A NOVEL TECHNIQUE FOR CONTROL OF CASCADED MULTILEVEL INVERTER FOR PHOTOVOLTAIC POWER SUPPLIES

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Abstract

Multilevel voltage source inverters offer several advantages compared to their conventional counterparts. By synthesizing the AC output terminal voltage from several levels of voltages, staircase wave forms can produced, which approach the sinusoidal wave form with low harmonic distortion, thus reducing filter requirements. The need of several sources on the DC side of the converter makes multilevel technology attractive for photovoltaic applications. The basic modulation techniques enable harmonic elimination by predetermination of the switching angles. This is determined according to a previously calculated and stored pulse width modulated waveform. It has the advantage of operating at fundamental frequency switching. However, this technique is seriously limited as the number of levels increases because of the increased complexity and the reduced accuracy of the non-linear solutions. This paper proposes a novel Multilevel PWM technique (phase-shifted sinusoidal PWM) to over come all these limitations while maintaining switching at fundamental frequency, found better THD. Simulation results are presented in the paper.

Introduction

A multi-level inverter is a power electronic system that synthesizes a desired voltage output from several levels of dc voltages as inputs. Several topologies for multi-level inverters have been proposed over the years; the most popular being the diode- clamped [1, 5], flying capacitor [1, 5] and cascaded H-bridge [1, 6] structure. Cascaded H-bridge inverter power circuit is simple and uses of least components among these three configurations. Also cascaded H-bridge is ideally suited for systems such as photovoltaic where isolated input dc source is available. Photovoltaic cells generate electric energy from solar energy. The electrical energy from the solar cells is dc form and it has to be stored and processed to required form to suite the load requirements. This can be achieved by cascaded H-bridge multilevel inverter.

Basic modulations techniques are used in multilevel power conversion applications are including multi-disposition PWM, stepped sine wave, and switching angle optimisation [2, 3, 4, 7]. Most of these methods use high frequency switching because it is the most effective at achieving the requirements. The problems associated with conventional PWM inverters are as follows

1. High dV/dt and voltage surge
2. High-frequency switching frequency will result in increased switching losses.
3. High-frequency switching generates Electro-Magnetic Interference (EMI)

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Control concept

The concept is similar to the single pulse width modulating technique. However, whereas the single pulse width modulating technique compares the carrier triangular wave with a fixed amplitude reference signal [8, 9], the novel technique compares the modulating sinusoidal wave with several fixed amplitude reference levels is shown in Fig-1.

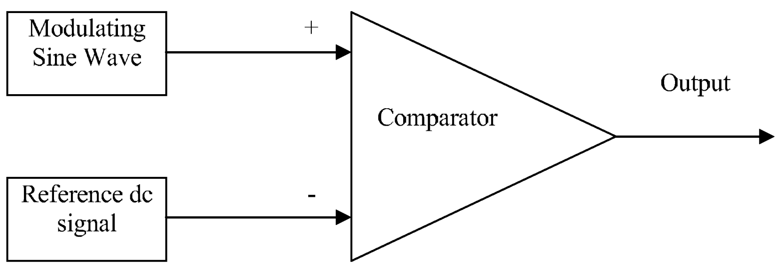

Fig.1: Controlling scheme

The fixed step reference signal and sinusoidal modulating wave is shown in Fig-2a. Note the difference in definitions for this technique. There is no carrier wave. As such, the amplitude modulating index is redefined as

$$ma = \frac{Vp}{Em} \qquad 1$$

where, Vp is the peak amplitude of the modulating sinusoidal wave,
and
Em is the total value of each individual steps, or the maximum dc value.

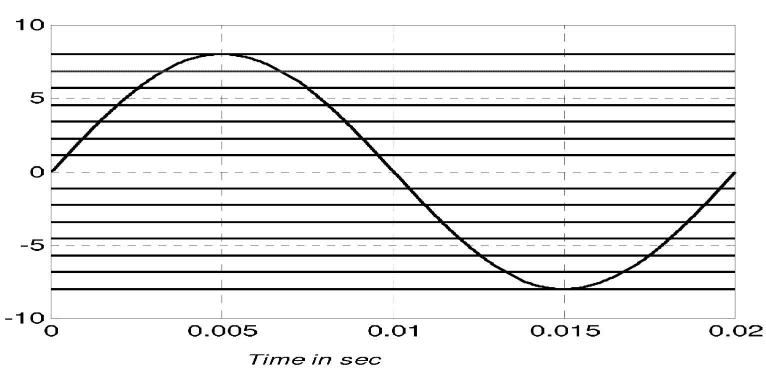

Fig-2a Control waveform with ma = 1

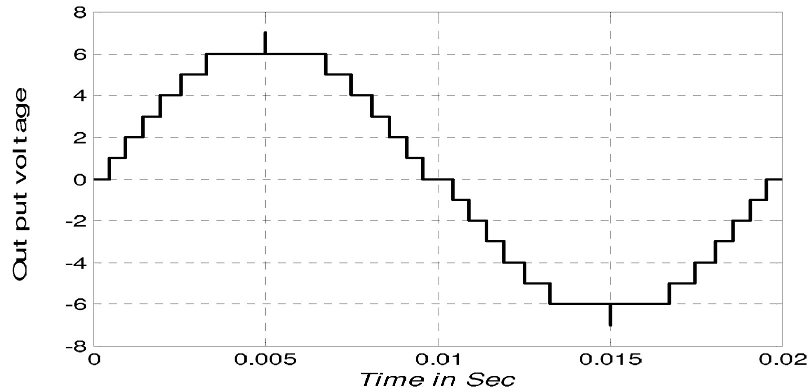

Fig.2b Output voltage for ma = 1

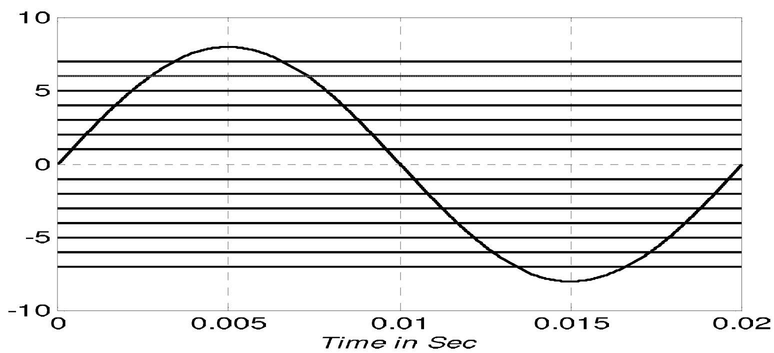

Fig-3a Control waveform with ma = 1.1

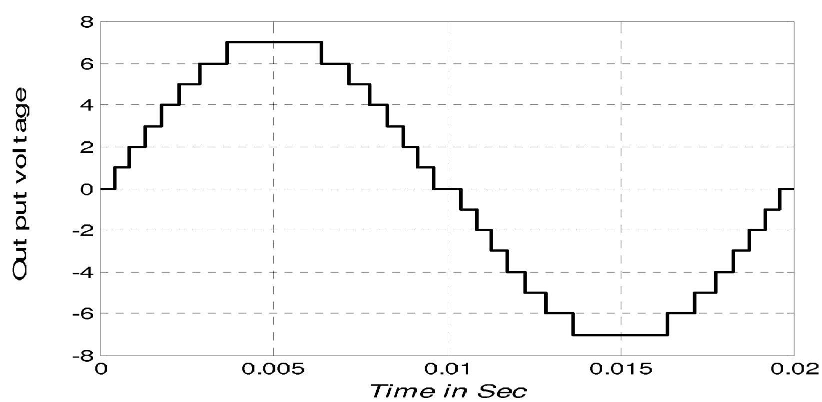

Fig-3b 15 level Output voltage at ma = 1.1

The Fig.2a and Fig.2b modulating index, ma = 1, the top level appears only as an impulse and does not contribute to the total output voltage. As such, to use all the voltage steps, a modulating index of greater than 1 is possible. Fig.3a and Fig.3b shows the control wave form and voltage output for a modulating index, ma = 1.1 for fifteen level inverter. The modulating index can thus theoretically be varied from 1 to infinity. However, practically, here will be voltage output only when the magnitude of the modulating sinusoidal waveform is greater than the incremental step voltage. Also the magnitude of the output voltage does not change appreciably for modulating index greater than1.5.

Harmonic analysis

The output voltage waveform exhibits half-wave odd symmetry. Hence, only the positive half-cycle need to be analyzed. The harmonic analysis is performed by first separating the intervals into its square wave components of equal magnitude but phase-shifted and perform the Fourier analysis on each component. The final harmonics will then be the sum of the individual harmonics for each component.

The formula used is

$$(Vo)h = \frac{4}{\pi h} Vd \sin(h\beta n) \qquad 2$$

where,

$(Vo)_h$=is the amplitude of the hth odd harmonics, V_d is the magnitude given by

$$Vd = \frac{Em}{S} \qquad 3$$

Em is the maximum dc input voltage, S is the number of DC input voltage is given by

$$S = \frac{m-1}{2} \qquad 4$$

m being the number of level of the converter

The duration of the pulse,

$$\beta n = \frac{\pi - \alpha n}{2} rad \qquad 5$$

Switching angle,

$$\alpha n = \sin^{-1}\left(\frac{nVd}{maEm}\right) \qquad 6$$

n being the nth level of the output voltage, and *ma* being the amplitude modulation index.

For the m-level converter, the harmonics are added up to give

$$(Voutput\ )h = \sum_{1}^{n} \frac{4}{\pi} VdSin\ (h\beta n) \qquad 7$$

From above equation, the total harmonic distortion (THD) is

$$\%THD = 100 * \sqrt{\sum_{3,5,7}^{\infty}\left[\frac{(Voutput)h}{(Voutput)1}\right]^2} \qquad 8$$

The most commonly used distortion index is the weighted total harmonic distortion (*WTHD*) [10] in which the inverter output voltage harmonics are weighted inversely with the harmonic frequency so as to approximate the current distortion in an inductive load. While it is the output voltage which is the quantity that is controlled in a voltage source/stiff inverter type system, it is the current which is frequently of most interest since losses, output power etc. typically involve this quantity rather than voltage directly. The *WTHD* is superior to the *THD* as a figure of merit for a non-sinusoidal converter waveform since the *WTHD* predicts the distortion in the current and subsequent additional losses which are typically the major issues in the application of such converters. Weighted total harmonic distortion (*WTHD*) becomes defined as

$$WTHD = \frac{\sqrt{\sum_{h=2}^{\infty}\left(\frac{Vh}{h}\right)^2}}{V1} \qquad 9$$

For photovoltaic application 15- level inverter is considered, harmonics of the output is analyzed and simulated using FFT block in simulink tool box of MATLAB5.3. For different modulating index, , *WTHD (%)* and *V rms* (pu) are plotted shown in Fig.4. From Fig it is observed that for *ma* 1.1 to 1.2, *WTHD* is less than 0.5% which is very much acceptable..

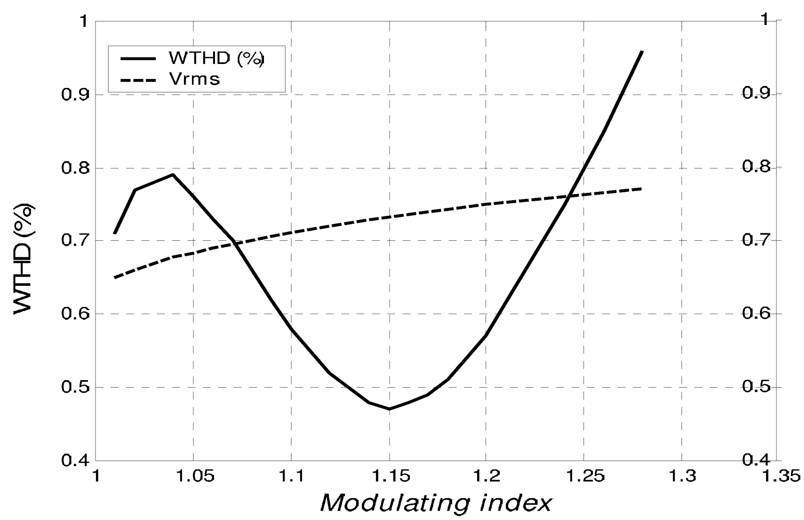

Fig-4 THD (%) in p u, Vrms (pu) V/s Modulating index (1 p u =326 V)

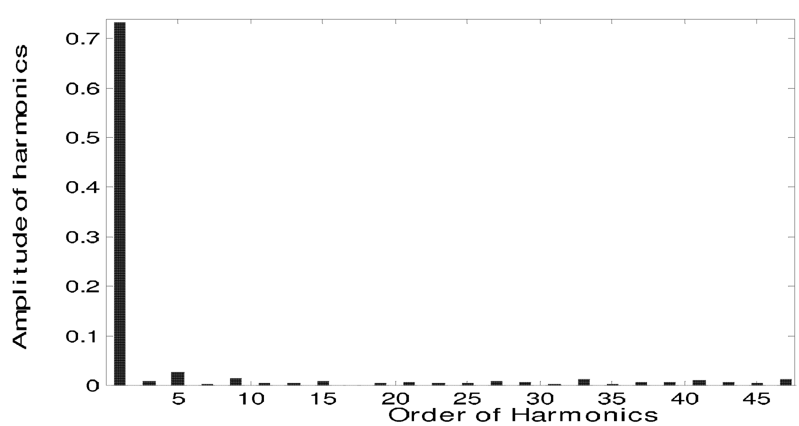

Fig-5 Harmonic spectra of fifteen level inverter for ma=1.15

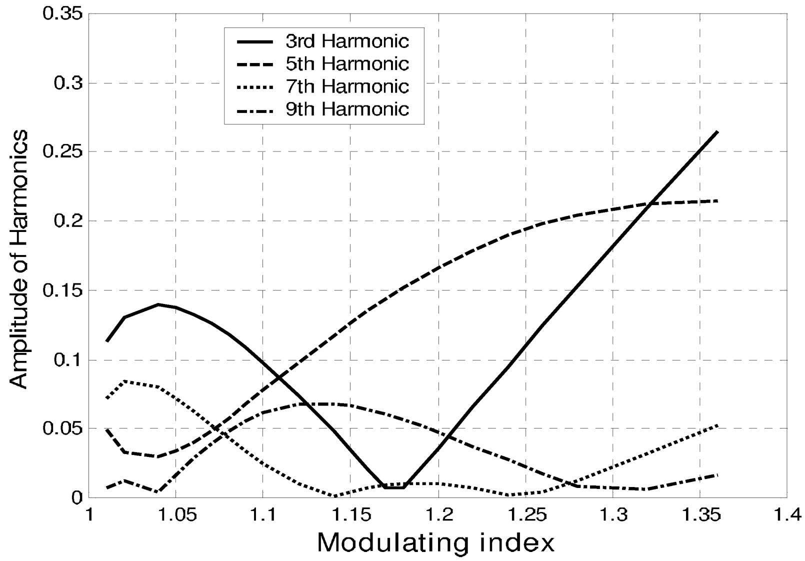

Fig.6a Amplitude of 3^{rd}, 5th, 7th, 9th harmonics in (pu)

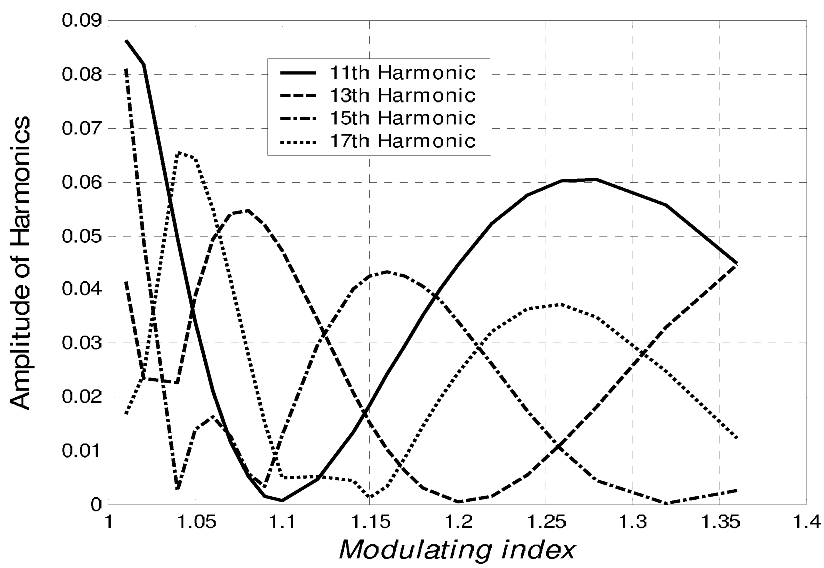

Fig.6b Amplitude of 11^{th}, 13^{th}, 15^{th}, 17^{th} harmonics in (pu)

For different modulating index Fig-6a and Fig.6b shows the variation of 3^{rd},, 5^{th}, 7^{th}, 9^{th}, 11^{th} ,13^{th},15^{th}, 17^{th} harmonic components of a 15 level inverter. It is observed that lower order odd harmonics is les than 10% of 1 (pu) which is very much acceptable. For modulating index 1.15 the harmonic spectra of phase voltage for the fifteen -level inverter is shown in Fig.5.

The switching angle is calculated for this novel technique using equation (6), for the Fifteen -level inverter with a modulating index of 1.15 switching angels are shown in table. I. Correspondingly duration of pulses are calculate using equation (5) shown in table. II. Individual harmonics are calculated for each level using equation (2). From equation.(7) and (8) the total harmonic distortion (THD) is calculated, for 15- level converter it is found to be 4.88%. Weighted THD of phase voltage is calculated using equation (9) for the proposed system for ma =1.15 WTH<0.5%

Table .I Switching angels

α_1	7.1808^0
α_2	14.4775^0
α_3	22.0243^0
α_4	30.0000^0
α_5	38.6822^0
α_6	48.5904^0
α_7	61.0450^0

Table .II Duration of pulses

$\beta 1$	172.8192^0
β_2	165.5225^0
β_3	157.9757^0
β_4	150.0000^0
β_5	141.3178^0
β_6	131.4096^0
β_7	118.9550^0

Results of harmonic analysis

The switching angles and THD for optimisation technique is taken from the reference [2, 3, 4, and 7] which is listed in the table. III. Harmonic analysis is performed for the novel technique for different levels for 2KVA, 0.866 p.f R-L load is used for the simulation. Simulation is performed using Simulink tool box in Mat Lab package. The switching angles and corresponding THD for 7 to 17 levels for novel technique are tabulated in table. IV.

Table .III Switching angle and THD for optimisation

Level	α1(°)	α2(°)	α3(°)	α4(°)	α5(°)	α6(°)	α7 (°)	α8(°)	THD(%)
7	11.50	28.72	57.11	--	---	---	--	--	8.17
9	9.84	20.38	38.41	60.42	---	---	---	--	6.26
11	6.57	18.94	27.18	45.14	62.24	---	---	--	4.81
13	6.38	15.61	23.25	33.94	49.89	63.24	---	--	4.04
15	7.22	13.07	20.84	27.75	39.13	54.53	62.72	--	3.47
17	7.38	11.85	16.93	24.44	30.84	41.85	59.29	59.29	2.98

Table .IV Switching angle and THD for novel technique

Level	α1(°)	α2(°)	α3(°)	α4(°)	α5(°)	α6(°)	α7 (°)	α 8 (°)	THD (%)
7	16.96	35.69	61.05	--	---	---	--	--	16.67
9	12.65	25.94	41.01	61.05	---	---	---	---	11.65
11	10.08	20.49	31.67	44.43	61.05	---	---	---	8.945
13	8.39	16.96	25.94	35.69	46.82	61.05	---	---	6.316
15	7.18	14.48	22.02	30.00	38.68	48.59	61.05	---	4.88
17	6.28	12.64	19.15	25.94	33.15	41.01	49.96	61.05	3.591

Comparison of results

Most important comparison must be the quality of the output from the converters; it is observed from Fig .7 that THD of phase shift (sinusoidal) is more than optimum method for the 7 to 17 level. But as the level increase the THD of proposed technique reduces, for 27 level THD (%) for both optimisation and novel technique will be equal. From literature it is found that as the level increases the results of optimum method is in accurate, more complex solving the non linear equations and the processor will remain in idle state. This Photovoltaic stand alone system is proposed for domestic loads for 230 V, 50 Hz supply in rural areas. The THD (%) is less than 5 % which is accepted. But one more index to measure the quality of wave from is the weighted THD shown in Fig. 8, which will measure the distortion and losses in current, which is very much essential in the inverter applications, for the proposed system it is found that WTHD (%) is < 0.5%. Another observation is that the output quality from the 15-level inverter using the sinusoidal wave modulation technique is comparable to that from the 11-level using sinusoidal technique inverter, having THD of 4.88% against 4.81% respectively. Since the normal acceptable THD is below 5%, the lowest number of levels required for the sinusoidal wave modulation technique is 1.15. When we consider WTHD (%) for fifteen -level inverter it less than .0.5% which is very much accepted.

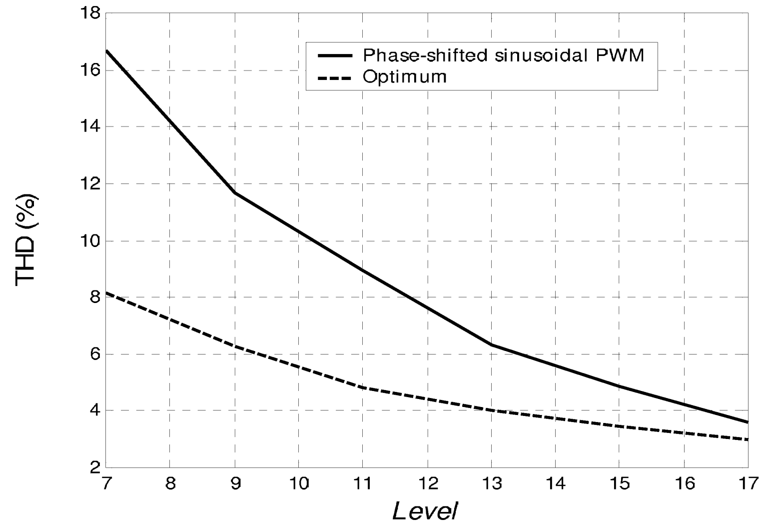

Fig .7 Comparisons of THDs for different levels

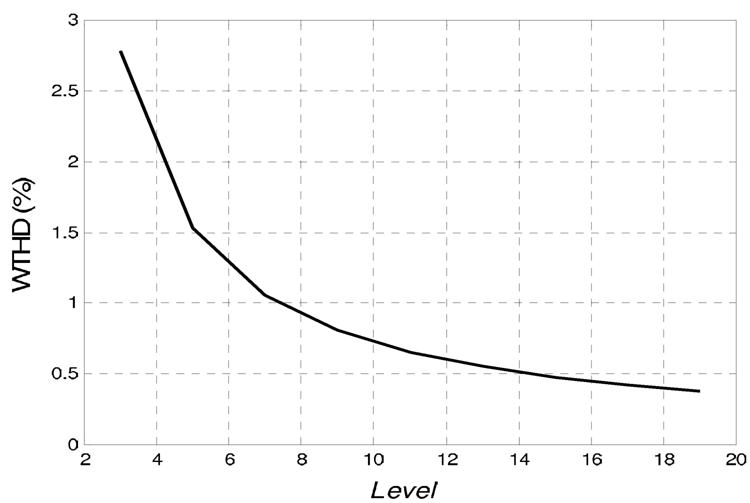

Fig .8 Weighted THDs for different levels

Conclusions

From the results of harmonic analysis performed, the following conclusions can be made:

- The output quality of the sinusoidal wave modulation technique improves with increasing levels.
- As the number of level increases, the output quality (THD) of the sinusoidal wave modulation technique approaches that of the optimisation technique.
- Using a quality standard of THD less than 5%, the minimum number of levels required for the sinusoidal wave modulation technique is 15 level

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