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(Research Article)

THD analysis and cost comparison for an N-level H-bridge inverter incorporating passive and active filters

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Abstract

Multilevel H-bridge inverters have grown in popularity in electronic direct current (DC) to alternating current (AC) power conversion. In the renewable energy field, H-bridge inverters are used for converting DC voltage obtained from solar panels to AC voltage. However, H-bridge inverters produce undesirable odd harmonics in their output. Several H-bridges are, therefore, usually cascaded to reduce the total harmonic distortion (THD) in their output, but the results aren't satisfactory in most cases. In this paper, both active and passive filters are incorporated in a cascaded H-bridge inverter to reduce the THD further. Then cost comparison is made of cascaded H-bridge inverters (3, 5, 7, 9, and 11-levels) without a filter and multilevel cascaded H-bridge inverters (3, 5, 7, 9, and 11-levels) with a passive filter or active filter. Powersim (PSIM) platform is used to perform the THD analysis.

Keywords: H-bridge; THD; Filters; Inverters

1. Introduction

The turn of the 21st century saw increased research into renewable energy sources such as solar energy, wind energy, hydroelectric energy, geothermal energy, etc., that can produce electricity to replace non-renewable resources. Renewable energy sources such as photovoltaic, wind, and hydropower can be coupled with multilevel inverters to produce AC voltage to power appliances, houses, and entire cities. In the literature, many references have discussed the research into multilevel inverters and their novel topologies [1]. The three types of inverters that have garnered the most attention are cascaded H-bridges (CHB) with separate DC sources, diode clamped inverters, and flying capacitors [2]. Unlike diode clamped inverters and flying capacitors, CHB inverters require a smaller number of total components, thus reducing the total cost of the system [3]. Furthermore, cascaded H-bridges have more advantages due to reduced dv/dt on switching devices, reduction of switching losses, and improved electromagnetic interferences [4]. Besides, CHB inverters have several separate DC sources that can be fed by PV modules.

The advancement in power electronic technology is partly due to the growth in power semiconductors switching devices such as thyristors and transistors (BJT, MOSFET, IGBT, etc.). However, the presence of undesired current and voltage harmonics in the output of systems incorporating these devices has the concern of researchers. Also, nonlinear loads on the power system cause harmonics. Some previous work has been done to analyze the nonlinear effect, such as THD in the AC output of PV systems caused by DC to AC inverters [5]. THD describes a nonlinear waveform's cumulative degree of distortion from the ideal sine waveform. THD is defined as the ratio between the RMS amplitude of higher harmonic frequencies to the RMS amplitude of the fundamental frequency. In North America, the fundamental frequency is 60 Hz. Mathematically, THD is expressed as:

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$$THD = \frac{\sqrt{\sum_{n=3,5,7..}^{\infty} V_n{}^2}}{V_1} * 100 \dots \dots \dots (1)$$

Where V_n is n^{th} Harmonic amplitude (RMS Volts), n is the harmonic, and V_1 is the magnitude of the fundamental (RMS Volts)

H-bridge inverters exhibit an unacceptable THD at their output. By cascading H-bridges inverters, however, the THD can be reduced. As the number of cascaded H-bridge inverters increases, the AC output voltage becomes a smoother sinusoidal staircase, as indicated in Figures 6 and 7 for 5-level and 7-level H-bridge inverters, respectively. Correspondingly, THD decreases [6,7]. However, the results have not shown THD levels below 5% as recommended by US, IEEE 519.

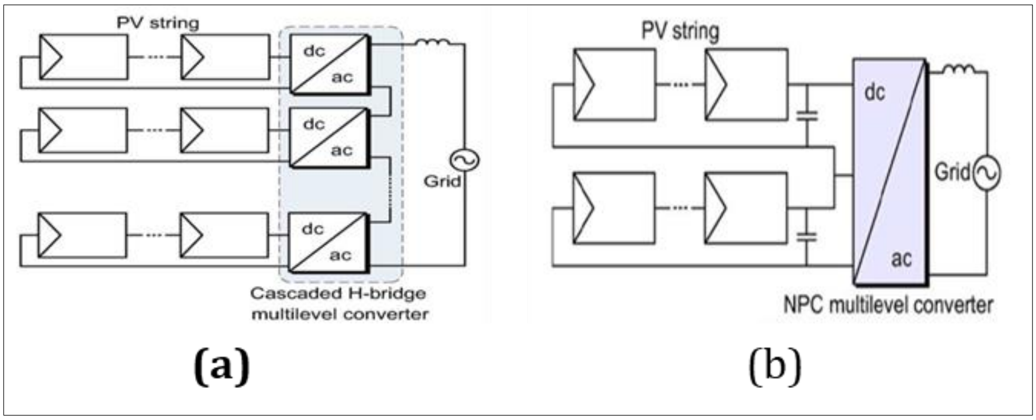

Figure 1 CHB multilevel grid-connected inverter [1]

Figure 1 (a) and (b) [1], illustrate a CHB multilevel inverter and neutral point-clamped inverter for multistring PV topology. The multistring topology increases the voltage while reducing the average switching frequency of the device. The increase in voltage reduces the harmonics and increases efficiency [1]. Additional filtering devices may be needed to further reduce THD [8]. In PV systems, CHB multilevel inverter's ability to reach medium to high voltage levels, relatively with simple switching logic, and low maintenance requirements, make it ideal for PV systems [9]. Low-switching frequency modulation schemes for MLI such as Selective Harmonic Mitigation (SHM) allow for efficient power conversion but lead to higher computational costs and increased hardware resources [10]. Hybrid multilevel inverters show advantages in lower levels compared to CHB multilevel inverters [11]. However, since PWM techniques are implemented, high frequency switches are needed per stage. Inverter reliability inevitably declines as high frequency switching devices are increased while increasing the cost drastically.

The importance of power quality has been well studied over the years [12]. The degree to which harmonics are acceptable in any system leads to either adding filters or foregoing them to minimize cost. This paper explores the cost and performs THD analysis of multilevel cascaded H-bridge inverters (3, 5, 7, 9, and 11-levels) with and without two types of filters, passive and active. With the analysis performed by the paper, we can choose the most appropriate multilevel CHB topology to give us both the most cost-effective and best-performing inverter topology for a given situation.

2. Methodology

2.1. Cascaded H-bridge

The single-phase cascaded H-bridge structure used in this paper has separate DC sources of 100 V and a MOSFET, acting as a switch. The number of DC sources determines the number of output voltage levels. The relationship between the number of output voltage levels and the number of DC sources is given in Equation 2.

$$m = 2s + 1 \dots \dots \dots \dots (2)$$

Where s is the number of H-bridges, and m is the number of voltage levels.

2.2. Single-phase five-level cascaded H-bridge Inverter

This subsection of the article reports on the simulation study for a 5-level CHB inverter. A single-phase five-level cascaded H-bridge inverter has two H-bridges connected in series to produce AC power from two separate DC voltage sources. A single-phase five-level CHB as used in PSIM is shown in Figure 2. The switching states of the single-phase five-level cascaded H-bridge inverter are shown in Table 1

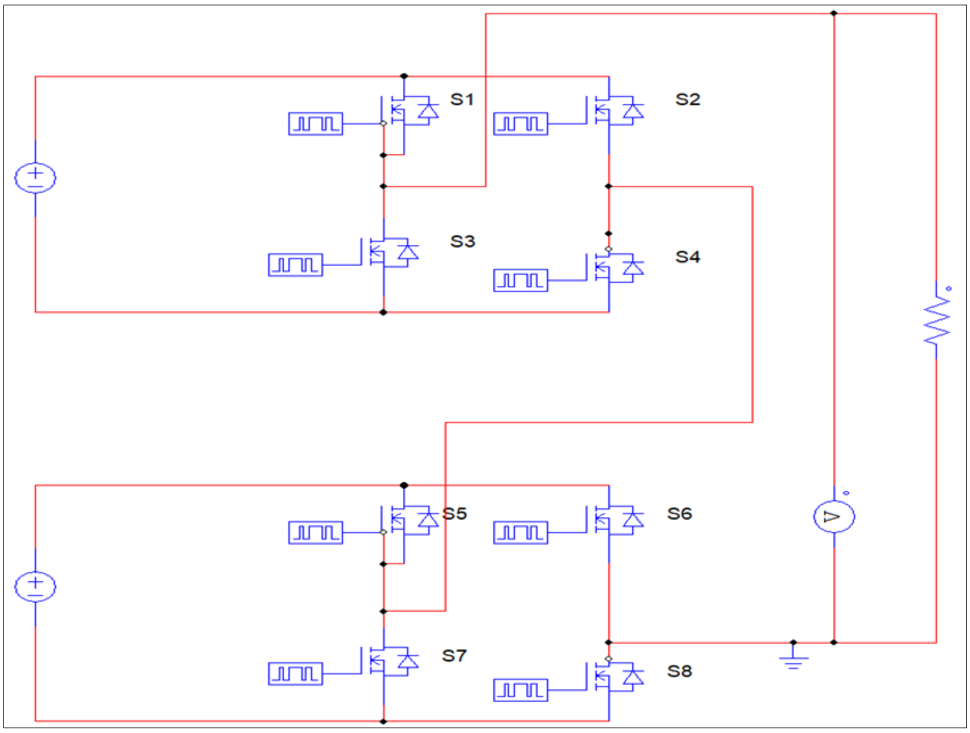

Figure 2 Single-phase five-level H-bridge Inverter

Table 1 Single-phase five-level H-bridge Inverter Switching States

State	Switching Sequences								Voltage Levels
	S1	S2	S3	S4	S5	S6	S7	S8	
1	1	0	0	1	1	0	0	1	+2Vdc
2	1	0	0	1	1	1	0	0	+Vdc
3	1	1	0	0	1	1	0	0	0
4	0	1	1	0	1	1	0	0	-Vdc
5	0	1	1	0	0	1	1	0	-2Vdc

2.3. Single-phase seven-level cascaded H-bridge Inverter

A single-phase seven-level cascaded H-bridge inverter has three H-bridges linked in series to produce AC power from three individual DC voltage sources as an input voltage source. A single-phase seven-level cascaded H-bridge inverter used in the simulation study is shown in Figure 3. A seven-level CHB inverter has an output voltage of +3Vdc, +2Vdc, +Vdc, 0, -Vdc, -2Vdc, and -3Vdc. The corresponding switching states of the single-phase seven-level cascaded H-bridge inverter are detailed in Table 2.

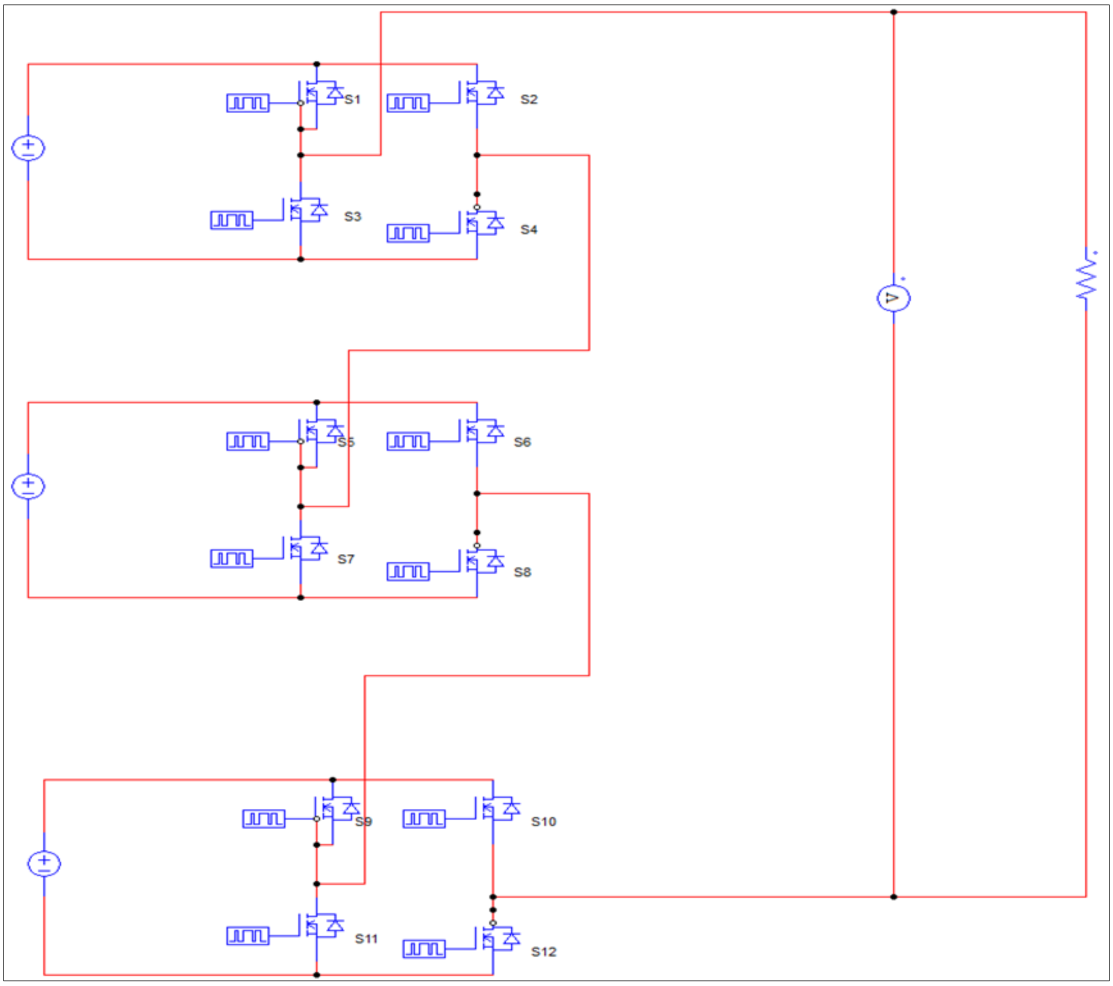

Figure 3 Single-phase Seven-level H-bridge Inverter

Table 2 Single-phase Seven-level H-bridge Switching States

State	Switching Sequences												Voltage Levels
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	
1	1	0	0	1	1	0	0	1	1	0	0	1	+3Vdc
2	1	0	0	1	1	0	0	1	1	1	0	0	+2Vdc
3	1	0	0	1	1	1	0	0	1	1	0	0	+Vdc
4	1	1	0	0	1	1	0	0	1	1	0	0	0
5	0	1	1	0	1	1	0	0	1	1	0	0	-Vdc
6	0	1	1	0	0	1	1	0	1	1	0	0	-2Vdc
7	0	1	1	0	0	1	1	0	0	1	1	0	-3Vdc

2.4. Single-phase three-level H-bridge Inverter incorporating filters

A filter is a circuit that allows desirable frequencies to pass while rejecting all other frequencies. There are two types of filters, active and passive filters. Passive filters have passive elements such as resistors, inductors, and capacitors. Passive elements do not generate power but can receive energy to store, dissipate, or release. As their name suggests, active filters have active components and passive elements. Active components can generate electrical energy. Examples of active components are operational amplifiers, bipolar junction transistors, silicon-controlled rectifiers, etc. The transfer function H (w) and cutoff frequency (w_c), for an RC filter, is given in Equation 3 and 4, respectively. The cutoff frequency was chosen as 65 Hz, to include only the fundamental frequency.

$$H(w) = \frac{1}{1 + jwRC} \dots \dots \dots \dots (3)$$

$$w_c = \frac{1}{RC} \dots \dots \dots \dots . (4)$$

Figure 4 illustrates the simulation setup of the five-level H-bridge inverter incorporating an RC filter with a cutoff frequency of 65 Hz. Figure 5 depicts the simulation setup of the five-level H-bridge inverter incorporating a second-order active RC filter with a cutoff frequency of 65 Hz.

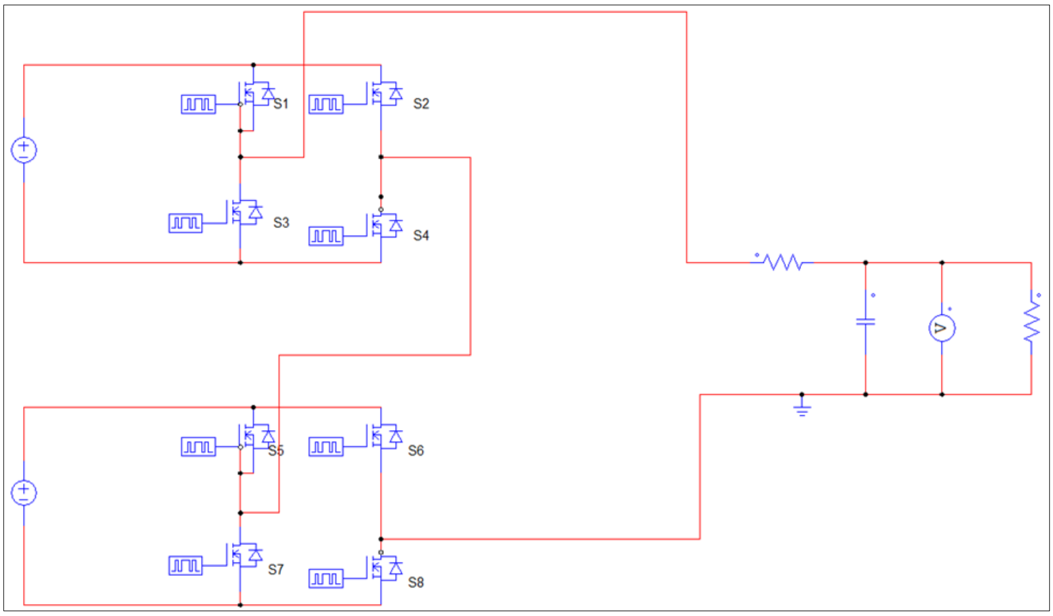

Figure 4 5-level H-bridge inverter incorporating passive lowpass filter

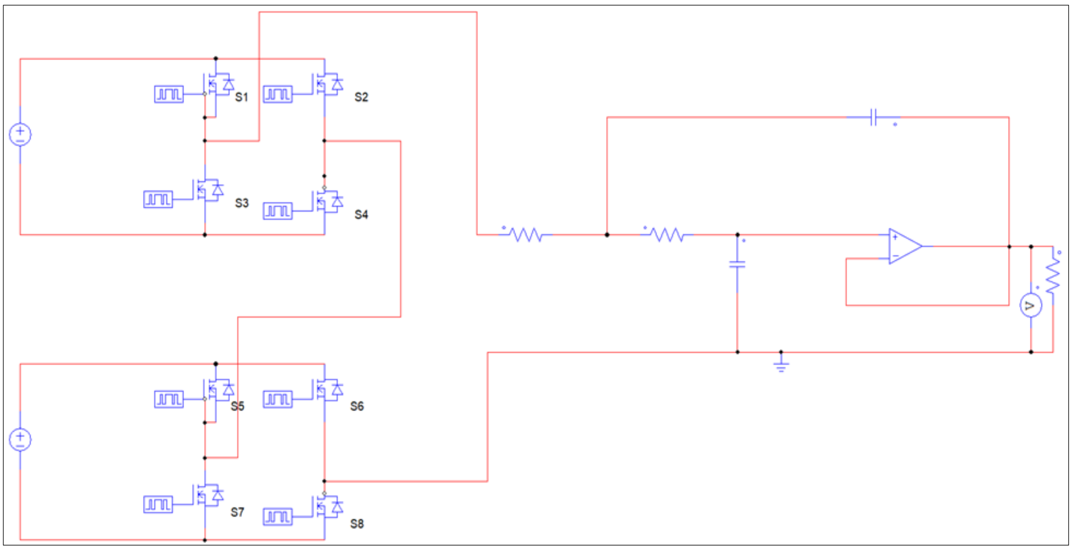

Figure 5 5-level H-bridge inverter incorporating second-order active lowpass filter

3. Results and discussion

The results from the simulation show that as the number of cascaded H-bridge inverters increases, the output voltage becomes a smoother sinusoidal staircase, as shown in Figures 6 and 7, respectively. The THD decreases further when a passive RC filter and second-order active filter are incorporated at the output of the H-bridge inverter. The second-order active filter is shown to provide the most significant THD reduction when integrated into the cascaded H-bridge multilevel inverter.

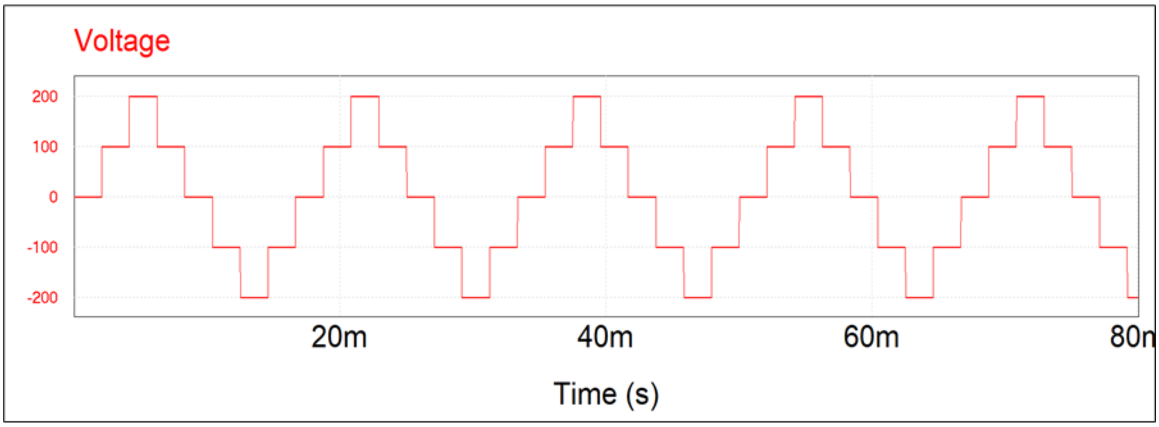

Figure 6 Output waveform of single-phase five-level H-bridge inverter

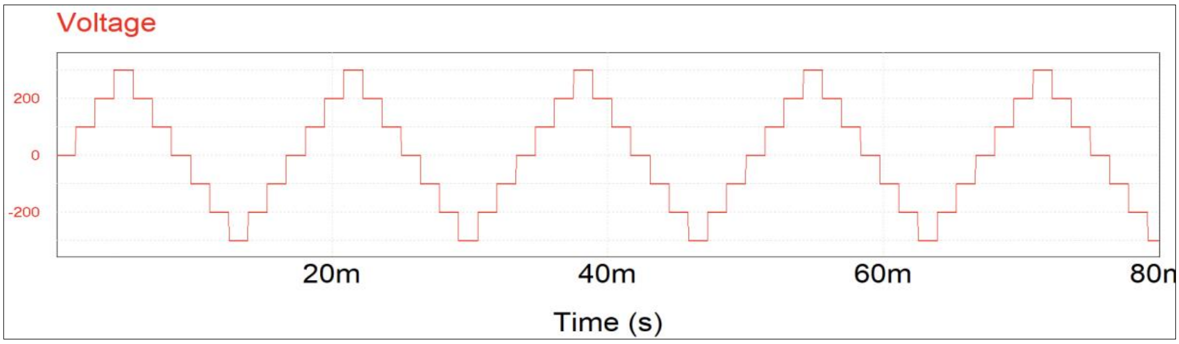

Figure 7 Output waveform of single-phase seven-level H-bridge inverter

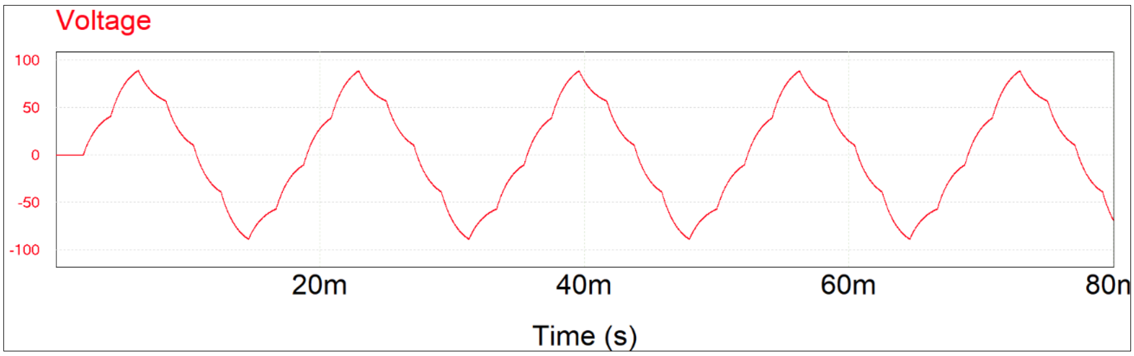

Figure 8 Output waveform of single-phase five-level H-bridge inverter incorporating passive filter

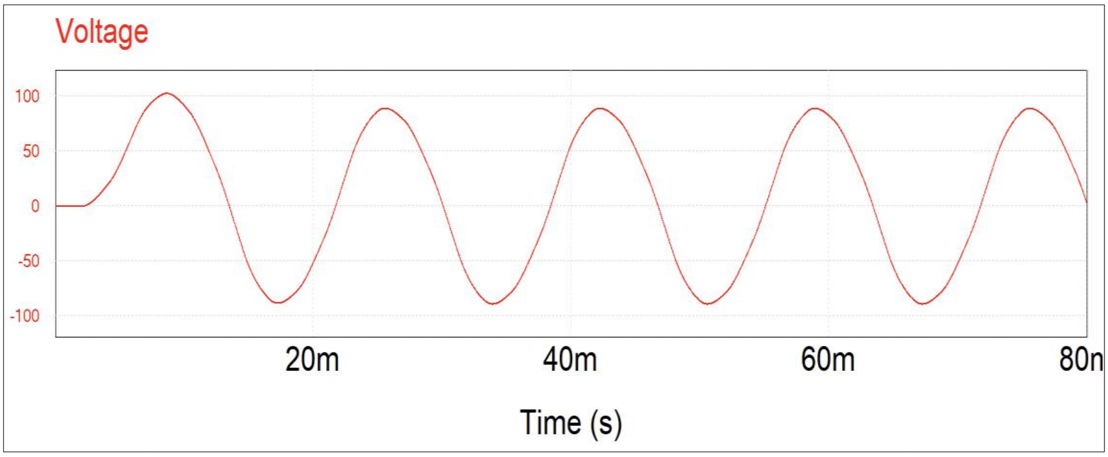

Figure 9 Output waveform of single-phase five-level H-bridge inverter incorporating second-order active filter

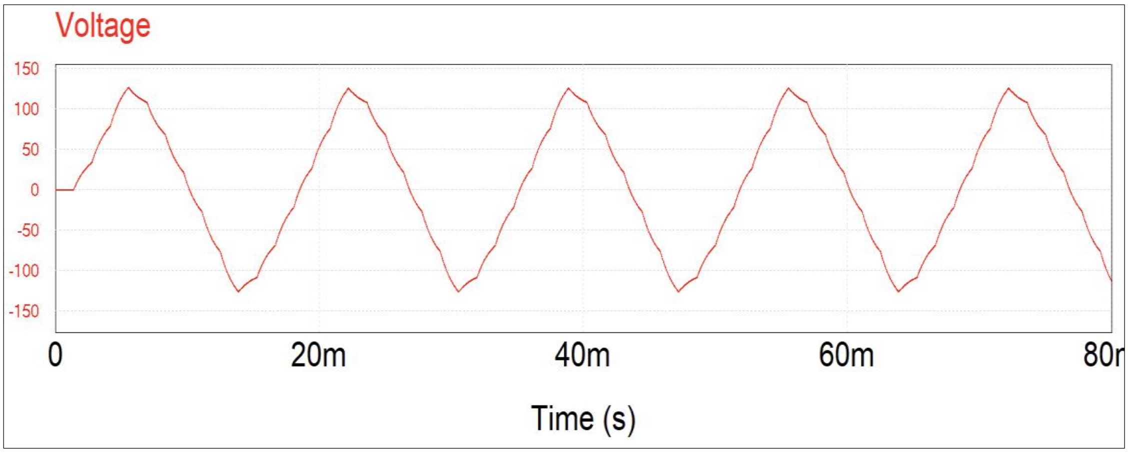

Figure 10 Output waveform of single-phase seven-level H-bridge inverter incorporating passive filter

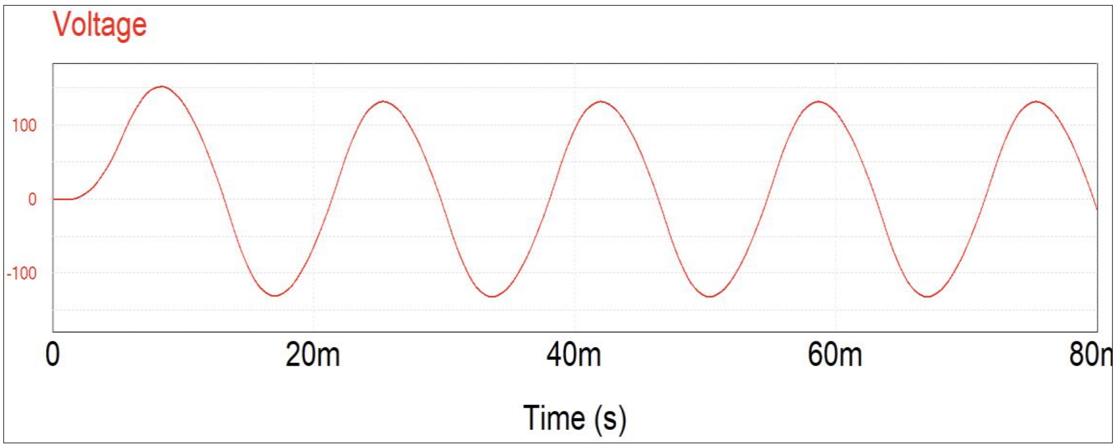

Figure 11 Output waveform of single-phase seven-level H-bridge inverter incorporating second-order active filter

Table 3 shows the THD and costs comparison results of a multilevel cascaded H-bridge inverter (MCHI), MCHI incorporating a passive filter, and MCHI incorporating an active filter. Furthermore, a cost increase is calculated after including a passive or active filter in the base cost of the (3, 5, 7, 9, and 11-levels) H-bridge inverters. For the base prices of the inverter and filters, see www.Digikey.com. A 90 kW H-bridge inverter is chosen as a reference.

Table 3 THD and Cost Comparison of H-bridge Inverter Type

H-Bridge Inverter Type	THD	Cost (USD)	Cost Increase %
3-Level	48.34%	$7,150	Base (0%)
3-Level Incorporating Passive Filter	23.98%	$7,497	4.85%
3-Level Incorporating 2nd Order Active Filter	7.34%	$8,191	14.56%
5-Level	28.96	$14,300	Base (0%)
5-Level Incorporating Passive Filter	11.20%	$14,647	2.43%
5-Level Incorporating 2nd Order Active Filter	3.11%	$15,341	7.28%
7-Level	21.59%	$21,450	Base (0%)
7-Level Incorporating Passive Filter	8.73%	$21,797	1.62%
7-Level Incorporating 2nd Order Active Filter	2.67%	$22,491	4.85%
9-Level	18.19%	$28,600	Base (0%)
9-Level Incorporating Passive Filter	7.93%	$28,947	1.21%
9-Level Incorporating 2nd Order Active Filter	2.54%	$29,641	3.64%
11-Level	16.27%	$35,750	Base (0%)
11-Level Incorporating Passive Filter	7.76%	$36,097	0.971%
11-Level Incorporating 2nd Order Active Filter	2.49%	$36,791	2.91%

4. Conclusion

A THD and cost comparisons are made of single-phase multilevel cascaded H-bridge inverters (3, 5, 7, 9, and 11-levels) without a filter, and single-phase multilevel cascaded H-bridge inverters (3, 5, 7, 9, and 11-levels) with a passive filter or active filter. PSIM platform is used to perform the THD analysis. Results obtained in the analysis show that by cascading H-bridge inverters, THD decreases. Further, a significant reduction of THD is obtained when a passive or active filter is added to the output of the H-bridge inverter. The cost of active filters is drastically higher than that of a passive filter. However, it is concluded that the benefits of improvement in THD due to incorporating a passive or active filter with the cascaded H-bridge inverter, far outweigh the minor increase in overall cost. Besides, the addition of the filters renders the THD results to satisfactorily meet the THD levels below 5% as recommended by US, IEEE 519.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that no conflict of interest exists between them.

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