Development of 7-level Cascaded H-bridge Inverter Topology for PV applications

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Abstract: **One of the basic problems in power conversion is the harmonic content at output level. Generally harmonics can be categorized as current and voltage harmonics. Harmonics can be minimized either by increasing the number of voltage levels or by using appropriate modulation techniques. In this paper both mechanisms are proposed. The proposed inverter is 7-level Cascaded Multilevel Inverter (CMLI). As per the simulation results number of output voltage levels increases harmonics will be reduced. And also different Pulse Width Modulation techniques are employed. Among these modulation techniques, selective harmonic elimination technique has fewer harmonic for same number of output voltage levels. The simulation work developed by using MATLAB-Simulink® software of version 13.3a. Comparison on different PWM carrier based and selective harmonic elimination method are also presented.**

Keywords: Cascaded Inverter, Total Harmonic Distortion (THD), Pulse Width Modulation (PWM).

I. INTRODUCTION

Nowadays renewable energy harvesting becomes very popular in power systems. Renewable energy is advantageous because it is clean form of energy. One major renewable energy source is solar energy. This energy can be collected using several photovoltaic (PV) modules. By using combination of PV modules and power conditioning circuit, alternating ac voltage can be produced from solar energy.

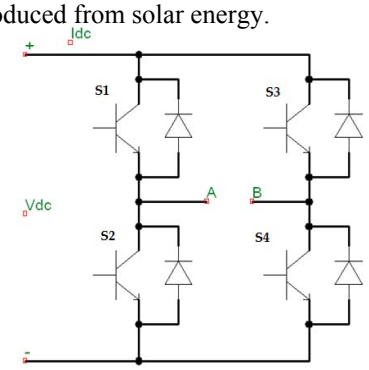

Figure 1: single phase H-bridge inverter

Conducting Switches	*Output Voltage (V_{AB})*
S_1,S_4	$+V_{dc}$
S_2,S_3	$-V_{dc}$
S_1,S_2 *or* S_3,S_4	*0*

Table 1: switching pattern for H-bridge inverter

There are several configurations of multilevel inverters such as Cascaded H-Bridge (CHB) inverter, Flying-Capacitors (FCs) inverter and Neutral Point Clamped (NPC) inverter, etc [1]. An m-level CMLI can be implemented by cascading *(m-1)/2* full H-bridges. Figure 1 and Table-1 shows H-bridge configuration and corresponding switching pattern.

In H-bridge module, turning ON S_1 & S_4 and turning OFF S_2 & S_3 or vice versa gives a voltage of $+V_{dc}$ and $-V_{dc}$ between terminals A and B. To generate zero level in a full-bridge inverter, the combination of S_1 & S_2 can be simultaneously turned ON while S_3 & S_4 are turned OFF or vice versa. The three possible levels referring to above discussion are shown in Table 1. Note that, either S_1 & S_3 or S_2 & S_4 should not be turned ON at same time. Otherwise, a short circuit would exist across the DC source (V_{dc}).

II. PROPOSED STRUCTURE

A proposed inverter is modular in structure and uses several separated DC sources so that inverter is very suitable for PV powered applications. Inverter uses several PV panels as DC sources and it synthesizes them to AC output. A seven level CHB inverter topology is shown in Figure 2.

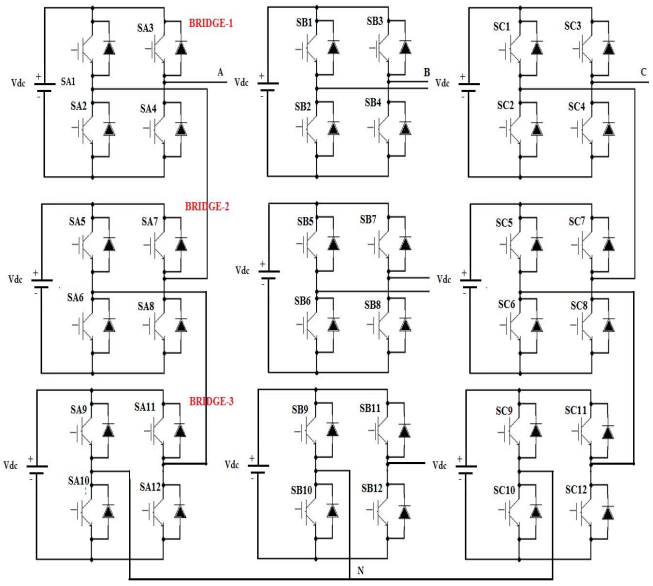

Figure 2: Three phase seven-level cascaded H-bridge inverter topology

CHB inverter module consists of number of individual H-bridge power conversion cells, each supplied by a number of isolated DC voltage sources and all are series-connected.

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Three separate DC sources are required per phase, which can be obtained from PV panels, batteries etc... The modulated output voltage of three CHB for 7-level inverter configuration is shown in Figure 6. Therefore, this 7-level output voltage may have magnitudes are of $\pm 3V_{dc}$, $\pm 2V_{dc}$, $\pm V_{dc}$, and 0. V_{dc} is the DC voltage supplied to each H-bridge module.

III. Modulation Strategies for MLI

Based on switching frequency modulation strategies are classified into two categories: 1) Fundamental switching frequency and 2) High switching frequency [9] [10]. In fundamental switching frequency techniques each inverter is switched once per cycle. *Examples:* Selective Harmonic Elemination (SHE) method, Space Vector Control (SVC). In High switching frequency, there are many switching states per cycle. *Examples:* Multilevel carrier based PWM, SVM.

Multilevel carrier based PWM strategies utilize many triangular carrier signals. Each carrier signal can be phase-shifted relative to other carriers and/or can also be adjusted to shift the level, minimize THD in output voltage as well as current [3] [8]. A carrier wave adjustment can be classified as follows: 1. Level shifted- carrier based PWM and 2. Phase shifted carrier based PWM. The following are Carrier-based sinusoidal PWM where sinusoidal reference signals are compared with (m-1) carrier signals to generate gating signal.

(i) In-phase disposition (IPD), all carrier waveforms are in phase and level-shifted.
(ii) Phase opposition disposition (POD), all carrier waveforms above zero reference have same phase and are out of phase by 180^0 with those below zero.
(iii) Alternate phase disposition (APOD), every carrier waveform is in out of phase with its neighboring carriers by 180^0.
(iv) Optimized Selective Harmonic Elimination technique (OSHE), this is fundamental switching frequency technique. Table 1 shows the switching angle pattern.

Figure 3, 4 and 5 show the corresponding output of series connected H-bridges bridge-1, bridge-2 and bridge-3 respectively with varying switching angles (β). Table 2 shows switching conditions of one leg of 7-level CHB inverter for quarter cycle.

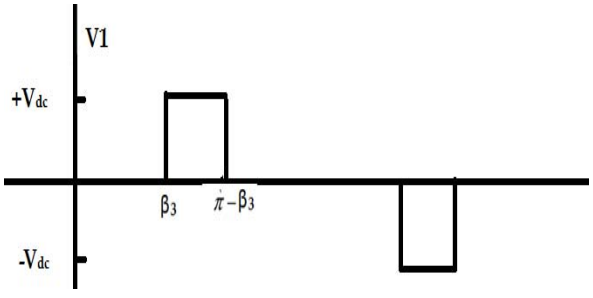

Figure 3: Output voltage of bridge-1

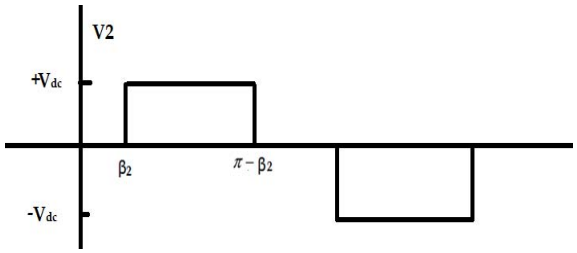

Figure 4: Output voltage of bridge-2

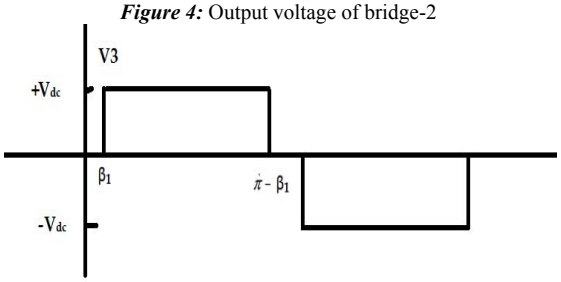

Figure 5: Output voltage of bridge-3

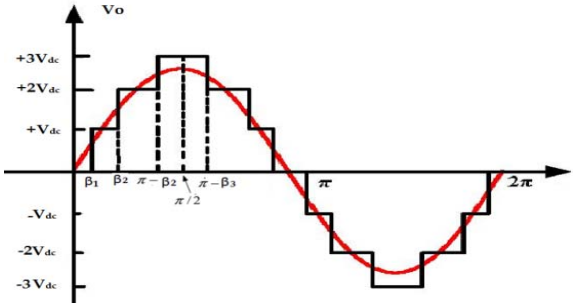

Figure 6: Output voltage of all three bridges

Table 2: Switching angles for quarter of a cycle

Switching angle (β)	**V_1**	**V_2**	**V_3**	**$V_0=V_1+V_2+V_3$**
$0 \le \beta \le \beta_1$	0	0	0	0
$\beta_1 \le \beta \le \beta_2$	0	0	V_{dc}	V_{dc}
$\beta_2 \le \beta \le \beta_3$	0	V_{dc}	V_{dc}	$2V_{dc}$
$\beta_3 \le \beta \le \pi/2$	V_{dc}	V_{dc}	V_{dc}	$3V_{dc}$

The conducting angles β_1, β_2 *and* β_3 can be chosen such that THD at output voltage is minimum. Normally, these angles are chosen so as to cancel dominant harmonics. Applying Fourier series analysis for Figure 6 the output voltage of the CMLI is given by,

$$V(\omega t) = \frac{4}{\pi} V_{dc} \times \sum_{n=1,3,5\ldots}^{\infty} \frac{1}{n} (\cos(n\beta_1) + \cos(n\beta_2) + \cos(n\beta_3)) \sin(n\omega t)$$

The above equation 5^{th}, 7^{th} harmonics will have magnitude of zero. It is not necessary to eliminate third harmonic as it is triple harmonics will be cancelled out in line-to-line voltage. The above equation gives the following sets of non-linear equations:

$$\frac{4}{\pi}V_{dc}(\cos(\beta_1)+\cos(\beta_2)+\cos(\beta_3))=V_1$$

$$(\cos(5\beta_1)+\cos(5\beta_2)+\cos(5\beta_3))=0$$

$$(\cos(7\beta_1)+\cos(7\beta_2)+\cos(7\beta_3))=0$$

A set of nonlinear transcendental equations can be solved by an iterative method such as the Newton–Raphson method [7]. Table 3 shows the calculated switching angles for different values of modulation index.

Algorithm to find β by NR method: The step by step procedure to solve SHE equations as follows:

Step 1: Define a switching angle matrix. Note: all switching angle must be 0 to π/2.

$$\beta old=[\beta_1 \quad \beta_2 \quad \beta_3]^T$$

Step 2: Specify the value of modulation index (MI) and number of line voltage levels.

Step 3: Define a non-linear matrix (F) as follows:

$$F=\begin{bmatrix}\cos(\beta_1)+\cos(\beta_2)+\cos(\beta_3)\\ \cos(5\beta_1)+\cos(5\beta_2)+\cos(5\beta_3)\\ \cos(7\beta_1)+\cos(7\beta_2)+\cos(7\beta_3)\end{bmatrix}$$

Step 4: Define corresponding harmonic amplitude matrix as

$$\mathrm{Hm}=\left[\frac{(m-1)MI}{2} \quad 0 \quad 0\right]$$

Step 5: Define *dervF* which is the derivative of the matrix *F* with respect to $\beta_1, \beta_2, \beta_3$

$$dervF=\begin{bmatrix}-\sin(\beta_1) & -\sin(\beta_2) & -\sin(\beta_3)\\ -5\sin(\beta_1) & -5\sin(\beta_2) & -5\sin(\beta_3)\\ -7\sin(\beta_1) & -7\sin(\beta_2) & -7\sin(\beta_3)\end{bmatrix}$$

Step 6: Initial values for the switching angles are entered as

$$\beta old\_0=[\beta_{10} \quad \beta_{20} \quad \beta_{30}]^T$$

Step 7: Solve for F and *dervF* at the initial values of *βs* on linearizing the set equations

$$F+(dervF*\Delta\beta)=H_M \quad ,$$

$\Delta\beta$: change in switching angle.

Step 8: Solve for $\Delta\beta$ using $\Delta\beta=INV(dervF)(H_M\text{-F})$

Step 9: Update the value of the switching angle

$$\beta new=\beta old+\Delta\beta$$

Step 10: Repeat step 2 *to* step 8 for whole range of MI and increment MI.

Step 11: Repeat steps 2 to 10 for whole range of MI.

Table 3: Based on modulation index (MI)

Modulation Index (MI)	*Conduction angle (β_1)*	*Conduction angle (β_2)*	*Conduction angle (β_3)*
0.4	*44.3*	*74.4*	-
0.5	*40.7*	*65.7*	*89.5*
0.6	*39.4*	*58.7*	*83.2*
0.7	*39.3*	*54.0*	*74.1*
0.8	*29.2*	*54.2*	*64.5*
0.9	*17.5*	*43.2*	*64.2*
1.0	*11.7*	*31.2*	*58.6*

IV. SIMULATION RESULTS:

Circuit simulation is developed by using MATLAB-Simulink® software. THD = $\frac{\sqrt{\sum_{n=2}^{\infty}{H_n}^2}}{H_1}$

where H_1 is the amlitude of the fundametal component at ω_0 and H_n is the amplitde of n[th] harmonic at $n\omega_0$

Alternate Phase Disposition (APOD): In APOD six carrier signals are used. These carrier signals are arranged in such a way that all neignbouring carriers are out of phase by 180º. And three sinusodal reference signals which are phase shifted by 120º having same peak-to peak amplitude are used. At every stage these reference signals are compared to triangular waveform in order to generate gating signals. Figure 7 shows the comparison reference signals to that of carrier signals.

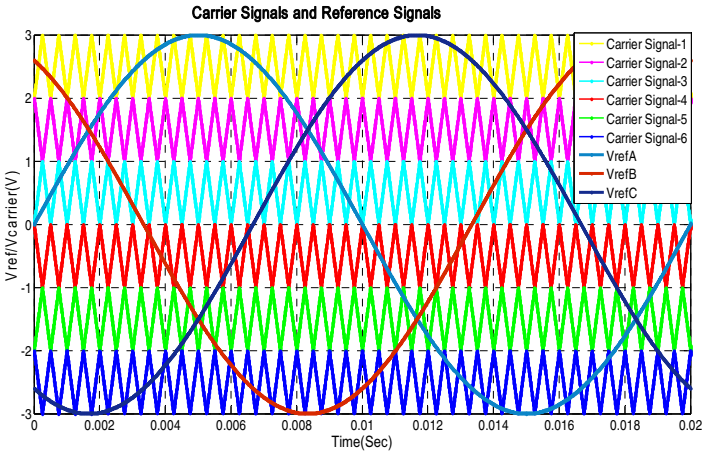

Figure 7: Carrier and reference signals for gate signal generation

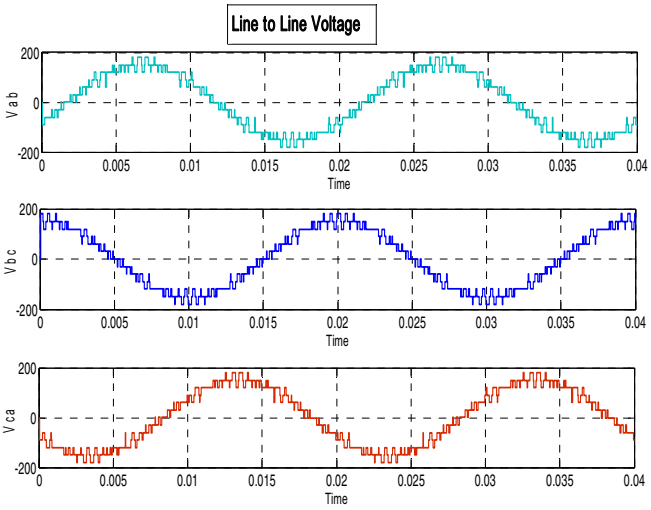

Figure 8: Output Line to Line Voltage for POD

A corresponding DC-link voltage of 30V applied for each H-bridge Cell. Three 30V separate DC sources per phase are required. A modulated 7-level line-to-line output voltage is shown in Figure 8. An output phase voltage of 180V peak-to-

peak, an output line-to-line voltage of 360 V peak-to-peak are obtained, which is shown in Figure 8. And Figure 9 show the corresponding FFT analysis for line-to-line voltage.

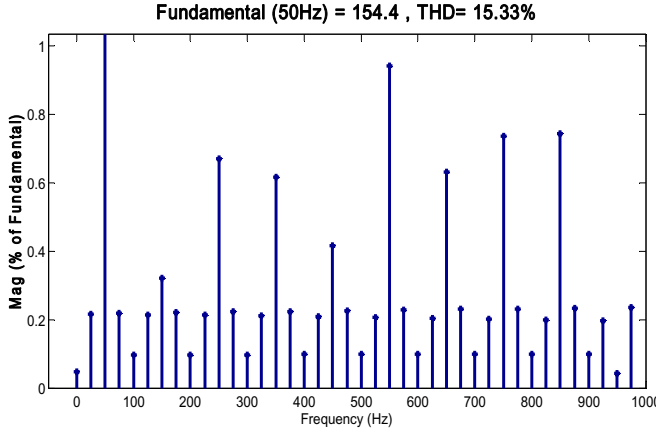

Figure 9: FFT analysis for APOD, calculation of THD=15.33%

Phase Opposition Disposition (POD):

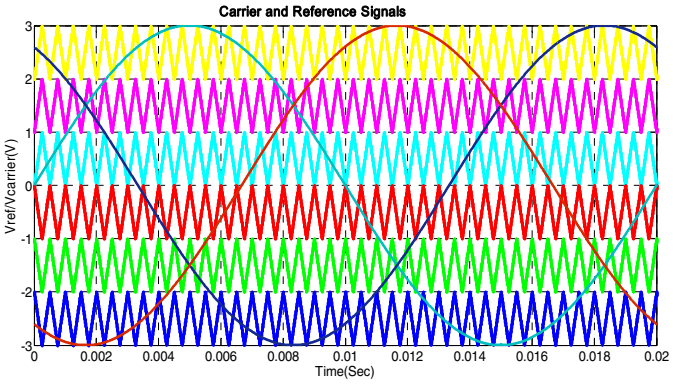

Figure 10: Carrier and reference signals for gate signal generation

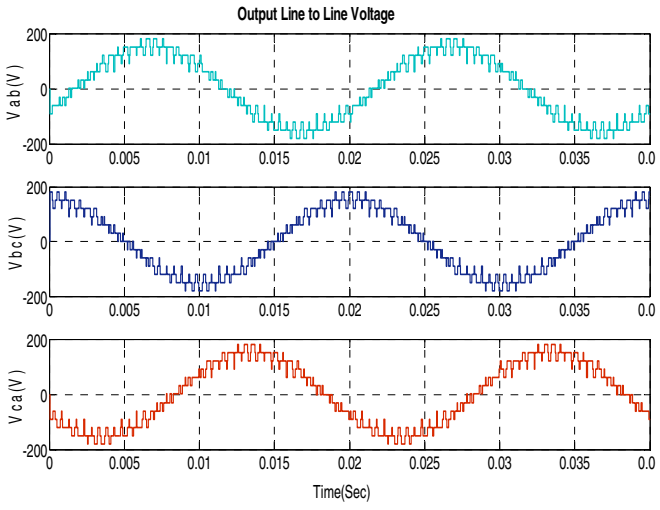

Figure 11: Output Line to Line Voltage for POD

In POD, all features are same with APOD technique but all carrier signals above zero level have same phase and all carrier signals which are below zero level have same phase and 180º phase-shifted to carrier signals which are above zero level. Figure 10 shows comparison of reference and carrier signals and Figure 11 show line to line voltage for POD. Figure 12 shows FFT analysis of one phase of line to line voltage.

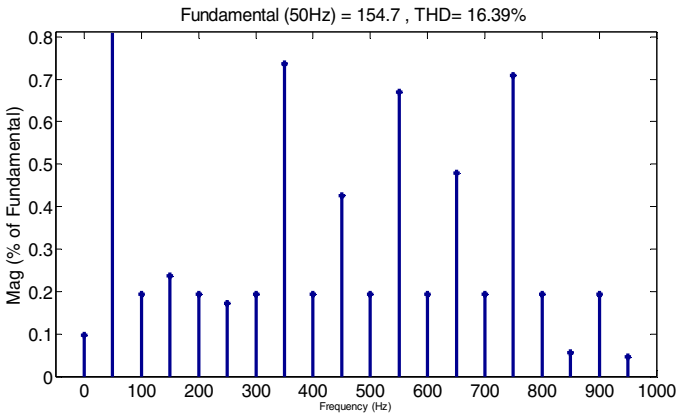

Figure 12: FFT analysis for POD, calculation of THD = 16.39%

In-Phase Disposition (IPD):

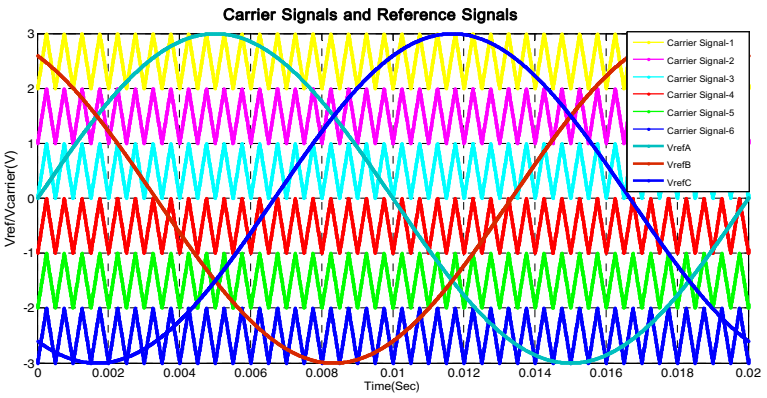

Figure 13: Carrier and reference signals for gate signal generation for IPD

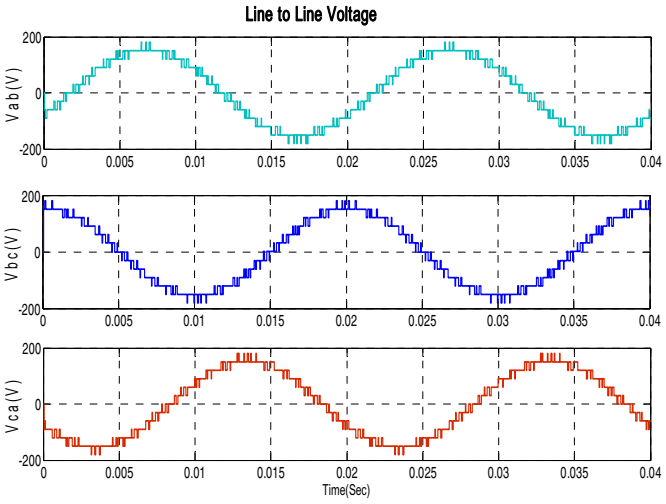

Figure 14: Output Line to Line Voltage for IPD

Different PWM strategy can also be obtained with IPD technique. In IPD, all carriers are level shifted and have same phase. Figure 13 and Figure 14 show comparison of reference and carrier signals and output line to line voltages, respectively. Figure15 shows the FFT analysis of IPD.

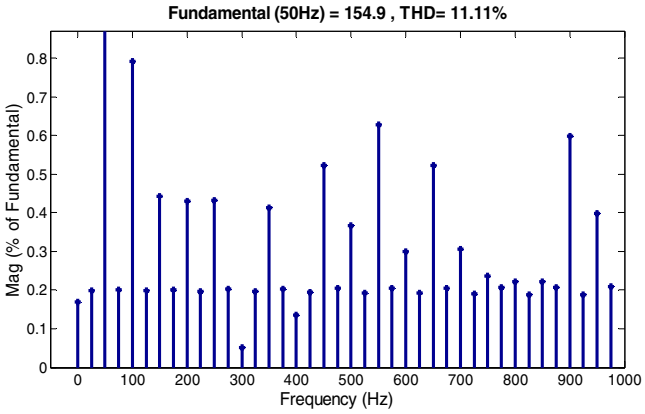

FIGURE 15: FFT ANALYSIS FOR IPD, CALCULATION OF THD=11.11%

Optimized Selctive Harmonic Elimination (OSHE) Technique :

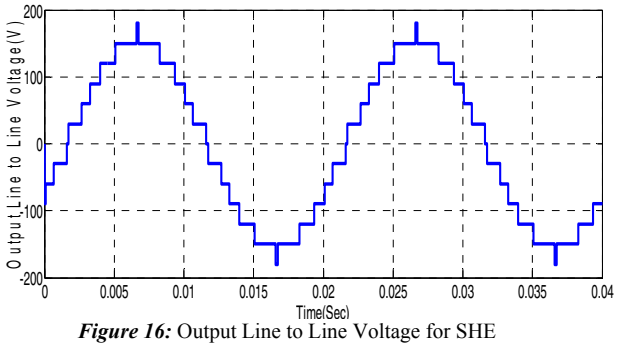

Figure 16: Output Line to Line Voltage for SHE

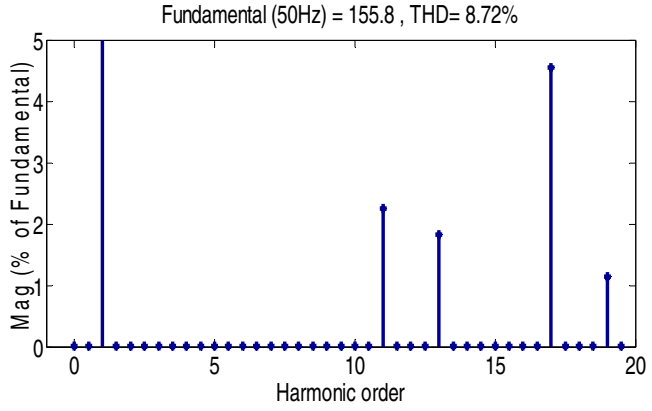

FIGURE 17: FFT ANALYSIS FOR POD

OSHE technique different from above PWM techniques discussed. OSHE is under category of fundametal swiching frequency. Therefore, this technique reduces switching losses as a result of high frequency carrier signals. Figure 16 shows the line to line voltage for OSHE technique and Figure 17 shows corresponding FFT analysis.

All the simulations are done for modulation Index (MI) of 1.0. In carrier-based PWM techniques the carrier signals have frequency of 2 kHz and the reference signals have 50 Hz. The FFT analysis for line-to-line voltage also calculated. The calculation shows that all Carrier-based SPWM techniques have higher THD value than the OSHE technique employed. Approaching seven-level CHB inverter using OSHE modulation strategy successfully eliminated 5^{th} and 7^{th} harmonics. By using this modulation technique, it is able to achieve THD value of 8.72% by selecting appropriate calculating switching angles. This THD value is comparatively less than other strategies. For four modulation strategy results summary are shown in Table 4.

Table 4: Comparison of different modulation strategies

S.No.	*Modulation strategy*	*THD*
1	*IPD*	*11.11%*
2	*POD*	*16.39%*
3	*APOD*	*15.33%*
4	*SHEPWM*	*8.72%*

Table 4 shows that comparison of the four modulation strategies based on the THD value at the output line to line voltage.

V. CONCLUSIONS

This paper has shown various modulation techniques for comparison purpose. A proposed configuration useful in ac power supplies as well as adjustable speed drive applications employing solar energy driven systems. Above results shows that with an employment of Optimized Selective Harmonic Elimination (OSHE) reduces total harmonic content to a level of 8.72%. OSHE technique has low switching frequency of 50Hz. This characteristic reduces the switching losses which may appear in the inverter as a result of using high switching frequency. The low THD output waveform obtained without any filter circuit. Since the devices are turned on and off one time per cycle, this technique reduces the device switching losses. OSHE technique for Seven Level CMLI has been developed and a part of hardware is implemented.

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