Stepped Multicarrier SPWM Techniques for Seven - Level Cascaded Inverter

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Abstract – In this paper, novel multicarrier pulse width modulation technique which uses stepped carrier waveform is proposed for seven-level cascaded inverter. In each carrier waveform different techniques such as phase disposition (PD), inverted phase disposition (IPD), phase opposition disposition (POD) and alternative phase opposition disposition (APOD) are implemented. The fundamental output voltage and harmonics obtained in each method are compared with the output waveform obtained with the triangular carrier waveform. The proposed switching technique enhances the fundamental component of the output voltage and improves total harmonic distortion. The different PWM methodologies adopting the constant switching frequency multicarrier with different modulation indexes are simulated for a 1kW, 3φ inverter using MATLAB/SIMULINK. The effect of switching frequency on the fundamental output voltage and harmonics are also analyzed.

Index Terms – Modulation Index (MI), Stepped Multicarrier SPWM (SMC SPWM), Total Harmonic Distortion (THD) and Triangular Multicarrier SPWM (TMC SPWM).

1. INTRODUCTION

The multilevel inverter is an effective solution for increasing power and reducing harmonics of ac waveform [1]. The elementary concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. The commutation of the power switches aggregate these multiple dc sources in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected [2].

In this paper, constant switching frequency multicarrier pulse width modulation method is used for the multilevel inverter [3]. The control objective is to compare the reference sine wave with multicarrier waves for three phase seven level cascaded inverters. Multilevel voltage source inverter (MVSI) structure is very popular especially in high power DC to AC power conversion applications. It offers several advantages that make it preferable over the conventional voltage source inverter (VSI). These include the capability to handle higher DC link voltage; the stress on each switching device can be reduced in proportional to the higher voltages [4]. Consequently, in some applications, it is possible to avoid expensive and bulky step-up transformer. Another significant advantage of a multilevel output is better sinusoidal voltage waveform. As a result, a lower total harmonic distortion (THD) is obtained [5], [6].

The concept of multilevel converter has been introduced since 1975 [7]. The term multilevel began with the three-level converter. Subsequently, several multilevel converter topologies have been developed, such as the Diode Clamped Multilevel Inverter (DCMLI) also known as Neutral Point Clamped (NPC) Inverter, Flying Capacitor Multilevel Inverter (FCMLI) and Cascaded Multilevel Inverter (CCMLI) [8], [9]. Among them, CCMLI topology is the most attractive, since it requires the least number of components and increases the number of levels in the inverter without requiring high ratings on individual devices and the power rating of the CCMLI is also increased. It also results in simple circuit layout and is modular in structure. Furthermore, CCMLI type of topology is free of DC voltage balancing problem, which is a common issue facing in the DCMLI and FCMLI topologies [10], [11].

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly [12]. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells can be easily interfaced to a multilevel converter system for high power application [13].

In motor applications, high dv/dt in power supply generates high stress on motor windings and requires additional motor

insulation. Further; high dv/dt of semiconductor devices increases the electromagnetic interference (EMI), common-mode voltage and possibilities of failure on motor [14], [15]. By increasing the number of levels in the output waveform, the switching dv/dt stress is reduced in the multilevel inverter [16], [17]. Multilevel inverters are suitable for power electronics applications such as flexible AC transmission systems, renewable energy sources, uninterruptible power supplies, electrical drives and active power filters.

2. CASCADED MULTILEVEL INVERTER

The single-phase structure of three phase seven-level cascaded inverter is illustrated in Figure 1. Each separate dc source is connected to a single-phase full-bridge, or H-bridge, inverter. Each inverter can generate three different outputs voltage level, $+V_{dc}$, 0 and $-V_{dc}$, by connecting the dc source to the ac output by different switching combinations of the four semiconductor switches S1, S2, S3 and S4. To obtain $+V_{dc}$, switches S1 and S2 are tuned on, whereas $-V_{dc}$ can be obtained by tuning on switches S3 and S4, By turning on S1 and S3 or S2 and S4, the output voltage is 0, The ac outputs of each of the full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs [18], [19].

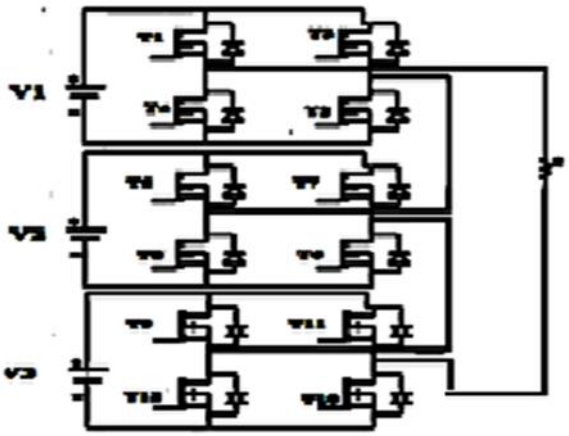

Figure 1 1φ structure of seven-level CCMLI

The CCMLI is producing seven level output and they are $3V_{dc}$, $2V_{dc}$, V_{dc}, 0, $-V_{dc}$, $-2V_{dc}$ and $-3V_{dc}$. This topology is suitable for applications where separate dc voltage sources are available, such as photovoltaic (PV) generators, fuel cells and batteries. The phase output voltage is generated by the sum of two output voltage of the full bridge inverter modules. The circuit in Figure1 utilizes three independent dc sources and consequently will create an output phase voltage with seven-level. In general, if N is the number of independent dc sources per phase, then the following relations apply [20]:

$$m = 2N + 1 \quad (1)$$

$$q = 2(m - 1) \quad (2)$$

Where m is the number of levels and q is the number of switching devices in each phase

The most well known SPWM which can be applied to a CCMLI is the Phase-Shifted SPWM. This modulation technique is the same as that of the conventional SPWM technique which is applied to a conventional single phase full-bridge inverter, the only difference being that it utilizes more than one carrier. The number of carriers to be used per phase is equal to twice the number of dc voltage sources per phase (2N) [21].

3. MODULATION TECHNIQUES

The Pulse Width Modulation (PWM) control strategies development tries to reduce the total harmonic distortion (THD) of the output voltage. Any deviation in the output voltage of the sinusoidal wave shape will result in harmonic currents in the load and this harmonic current produces the electromagnetic interference (EMI), harmonic losses and torque pulsation in the case of motor drives. Increasing the switching frequency of the PWM pattern reduces the lower frequency harmonics by moving the switching frequency carrier harmonic and associated sideband harmonics away from the fundamental frequency component [22]. This increased switching frequency reduces harmonics, which results in a lower THD with high quality output voltage waveforms of desired fundamental RMS value and frequency which are as close as possible to sinusoidal wave shape [23].

The carrier frequency defines the switching frequency of the converter and the high order harmonic components of the output voltage spectrum and the sidebands occur around the carrier frequency and its multiples. The higher switching frequency can be employed for low and medium power inverters, whereas, for high power and medium voltage applications the switching frequency should be low. Harmonic reduction can then be strictly related to the performance of an inverter with any switching strategy [24], [25]. The three phase multi level inverter requires three modulating signals or reference signals which are three sine-waves with 120 degree phase shift and equal in magnitudes. In this paper, new carrier based PWM techniques are developed which are as Stepped Multicarrier Sinusoidal PWM (SMC SPWM).

Each carrier is to be compared with the corresponding modulating sine wave [26], [27]. The reference or modulation waveform has peak amplitude A_r and frequency f_r and it is centered in the middle of the carrier set. The general principle of a carrier based PWM technique is the comparison of a sinusoidal waveform with a carrier waveform, this typically being a triangular carrier waveform. The reference is continuously compared with the carrier signal. If the reference is greater than the carrier signal, then the active device corresponding to that carrier is switched on, and if the reference is less than the carrier signal, then the active device

corresponding to that carrier is switched off [28], [29]. In multilevel inverters, the amplitude modulation index, M_a and the frequency ratio, M_f are defined as,

$$M_a = \frac{A_r}{(m-1)A_c} \quad (3)$$

$$M_f = \frac{f_c}{f_r} \quad (4)$$

Where A_r and A_c are amplitude of reference and carrier signal respectively. f_r and f_c are frequency of reference and carrier signal respectively.

In this paper, modulation indexes used are 0.7, 0.8, 0.9 and 1 for seven-level CCMLI. For multilevel applications, carrier based PWM techniques with multiple carriers are used. The Multicarrier Modulation (MCM) techniques can be divided in to the following categories such as [30], [31],

1. Phase disposition (PD) where all the carriers are in phase.
2. Inverted phase disposition (IPD) where all the carriers are in phase and is inverted.
3. Phase opposition disposition (POD) where the carriers above the zero reference are in phase but shifted by 180 degrees from those carriers below the zero reference.
4. Alternative phase opposition disposition (APOD) where each carrier band is shifted by 180 degrees from the adjacent carrier bands [2].

The above modulation strategies are implemented for stepped carrier wave. The phase voltage and line voltage waveform, harmonic spectrums of the line voltage are shown for different modulation techniques by doing simulation using MATLAB/SIMULINK for seven-level CCMLI and the results obtained are compared.

3.1. Triangular Multicarrier Sinusoidal PWM (TMC SPWM)

The performance of the multilevel inverter is based on the multicarrier modulation technique used. Two-level to multilevel inverters are made using several triangular carrier signals and one reference signal per phase. Carrara [5] developed multilevel sub harmonic PWM (SH-PWM), which is as follows, for m-level inverter, m-1 carriers [32] with the same frequency f_c and same amplitude A_c are disposed such that the bands they occupy are contiguous. They are defined as

$$C_i = A_c\left((-1)^{f(i)} y_c(\omega_c, \varphi) + t - \frac{m}{2}\right), \quad i = 1, \ldots\ldots (m-1) \quad (5)$$

Where y_c is a normalized symmetrical triangular carrier defined as,

$$y_c(\omega_c, \varphi) = (-1)^{[\alpha]}((\alpha \bmod 2) - 1) + \frac{1}{2} \quad (6)$$

$$\alpha = \frac{\omega_c t + \varphi}{\pi}, \omega_c = 2\pi f_c \quad (7)$$

φ represents the phase angle of y_c. y_c is a periodic function with the period $T_c = \frac{2\pi}{\omega_c}$. It is shown that using symmetrical triangular carrier generates less harmonic distortion at the inverters output [33], [34]. The carrier waveforms, output voltage waveforms and %THD chart are shown only for selected PWM techniques in order to restrict the number of figures.

In TMC SPWM, so far only the PD, POD and APOD techniques are discussed earlier in the literature. In this paper, IPD scheme is also applied to TMC SPWM and it is found that this scheme gives the lowest THD among the TMC SPWM schemes. The multicarrier modulation techniques such as PD, IPD, POD and APOD are implemented using triangular multicarrier signals for seven-level CCMLI with different modulation indexes and are shown in Figure 2(a) and 2(b) respectively.

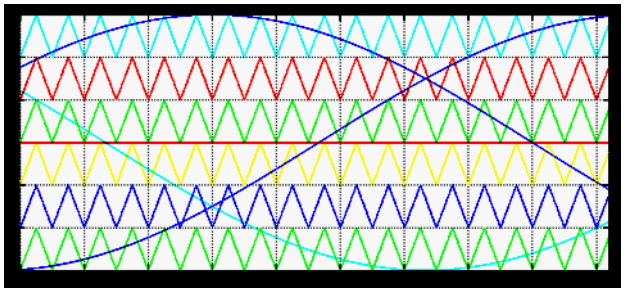

Figure 2(a) PD TMC SPWM with $M_a = 1$

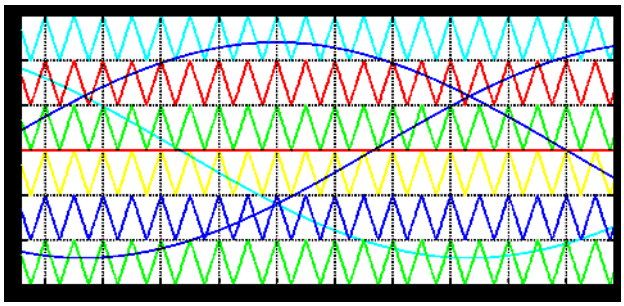

Figure 2(b) IPD TMC SPWM with $M_a = 0.8$

3.2. Stepped Multicarrier Sinusoidal PWM (SMC SPWM)

The Stepped wave is also known as approximated or modified sine wave, refers to a sine wave that instead of looking like a smooth curve where the wave gradually ramps up and down over the course of the cycle, there are a series of "steps" or jumps in wave from one plateau to another. The simulink block provides a step between two definable levels at a specified time. Each cycle constitutes eight steps. Every step is equal in

magnitude and in time. At the beginning and ending of the cycle, the signal has magnitude zero and retains for half the value of the one step time period. The angle of each step is φ which is given by.

$$\varphi = \frac{360^{\circ}}{n_S} \quad (8)$$

Where n_s is the number of steps in one cycle, since $n_s = 8$ the angle for each step is 45^0.

The multicarrier modulation techniques such as PD, IPD, POD and APOD are implemented using stepped multicarrier signals for seven-level CCMLI with different modulation indexes and are shown in Figure 3(a) and 3(b) respectively.

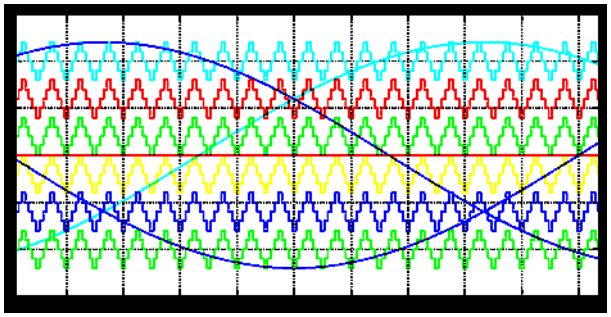

Figure 3(a) PD SMC SPWM with $M_a = 1$

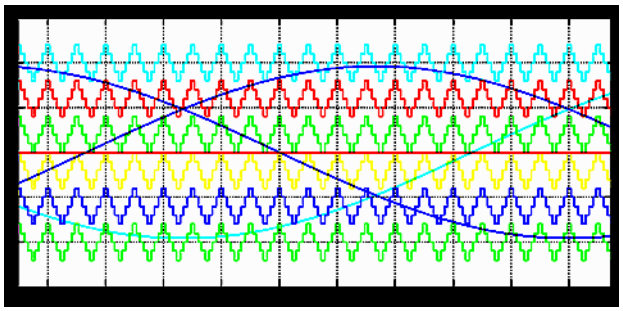

Figure 3(b) IPD SMC SPWM with $M_a = 0.8$

4. SIMULATION RESULTS

The seven-level cascaded multilevel inverter model with different modulation indexes was implemented in MATLAB/SIMULINK software to demonstrate the feasibility of PWM techniques. Phase disposition, inverted phase disposition, phase opposition disposition and alternative phase opposition disposition techniques are used for the various multicarrier SPWM techniques such as

1. Triangular Multicarrier Sinusoidal PWM
2. Stepped Multicarrier Sinusoidal PWM

The line voltage waveform with its harmonic spectrum at fundamental frequency of 50Hz and switching frequency of 2kHz and 10kHz are obtained for the proposed CCMLI. For comparison, the total harmonic distortion (THD) was chosen to be evaluated for all the modulation techniques. In order to get THD level of the waveform, a Fast Fourier Transform (FFT) is applied to obtain the spectrum of the output voltage [35] – [38]. The THD is calculated using the following equation in this work.

$$THD = \frac{\sqrt{\sum_{n=2}^{80} v_n^2}}{v_1} \quad (9)$$

Where n is the harmonic order, v_n is the RMS value of the n^{th} harmonic component and v_1 is the RMS value of the fundamental component. Here the %THD is calculated up to a harmonic order which is twice the switching frequency. For 2kHz switching frequency up to 80^{th} order harmonics is taken in to account for calculating THD and for 10kHz switching frequency up to 400^{th} order harmonics is taken in to account for calculating THD.

Figure 4 presents the simulation model of a three-phase seven-level CCMLI and is developed using MATLAB/SIMULINK. The simulation results are obtained for the output phase voltage and line voltage of the three phase seven-level CCMLI with 1kW, 3φ resistive loads for various PWM techniques.

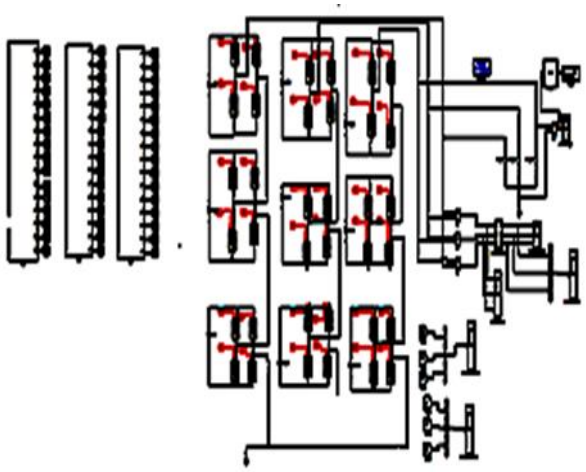

Figure 4 Simulation model of 3φ seven-level CCMLI

4.1. Triangular Multi Carrier SPWM (TMC SPWM)

Figure 5(a) and 5(b) show the line voltage waveforms and the percentage THD of the line voltage for seven level using the phase disposition technique for triangular multi carrier sinusoidal PWM with Ma=1.

Table 1 shows the percentage line voltage THD for the seven-level CCML with triangular multicarrier signal with different multicarrier PWM techniques with a switching frequency of 2kHz and 10kHz respectively for different modulation indexes.

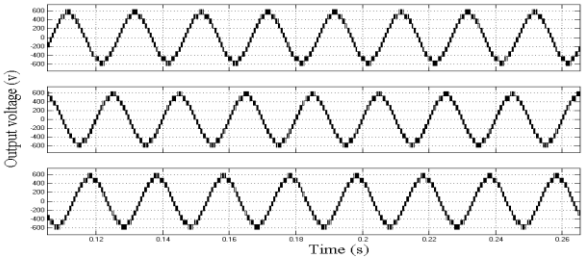

Figure 5(a) Line Voltage for PD SPWM with $M_a = 1$

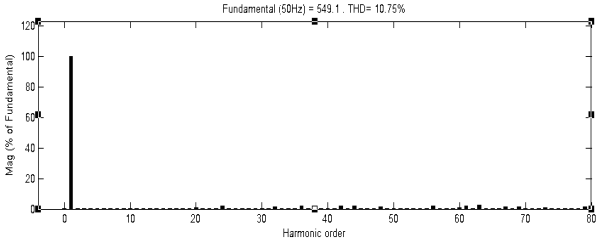

Figure 5(b) Line Voltage %THD for PD SPWM with $M_a = 1$

Table 1: Line voltage %THD for CCMLI with TMC SPWM

Switching frequency	Modulation Technique	Modulation Indexes			
		M_a=1	M_a=0.9	M_a=0.8	M_a=0.7
2kHz	PD	10.75	12.69	13.19	16.61
	IPD	10.75	12.69	13.19	16.61
	POD	15.22	20.62	21.98	20.10
	APOD	14.91	18.04	19.65	23.86
10kHz	PD	10.90	12.78	13.40	16.15
	IPD	10.90	12.78	13.40	16.15
	POD	16.25	20.92	22.31	21.41
	APOD	15.09	18.53	20.53	24.65

From the above table, it is observed that, when the switching frequency of the CCMLI is increased, the percentage line voltage THD is reduced for the PD and IPD schemes with modulation index of 0.7 in seven level CCMLI. In the POD and APOD schemes, when the switching frequency of the CCMLI is increased, the percentage line voltage THD is reduced with modulation index of 0.8. If the output voltage level increases the percentage line voltage THD decreases. From the simulation result in the triangular multi carrier SPWM technique PD and IPD PWM schemes, from 3rd order harmonics to 17th order harmonics and higher odd order harmonics (above 17th harmonics) are less than 1%. Few of the even order harmonics from 18th harmonics to 54th harmonics for the above mentioned scheme are less than 2%. The dominant 57th harmonic factor is about 2% for the PD and IPD schemes.

In the POD scheme, from 3rd odd order harmonics to 19th odd order harmonics are less than 1% and all even order harmonics are zero. Few of the odd order harmonics from 21st harmonics to 69th harmonics are 1% to 2%. The dominant 39th and 41st harmonic factor are 5.37% and 5.59% respectively for the POD scheme. In the APOD scheme, from 3rd odd order harmonics to 25th odd order harmonics are less than 1% and all even order harmonics are 0.01%. Few of the odd order harmonics from 27th harmonics to 69th harmonics are present. The dominant 29th and 51st harmonic factor are 4.70% and 4.59% respectively for the APOD scheme. It is observed that, when the switching frequency of the CCMLI is increased, the percentage line voltage THD, the fundamental phase and line voltage are decreased very slightly for the PD and IPD schemes. In the POD and APOD schemes, if the switching frequency is increased, the percentage line voltage THD is increased very slightly and the fundamental phase and line voltage are decreased very slightly. Also the fundamental line voltage is maximum for POD and APOD schemes and is minimum for PD and IPD schemes.

4.2. Stepped Multi Carrier SPWM (SMC SPWM)

Figure 6(a) and 6(b) show the line voltage waveforms and the percentage THD of the line voltage for seven-level using the inverted phase disposition technique for stepped multicarrier sinusoidal PWM with Ma=1.

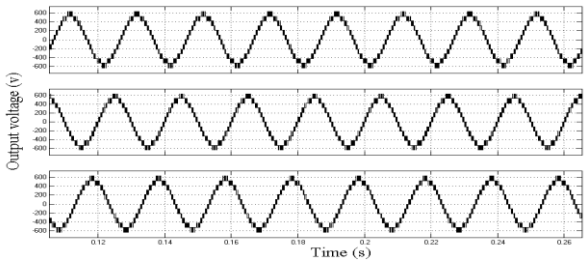

Figure 6(a) Line Voltage for PD SPWM with $M_a = 1$

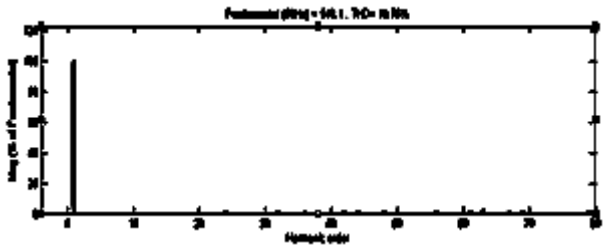

Figure 6(b): Line Voltage %THD for IPD SPWM with Ma=1

Table 2 shows the percentage line voltage THD for the seven-level CCML with stepped multicarrier signal with different multicarrier PWM techniques with a switching frequency of 2kHz and 10kHz respectively for different modulation indexes.

Table 2: Line voltage %THD for CCMLI with SMC SPWM

Switching frequency	Modulation Technique	Modulation Indexes			
		M_a=1	M_a=0.9	M_a=0.8	M_a=0.7
2kHz	PD	11.18	12.83	13.16	16.62
	IPD	11.18	12.83	13.16	16.62
	POD	17.28	22.02	22.80	23.77
	APOD	15.71	18.69	21.33	25.35

10kHz	PD	11.00	13.13	13.09	16.46
	IPD	11.00	13.13	13.09	16.46
	POD	15.73	20.11	21.46	21.73
	APOD	14.49	17.76	19.35	23.67

From the above table, it is observed that, when the switching frequency of the CCMLI is increased, the percentage line voltage THD is reduced for all PWM schemes, except PD and IPD schemes with modulation index of 0.9. From the simulation result in the stepped multi carrier SPWM technique PD and IPD PWM schemes, from 3rd order harmonics to 54th order harmonics and higher even order harmonics (above 54th harmonics) are less than 1%. Few of the odd order harmonics from 55th harmonics to 79th harmonics for the above mentioned scheme are less than 2%. The dominant 57th harmonic factor is about 2% for the PD and IPD schemes.

In the POD scheme, from 3rd odd order harmonics to 19th odd order harmonics are less than 1% and all even order harmonics are 0.01%. Few of the odd order harmonics from 21st harmonics to 79th harmonics are 1% to 2%. The dominant 39th and 41st harmonic factor are 6.55% and 6.16% respectively for the POD scheme. In the APOD scheme, from 3rd odd order harmonics to 25th odd order harmonics are less than 1% and all even order harmonics are 0.01%. Few of the odd order harmonics from 27th harmonics to 79th harmonics are present. The dominant 29th and 51st harmonic factor are 5.17% and 4.98% respectively for the APOD scheme.

It is observed that, when the switching frequency of the CCMLI is increased, the percentage line voltage THD is decreased very slightly and the fundamental phase and line voltage are increased very slightly for the PD and IPD schemes. In the POD and APOD schemes, if the switching frequency is increased, the percentage line voltage THD is decreased very slightly and the fundamental phase and line voltage are increased very slightly. Also the fundamental line voltage is maximum for POD and APOD schemes and is minimum for PD and IPD schemes.

5. CONCLUSION

In this paper, the performance of different multicarrier PWM techniques which uses triangular multicarrier waveform and stepped multicarrier waveform in multilevel inverters is found out. In all the above PWM techniques, different modulation strategies such as phase disposition (PD), inverted phase disposition (IPD), phase opposition disposition (POD) and alternative phase opposition disposition (APOD) are implemented. The results are verified by doing simulation for a 1kW, 3φ seven-level cascaded inverter in MATLAB/SIMULINK. The output quantities like fundamental phase and line voltage, percentage THD of the line voltage and percentage dominant harmonic factor are measured in the all the above PWM schemes and the results are compared.

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