Board," Germany: DS1102 User's Guide, 1996.