

## Analysis and Simulation of Single Phase Cascaded H-Bridge Multilevel Inverter Using Multicarrier PWM for Photovoltaic System

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**Abstract:** Photovoltaic energy is considered one of the most promising energy sources due to its infinite power and has many advantages like longer life span, less maintenance, pollution free, simple installation, static and quick than the other alternative energy sources like wind, solar, ocean, biomass, geothermal, etc. In photovoltaic power generation system cascaded H-bridge multi level inverters play a vital role in power conversion. Diode clamped inverter, cascaded H-bridge inverter and flying capacitor inverter are the three widely used topologies of multilevel inverters. Among these three topologies, cascaded H-bridge multilevel inverter becomes a very attractive feature in the case of photovoltaic systems because solar cells can be assembled in a number of separate generators and each H-bridge cell will be available in a single module. This research study deals with harmonic analysis in 5, 7, 9 and 11 levels by considering upto 23rd harmonics of single phase cascaded H-bridge multilevel inverter employing multicarrier pulse width modulation technique for grid connected photovoltaic system. From this harmonic analysis, it is found that the total harmonic distortion in output voltage decrease and output voltage increase with increase in number of levels, reducing switching losses, reducing voltage stress and hence the efficiency of the system will be improved. The effect of cascaded H-bridge multilevel inverter topology and change in PV input parameters irradiation and temperature on the performance parameters has been analyzed and studied by the MATLAB/Simulink. The simulated output shows very favorable results. It can also be easily extended to more levels.

**Key words:** Multilevel inverter, cascaded H-bridge multilevel inverter, total harmonic distortion, photovoltaic cell, multicarrier pulse width modulation, harmonic analysis

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### INTRODUCTION

Photovoltaic power supplied to the utility grid is gaining more and more visibility while the world's power demand is increasing (Calais and Agelidis, 1998). Not many PV Systems have so far been placed into the grid due to the relatively high cost, compared with more traditional energy sources such as oil, coal, gas, nuclear, hydro and wind. Solid state inverters have been shown to be the enabling technology for putting PV Systems into the grid.

A renewable energy application such as Photovoltaic (PV) System has been widely used for a few decades since PV energy is free, abundant and distributed throughout the earth. The focus of the engineers is to make use of abundantly available PV energy and so to design and control an inverter suitable for photo voltaic applications. Power electronic circuits with Pulse Width Modulation (PWM) are mostly used in energy conversion systems to achieve closed loop control. But even updated Pulse

Width Modulation (PWM) techniques do not produce perfect waveforms (Bhagwat and Stefanovic, 1983) which strongly depend on the semiconductors switching frequency. Also, it is well known that distorted voltages and currents waveforms produce harmonic contamination, additional power losses and high frequency noise that can affect not only the load power but also the associated controller.

Recently multilevel inverters have become more attractive to researchers and industrial companies due to fast developing of high power devices and related control techniques (Khajehoddin *et al.*, 2007). The recent advancement in power electronics has initiated to improve the level of inverter to cater to the need of medium voltage high power applications without transformer (Kjaer *et al.*, 2005).

The three common topologies for multilevel inverters are as follows: Diode clamped (neutral clamped), capacitor clamped (flying capacitors), cascaded H-bridge inverter but the one considered in this study is the cascaded

H-bridge multilevel inverter. These converter topologies can generate high-quality voltage waveforms with power semiconductor switches operating at a frequency near the fundamental. It significantly reduces the harmonics problem with reduced voltage stress across the switch (Kjaer *et al.*, 2005).

The cascaded H-bridge multilevel inverter topology has many advantages not only in terms of its simple structure but also allows the use of a single dc source as the first dc source with the remaining (n-1) dc sources being capacitors (Seyezhai and Mathur, 2010). The voltage regulation of the capacitor is the key issue and this is achieved by the switching state redundancy of the proposed modulation strategy. This scheme also provides the ability to produce higher voltages at higher speeds with low switching losses and high conversion efficiency. The cascaded multilevel control method is very easy when compared to other multilevel inverter because it doesn't require any clamping diode and flying capacitor (Mathurm and Seyezhai, 2008).

The diode-clamped inverter (neutral-point clamped), capacitor-clamped (flying capacitor) requiring only one dc source and the cascaded bridge inverter requiring separate dc sources. The latter characteristic which is a drawback when a single dc source is available becomes a very attractive feature in the case of PV Systems because solar cells can be assembled in a number of separate generators. In this way, they satisfy the requirements of the CHB-MLI, obtaining additional advantages such as a possible elimination of the dc/dc booster (needed in order to adapt voltage levels), a significant reduction of the power drops caused by sun darkening (usually, it influences only a fraction of the overall PV field) and therefore, a potential increase of efficiency and reliability (Aghdam *et al.*, 2008).

Performance of the multilevel inverter (such as THD) is mainly decided by the modulation strategies. For the cascaded multilevel inverter there are several well known pulse width modulation strategies such as space vector pwm, sinusoidal pwm, selective harmonics elimination and multicarrier pwm (Tolbert *et al.*, 1999). Compared to the conventional method, the proposed method is subjected to a new modulation scheme adopting the multicarrier pulse width modulation concept which uses multiple modulating signals with a single carrier reduces the total harmonic distortion (Rodriguez *et al.*, 2002).

This research study deals with harmonic analysis in 5, 7, 9 and 11 levels by considering upto 23rd harmonics of single phase cascaded H-bridge multilevel inverter employing multicarrier pulse width modulation technique

for grid connected photovoltaic system. The effect of cascaded h-bridge multilevel inverter topology and change in PV input parameters irradiation and temperature on the performance parameters has been analyzed.

## PHOTOVOLTAIC SYSTEM

A Photovoltaic (PV) System directly converts solar energy into electrical energy. This Photovoltaic System consists of main parts such as PV module, charger, battery, inverter and load. The basic device of a PV system is the PV cell. Cells may be grouped to form arrays. The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors or connect to a grid by using proper energy conversion devices (Kumar *et al.*, 2013). A photo voltaic cell is basically a semiconductor diode whose p-n junction is exposed to light. Photovoltaic cells are made of several types of semiconductors using different manufacturing processes. The incidence of light on the cell generates charge carriers that originate an electric current if the cell is short circuited (Villalva *et al.*, 2009).

**Mathematical model:** A photovoltaic cell is a device used to convert solar radiation directly into electricity. It consists of two or more thin layers of semiconducting material, most commonly silicon. When the silicon is exposed to light, electrical charges are generated. A PV cell is usually represented by an electrical equivalent one-diode model shown in Fig. 1.

The model contains a current source, one diode, internal shunt resistance and a series resistance which represents the resistance inside each cell. The net current is the difference between the photo current and the normal diode current is given by the equation (Rodriguez *et al.*, 2002):

$$I_D = I_0 \frac{q(V+I R_s)}{e K T - 1} \tag{1}$$

$$I = I_L - I_0 \frac{q(V+I R_s)}{e K T - 1} - \frac{V+I R_s}{R_{sh}} \tag{2}$$

Where:

- I = The cell current (A)
- q = The charge of electron (coul)
- K = The Boltzmann's constant (J/K)
- T = The cell temperature (K)
- I<sub>L</sub> = The photo current (A)

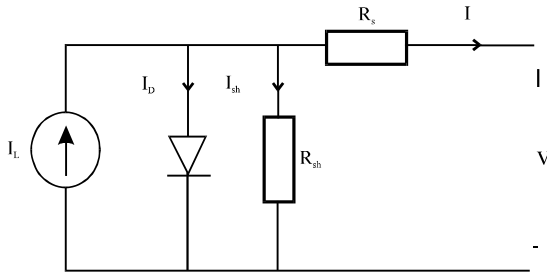


Fig. 1: Single PV cell model

- $I_o$  = The diode saturation current (A)
- $R_s, R_{sh}$  = Cell series and shunt resistances (ohms)
- $V$  = The cell output voltage (V)

**CASCADED H-BRIDGE MULTILEVEL INVERTER FOR PHOTOVOLTAIC APPLICATIONS**

Figure 2 shows the single phase n-level structure of cascaded H-bridge inverter for PV applications, consisting of k dc generators and k cascaded H-bridges arranged in a single-phase multilevel inverter topology. Each dc generator consists of PV cell arrays connected in series and in parallel thus obtaining the desired output voltage and current. H-bridges basically consist of four Metal Oxide Semiconductor Field-Effect Transistors (MOSFETs) embedding an antiparallel diode and a driver circuit. The number k of H-bridges depends on the number  $n = 2k+1$  of desired levels which has to be chosen by taking into account both the available PV fields and design considerations (Josh *et al.*, 2013). The circuit has many advantages like simple, modular, improved waveform which results in reduced total harmonic distortion. The cascaded H-bridge multi-level inverter circuit provides high quality output when the number of levels in the output increases and also this reduces the filter components size and cost (Lai and Peng, 1995).

Figure 3 shows the output phase voltage waveform for a n-level cascaded H-bridge inverter. The phase voltage:

$$V_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5}$$

For a stepped wave form such as the one depicted in Fig. 3 with steps, the Fourier transform for this waveform follows (Tolbert *et al.*, 1999):

$$V(\omega t) = \left( \frac{4VDC}{\pi} \right) \sum [\cos(n\theta_1) + \cos(n\theta_2) + \dots + \cos(n\theta_n)]$$

where  $n = 1, 3, 5, 7, \dots$

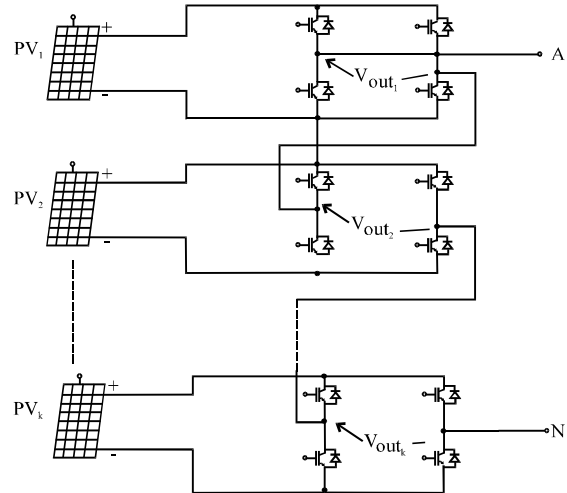


Fig. 2: Single phase n-level structure of cascaded H-bridge inverter for PV applications

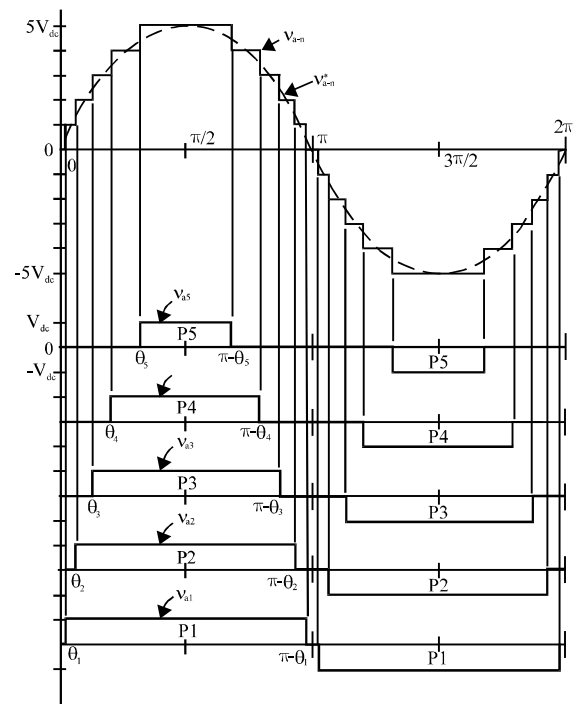


Fig. 3: Output phase voltage waveform of a n-level cascaded H-bridge inverter

The conducting angles,  $\theta_1, \theta_2, \dots, \theta_s$  can be chosen such that the voltage total harmonic distortion is a minimum. Generally, these angles are chosen so that predominant lower frequency harmonics, 5th, 7th, 11th and 13th, harmonics are eliminated.

**MULTICARRIER PULSE WIDTH MODULATION FOR HARMONICS REDUCTION**

Several modulation strategies have been developed for multilevel inverters. The most commonly used is the multi carrier PWM technique. The principle of the multicarrier PWM is based on a comparison of a sinusoidal reference waveform with triangular carrier waveforms.  $m-1$  carriers are required to generate  $m$  levels. The carriers are in continuous bands around the reference zero. They have the same amplitude  $A_c$  and the same frequency  $f_c$ . The sine reference waveform has a frequency  $f_r$  and  $A_r$  is the peak to peak value of the reference waveform. At each instant, the result of the comparison is 1 if the triangular carrier is greater than the reference signal and 0 otherwise. The output of the modulator is the sum of the different comparisons which represents the voltage level. The strategy is therefore characterized by the two following parameters called amplitude modulation index  $m_a$  and frequency modulation index  $m_f$  (Mathurm and Seyezhai, 2008). Frequency modulation ratio is defined as the ratio of carrier frequency and modulating frequency.

Amplitude modulation ratio is defined as the ratio of amplitude of modulating signal and amplitude of carrier signal (Aghdam *et al.*, 2008).

**SIMULATION RESULTS**

In this study, the simulation model is developed with MATLAB/SIMULINK. The simulink model of the

proposed cascaded H-bridge multilevel inverter and the subsystem are shown in Fig. 4 and 5 and the switching scheme is shown in Fig. 6. The generated output pulses from the pulse generator is shown in the Fig. 7 and those pulses generated are to drive the devices in to ON for a H-bridge multilevel inverter topology. The proposed circuit needs independent dc source which is supplied from photovoltaic cell. For each of the H-bridges in the cascaded multilevel inverter, 12 V photovoltaic power source is used. The switching device used is MOSFET. In case of five level inverter requires eight switches to get the five level output voltage and the simulated line voltage and THD analysis for five level h-bridge inverter is shown in Fig. 8 and 9. The simulated value of THD is 61.42%. In case of seven level inverter requires twelve switches to get the seven level output voltage and the

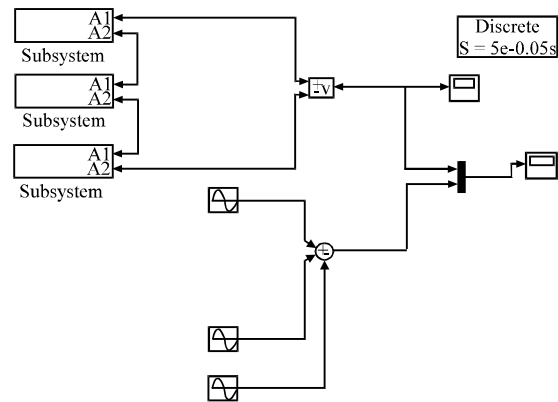


Fig. 4: Simulink model of the proposed inverter

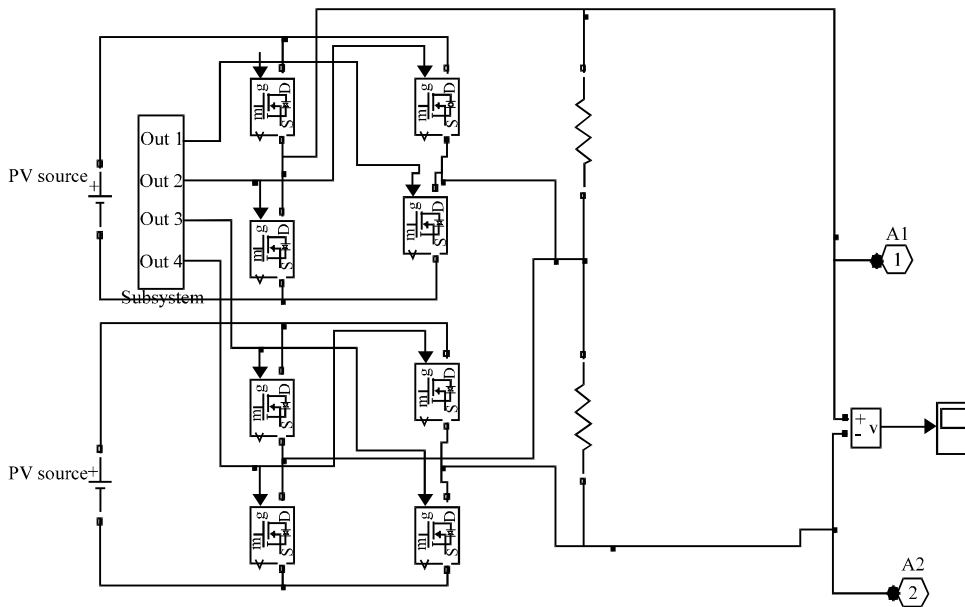


Fig. 5: Subsystem

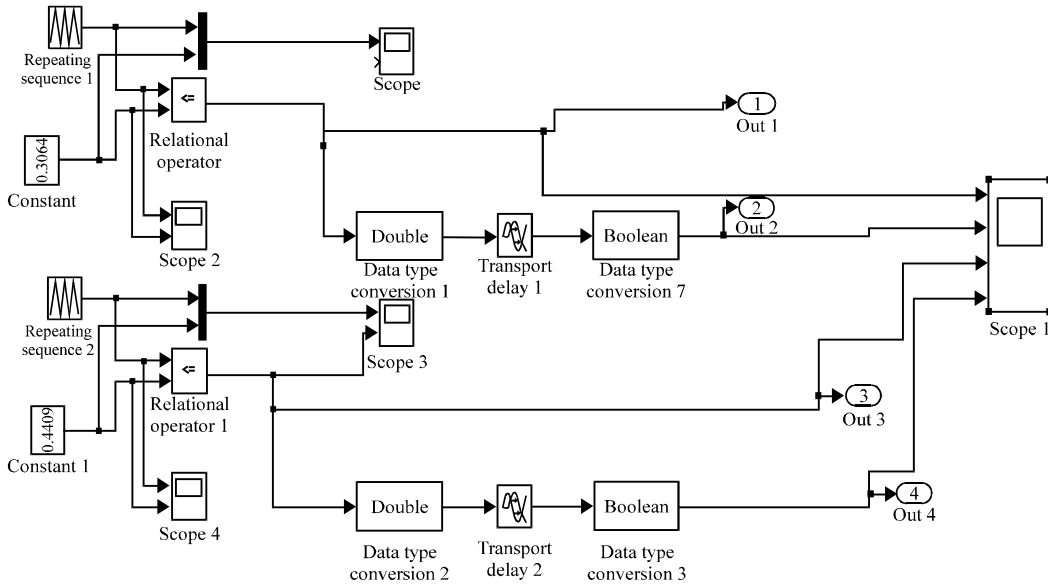


Fig. 6: Switching scheme

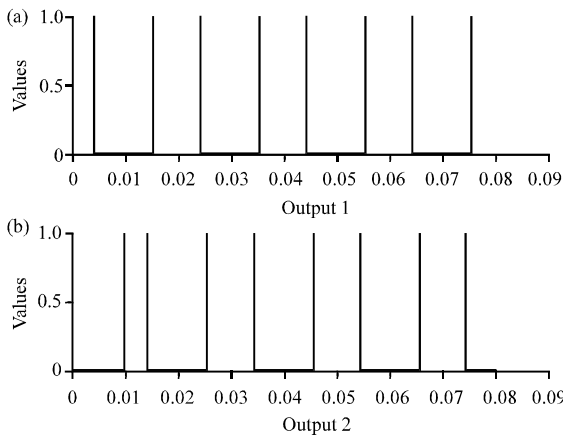


Fig. 7: Generation of pulses

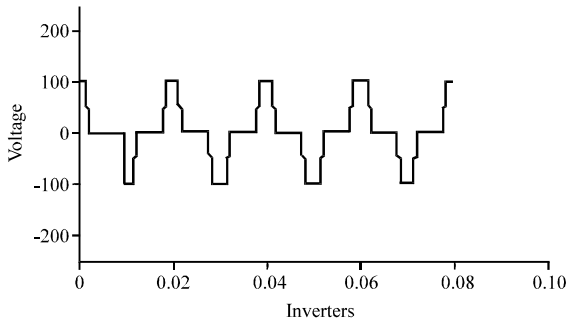


Fig. 8: Simulated line voltage waveform of five level inverter

simulated line voltage and THD analysis for seven level h-bridge inverter is shown in Fig. 10 and 11. The THD

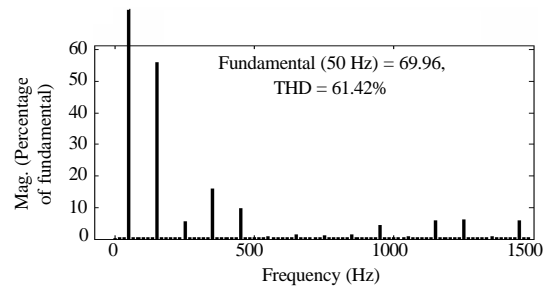


Fig. 9: FFT analysis for five level inverter

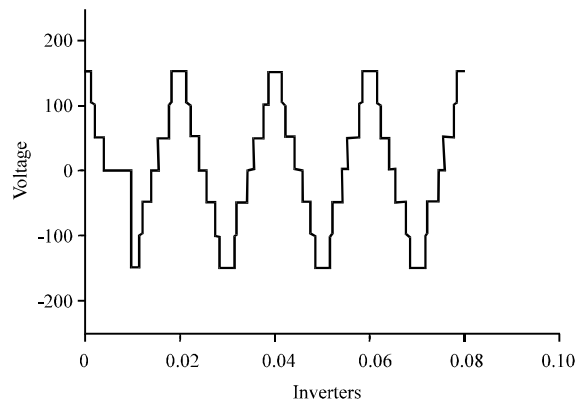


Fig. 10: Simulated line voltage waveform of seven level inverter

value is 24.64%. In case of nine level inverter requires sixteen switches to get the nine level output voltage and the simulated line voltage and THD analysis is shown in Fig. 12 and 13. The THD value is 20.75%. In case of eleven

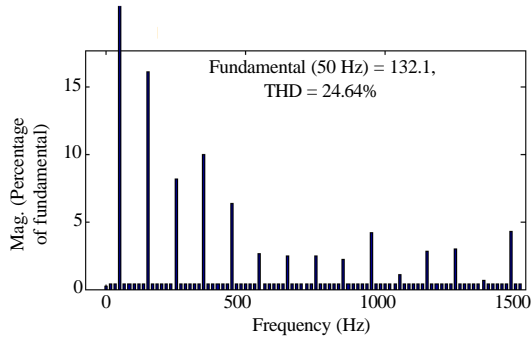


Fig. 11: FFT Analysis for seven level inverter

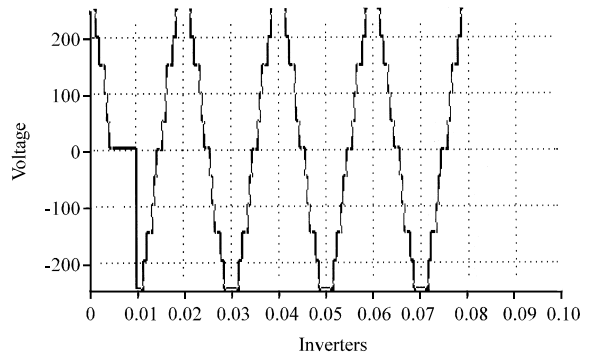


Fig. 14: Simulated line voltage waveform of eleven level inverter

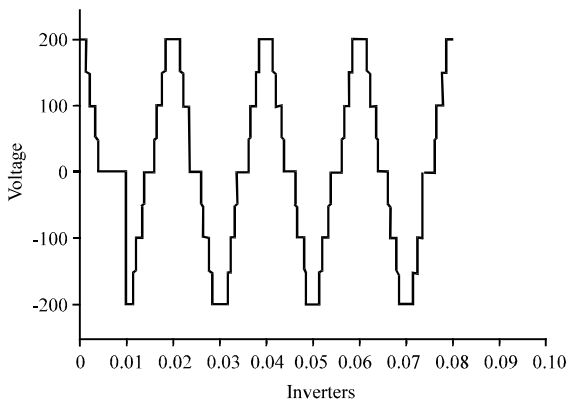


Fig. 12: Simulated line voltage waveform of nine level inverter

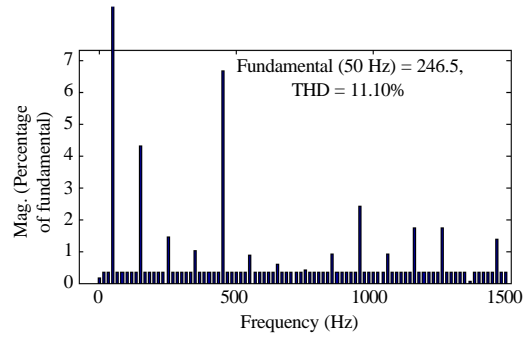


Fig. 15: FFT analysis for eleven level inverter

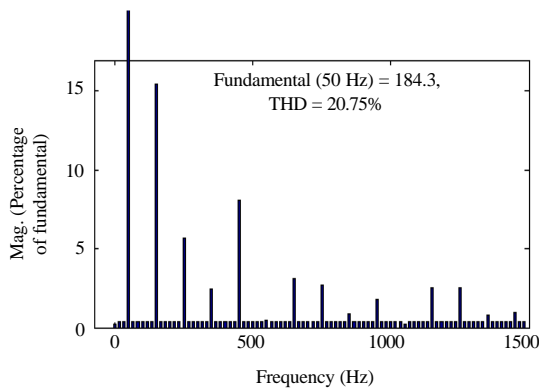


Fig. 13: FFT analysis for nine level inverter

level inverter requires twenty switches to get the eleven level output voltage and the simulated line voltage and THD analysis is shown in Fig. 14 and 15. The THD value is 11.10%.

Here, load is taken as R load and a detailed harmonic analysis is done from 5th level to 11th level by considering upto 23rd harmonics is shown in Table 1 and 2. Table 3 shows the cascaded H-bridge multilevel inverter topology of various levels.

Table 1: Harmonics in different levels of cascaded H-bridge multilevel inverter

Levels	THD (%)	Harmonic contents (%)					
		3rd	5th	7th	9th	11th	13th
5	61.42	20.47	12.28	8.77	6.82	10.58	9.68
7	24.64	13.53	7.53	5.49	4.19	3.38	3.28
9	20.75	0.52	3.01	3.35	4.28	3.32	2.12
11	11.10	9.42	3.11	2.01	1.11	0.77	0.68

Table 2: Harmonic analysis in different level of R load

Levels	Harmonic contents (%)				
	15th	17th	19th	21st	23rd
5	3.52	5.44	3.13	3.98	3.88
7	6.25	5.73	2.21	1.75	1.69
9	0.98	0.31	5.09	4.63	0.15
11	0.61	0.66	0.72	0.59	0.67

Table 3: Cascaded H-bridge multilevel inverter topology

Levels	DC sources	Bridges	Switches	THD (%)
5	2	2	8	61.42
7	3	3	12	24.64
9	4	4	16	20.75
11	5	5	20	11.10

From the above simulated analysis, it is found that the total harmonic distortion of the system will be reduced

Table 4: Effect of change in irradiation T = 25°C

Irradiation (W/m <sup>2</sup> )	Output voltage (V)			
	5 level	7 level	9 level	11 level
800	96.52	97.68	98.49	99.12
600	95.13	95.98	97.67	98.21
400	94.89	93.71	96.51	97.03

Table 5: Effect of change in temperature irradiation = 1000 Wm<sup>2</sup>

Temperature (°C)	Output voltage (V)			
	5 level	7 level	9 level	11 level
28	99.1	99.20	99.5	99.60
32	97.1	97.12	97.3	97.40
36	95.2	95.40	95.8	95.78

by increasing the number of levels in the output waveform and hence the efficiency of the system will be improved.

### EFFECT OF CHANGE IN IRRADIATION AND TEMPERATURE

It is assumed that PV cell produces constant rated voltage because nominal irradiation (1000 W/m<sup>2</sup>) and temperature (25°C). Table 4 shows the effect of change in irradiation with constant temperature. Table 5 shows the effect of change in temperature keeping irradiation at nominal value. It has been found from the results that output voltage of the PV fed single phase cascaded h-bridge multilevel inverters decreasing with decrease in irradiation and increase in temperature though there is no much change in total harmonic distortion.

### CONCLUSION

In the present research, this research focus on the detailed harmonic analysis in 5, 7, 9 and 11 levels by considering upto 23rd harmonics of cascaded H-bridge Multilevel Inverter for grid connected photovoltaic power system. Multicarrier pwm technique is being used in this H-bridge multilevel inverter topology. The simulated output shows very low total harmonic distortion by increasing the number of levels, low switching losses and low voltage stress. Thus, it eliminates the need for filter. Hence, researchers could achieve the improved efficiency of the system. The effect of change in irradiation and temperature on the performance parameters has been analyzed and studied by the MATLAB/Simulink. When irradiation reduces, output voltage also proportionately decreases whereas it increases with decrease in temperature. Hence, the future research may be focused on implementing closed loop control with suitable pwm technique to achieve better performance of the H-bridge multilevel inverter.

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