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OPERATION AND CONTROL OF CASCADED H-BRIDGE MULTILEVEL INVERTER WITH PROPOSED SWITCHING ANGLE ARRANGEMENT TECHNIQUES

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Abstract

Cascaded H-bridge multilevel inverter is one of the most promising inverter topologies for converting the DC output of renewable energy resources such as: photovoltaic power systems, fuel cells and solar thermal panel into AC power supply. It has received wide spread acceptability due to its capability to produce high quality output AC waveform with low switching frequency. However, cascaded H-bridge inverter topology is not capable of producing good output voltage AC waveform when switching angle arrangement techniques are not appropriately selected. Therefore, this research work has been performed motivated strongly by this key issue in this field of research to be resolved. In this paper, a new set of switching angle arrangement techniques have been proposed to obtain good quality output voltage and current waveform from cascaded H-bridge multilevel inverter. The validity and effectiveness of proposed switching angle arrangement techniques have been verified using a simulation of a cascaded H-bridge multilevel inverter with inductive load through PSIM software. Simulation results indicate that the output voltage and current AC waveform produced via proposed switching angle arrangement techniques have the lowest total harmonic distortion as compared to those produced by Equal-phase method and Half-equal-phase method.

Keywords: Multilevel inverter, Photovoltaic, Power quality, Switching angle, Total harmonic distortion.

1. Introduction

Currently, researchers are focusing on the generation of electrical energy from modern methods utilizing renewable energy resources. Among the renewable resources of energy, solar thermal panels, photovoltaic (PV) panels, fuel cells, and

Abbreviations

PV	Photovoltaic
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
THD	Total Harmonic Distortion

micro-turbines are major energy sources all over the world today [1]. It has been reported that PV systems offer better performance compared to other renewable energy resources due to the vast availability of solar radiations. Thus, PV technology is gaining popularity for electrical energy generation nowadays as it is the cleanest source of energy and available all over the world [2]. The electrical energy generated from PV system is in DC form and it needs to be converted to AC voltage output waveform through an inverter [3]. Different types of inverters have been proposed by different group of researchers. The staircase AC voltage output waveform of multilevel inverter consists of low total harmonic distortion (THD) and hence it does not require expensive filters. Therefore, multilevel inverters have gained high popularity and applications among different types of inverters [4].

The concept of multilevel inverters was introduced in 1975 and the first multilevel inverter was proposed by Baker and Bannister. The term multilevel began with the three-level inverter. There are three basic configurations of multilevel inverters such as; diode-clamped multilevel inverter, flying-capacitor multilevel inverter and cascaded H-bridge multilevel inverter have been proposed by researchers. In 1981, Nabae and Akagi proposed diode-clamped multilevel inverter which is also known as the neutral-point clamped multilevel inverter [5]. This configuration required a large number of clamping-diode and capacitors in series to divide the DC bus voltage into a set of voltage levels. The charging and discharging rate of each capacitor is different and it resulted higher THD. The flying-capacitor (capacitor-clamped) multilevel inverter was introduced by Meynard and Foch [6]. The flying capacitors multilevel inverter consists of large number of storage capacitors and the balancing of storage capacitor makes the inverter control complicated. In addition, this topology has poor switch utilization due to the several switching redundancies for producing same level of voltage [7-8].

Cascaded H-bridge multilevel inverter was proposed by Jih-Sheng and it has recently become the most popular topology among different types of multilevel inverter for stand-alone PV systems [9-10]. The optimized circuit layout and packing of cascaded H-bridge multilevel inverter is possible because each level has the same structure and there is no extra clamping diode and voltage-balancing capacitor. The number of output voltage levels can be easily adjusted by adding or removing the H-bridge. In addition, cascaded H-bridge multilevel inverter has easier switching control and lower probability of system failure due to lower number of components. But the operation of cascaded H-bridge multilevel inverter depends on switching angle thus, the selection of appreciate switching angle arrangement technique is necessary. Equal-phase and Half-equal-phase method based on traditional concept has been proposed by researchers in literature [11]. These techniques still produce high THD and its can be improved further. Thus, this paper presents a new set of switching angle arrangement techniques based on the concept of a traditional method to determine the switching angle which is able to achieve lower THD and produce smoother AC output.

The reminder of this paper is organized as follows. Section 2 provides the detail description of the methodology. Section 3 present results and discussion of cascaded H-bridge multilevel inverter with proposed and conventional switching angle arrangement techniques. Finally, the conclusion is provided in Section 4.

2. Methodology

This section consists of two subsections as follows: Section 2.1 provides a briefly operation of 5-level cascaded H-bridge multilevel inverter. Section 2.2 presents the concept and detail description of proposed switching angle arrangement techniques.

2.1. Operation of cascaded H-bridge multilevel inverter

The 5-level cascaded H-bridge inverter uses two H-bridge for accomplishing a five-level voltage output waveform. Basically, each H-bridge consists of four power MOSFETs and four freewheeling diodes, which can be seen from Fig. 1. The 5-level cascaded H-bridge inverter circuit consists of eight power MOSFETs, eight freewheeling diodes and two DC sources. From Table 1, there are six switching combinations to synthesized the five output voltage levels, i.e., +2VDC, +VDC, 0, -VDC and -2VDC across the load. From Fig. 1, during inverter operation for the positive value, switches S_1 and S_4 are closed at the same time to produce +VDC. To produce the +2VDC switches S_5 and S_8 are turned on at the same time. For the negative value, switches S_2 and S_3 are closed to provide –VDC and to achieve the -2VDC the switches S_6 and S_7 are turned on at the same time. For generating the zero-level, swapped zero-level switching method is used in order to maintain the equal operational time for each switch.

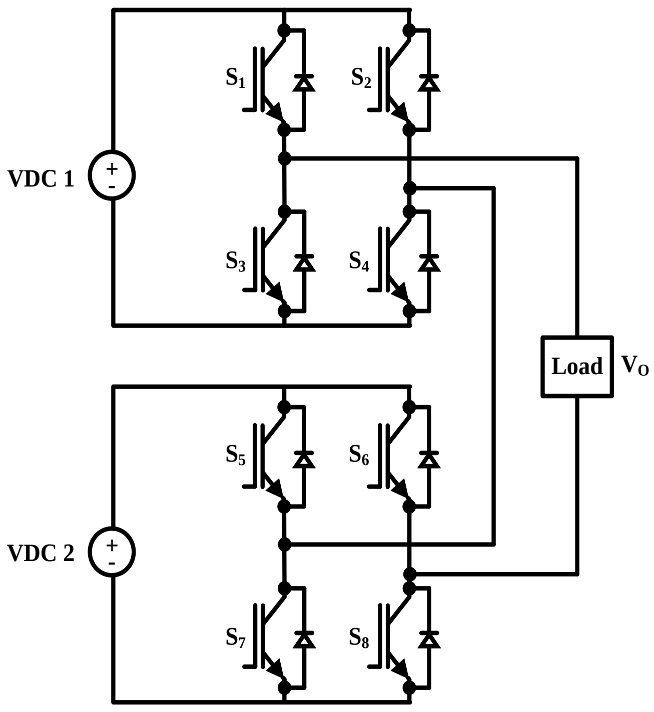

Fig. 1. 5-level cascaded H-bridge multilevel inverter.

Table 1. Switching states of 5-level cascaded H-bridge multilevel inverter.

V_o	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
2VDC	1	0	0	1	1	0	0	1
VDC	1	0	0	1	0	0	1	1
0	1	1	0	0	1	1	0	0
	0	0	1	1	0	0	1	1
-VDC	0	1	1	0	1	1	0	0
-2VDC	0	1	1	0	0	1	1	0

(Zero indicate the switch is off and 1 indicate the switch is on)

A simple gate signal using swapped zero-level switching pattern is shown in Fig. 2 for 5-level cascaded H-bridge multilevel inverter. In swapped zero-level switching method, to produce the first zero stage (P1 and P5) switches S_1, S_2, S_5 and S_6 are turned on; then, in the second zero stage (P6 and P10) switches S_3, S_4, S_7 and S_8 are turned on instead of S_1, S_2, S_5 and S_6.

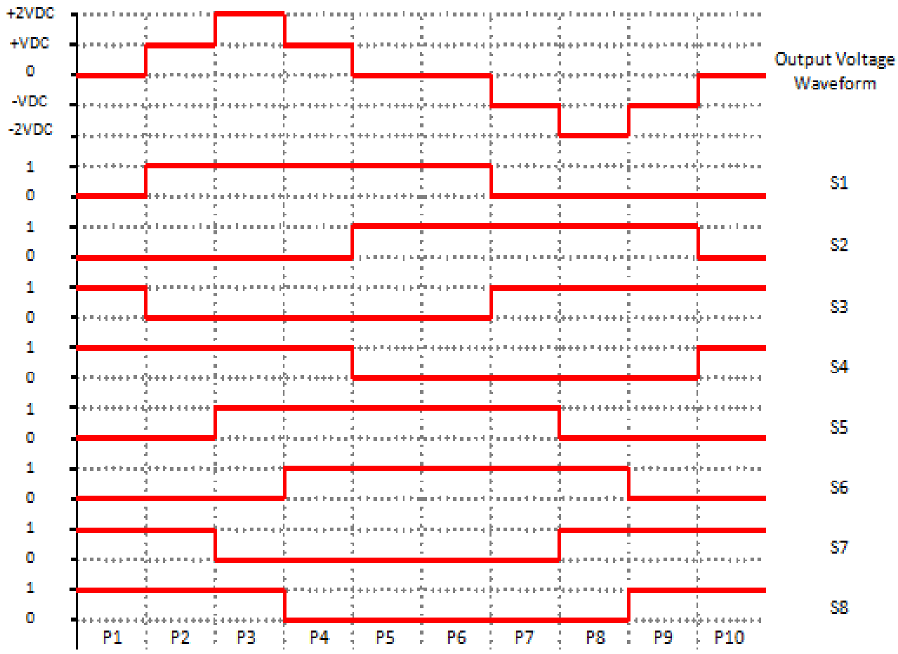

Fig. 2. Swapped zero-level switching pattern.

2.2. Proposed switching angle arrangement techniques

Multilevel inverters have various configurations and several advantages. However, the exiting topologies of multilevel inverters fail to produce pure sinusoidal output waveform because the switching angles are not selected properly [12]. In this paper, two different switching angle arrangement techniques are proposed and carefully investigated in order to achieve the lowest THD and good power quality.

The moment of the level change is basically known as switching angle. The output voltage waveform for an m-level multilevel inverter is shown in Fig. 3. For an m-level waveform in the period (0-2π), there are 2(m-1) switching angles which need to be determined. The switching angles are defined as $\theta_1, \theta_2, ..., \theta_{m-2}, \theta_{m-1}$ by the time sequences. The sine wave is divided into four quadrants.

The switch angle ((*m*-1)/2) in first quadrant (0-π/2) are define as main switching angles for an m-level (*m* is an odd number) waveform. The detail of switching angles in first, second, third and fourth quadrant are described in Table 2. However, only the main switching angles are need to be determined for purpose of analysing and the other switching angles can be derived from the main switching angles in the first quadrant (0-π/2).

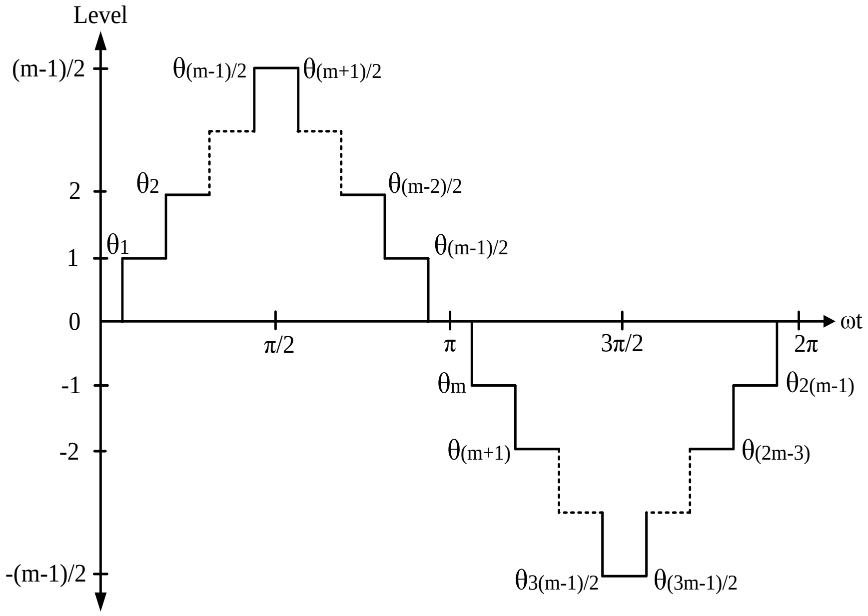

Fig. 3. Output voltage waveform for multilevel inverter.

Table 2. Switching angle calculation.

Quadrant Number	Period	Switching Angle
First	0-π/2	$\theta_1, \theta_2, ..., \theta_{(m-1)/2}$
Second	π/2-π	$\theta_{(m+1)/2} = \pi + \theta_1$
Third	π-3π/2	$\theta_m = \pi + \theta_{(m-1)/2}$
Forth	3π/2-2π	$\theta_{(3m-1)/2} = 2\pi - \theta_1$

2.1.1. Tri-equal-width method

The Tri-equal-width method is derived from the simplest idea that when the function value increases to the half-height of waveform level than the switching angles in the range 0 – π/2 is set and thus output waveform is obtained. In this method, the width of zero-level is set to approximately three times of the width of first-level and the main switching angles from this method are calculated by the following formula:

$$\theta_i = tan^{-1}(\frac{2i}{m-1}) \quad (1)$$

Here, $i = 1, 2, ... \frac{m-1}{2}$.

2.1.2. Half-equal-width method

The output voltage waveform of multilevel inverter obtained from Tri-equal-width method looks very narrow, like a triangle waveform. Hence, to obtain a better output waveform another method has been introduced to determine the main switching angle which is known as Half-equal-width method. Half-equal-width method is basically derived from simplest concept that the width of zero-levels is roughly set to half of the width of top-level. The main switching angles are in the range 0–π/2, which is determined by using Eq. (2).

$$\theta_i = i * (\frac{90^\circ}{m-1}) \quad (2)$$

Here, $i = 1, 2, ... \frac{m-1}{2}$.

3. Results and Discussion

A 3-, 5-, 7-, 9-, and 11-level cascaded H-bridge multilevel inverters are simulated using PSIM software. Equal-phase, Half-equal-phase, and proposed methods, i.e., Tri-equal-width and Half-equal-width methods are applied to 3-, 5-, 7-, 9-, and 11-level cascaded H-bridge inverter and the simulation results are presented and discussed in this section. The constant switching frequency of 50 Hz and DC input voltage is equal to 50 V. While the power MOSFET are idle, an inductive load is equal to 10 Ω resistor and 0.028 H inductor and the switching angles are derived from Equal-phase, Half-equal-phase and proposed methods, i.e., Tri-equal-width and Half-equal-width switching angle arrangement techniques. The voltage output waveform for the 5-level cascaded H-bridge multilevel inverter is shown in Fig. 4 whilst, the output waveform of current for the 5-level cascaded H-bridge multilevel inverter are shown in Fig. 5.

The simulation results indicate that the number of levels of a cascaded H-bridge multilevel inverter has a direct relationship with the THD. It was observed that the THD decreased as the number of level of cascaded H-bridge multilevel inverter increased. As the THD decreased, the output waveform became more sinusoidal, similar to an AC waveform. Figure 6 illustrates the perceived of voltage THD versus the number of levels of cascaded H-bridge multilevel inverters, which indicates that the voltage THD of 3-level to 11-level cascaded H-bridge multilevel inverter from Equal-phase, Half-equal-phase, Tri-equal-width and Half-equal-width methods are decreased from about 80.32% to 22.33%, 48.38% to 19.95%, 48.37% to 12.00%, and 48.37% to 09.80%, respectively.

On the other hand, Fig. 7 shows the current THD versus the number of levels of cascaded H-bridge multilevel inverters. It is analysed by simulation results that the current THD of 3-level to 11-level cascaded H-bridge multilevel inverters from Equal-phase, Half-equal-phase, Tri-equal-width and Half-equal-width methods are decreased from about 32.42% to 08.99%, 17.36% to 08.20%, 17.30% to 02.73%, and 17.30% to 02.03%, respectively. The inductive load only affects the THD of the current; it does not affect the THD of the voltage because the function of the inductor is to filter the current distortion. Therefore, the voltage THD was higher as compared to current THD. Furthermore, when the inductor value increased, the current THD decreased and the current output waveform becomes smoother, similar to a sinusoidal waveform. Table 3 shows the voltage and current THD of 3-level to 11-level cascaded H-bridge multilevel inverter.

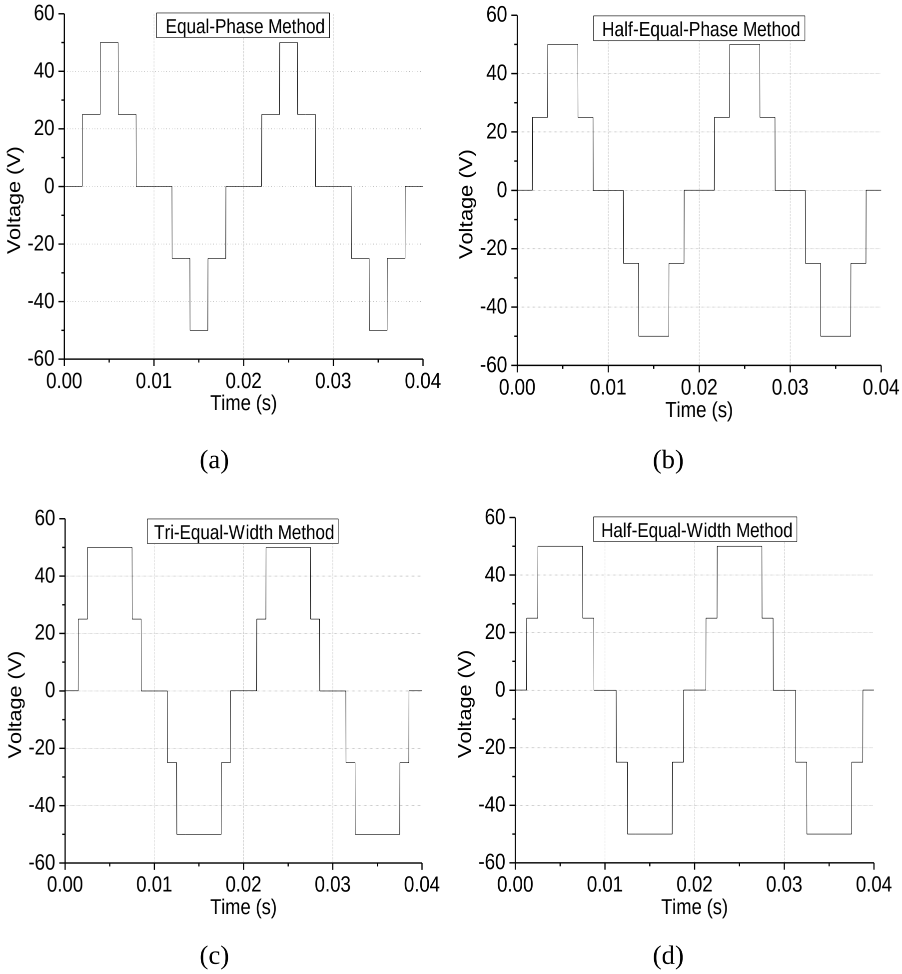

Fig. 4. Voltage output waveform with Equal-phase method, Half-equal-phase method and proposed methods (Tri-equal-width method and Half-equal-width method).

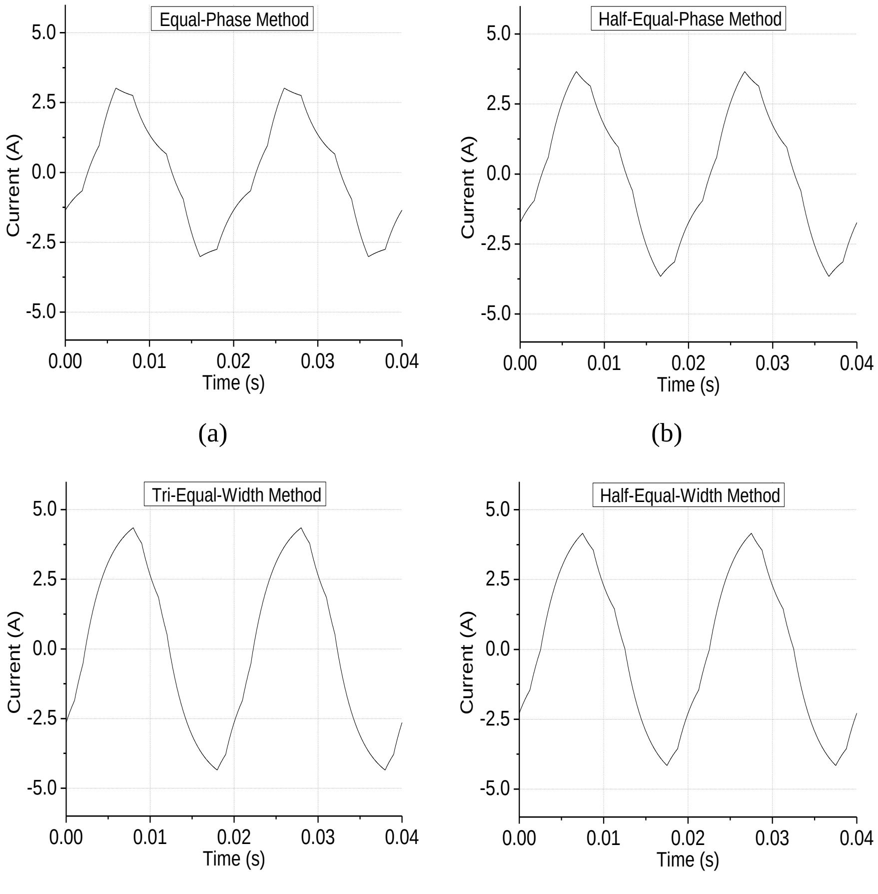

Fig. 5. Current output waveform with Equal-phase method, Half-equal-phase method and proposed methods (Tri-equal-width method and Half-equal-width method).

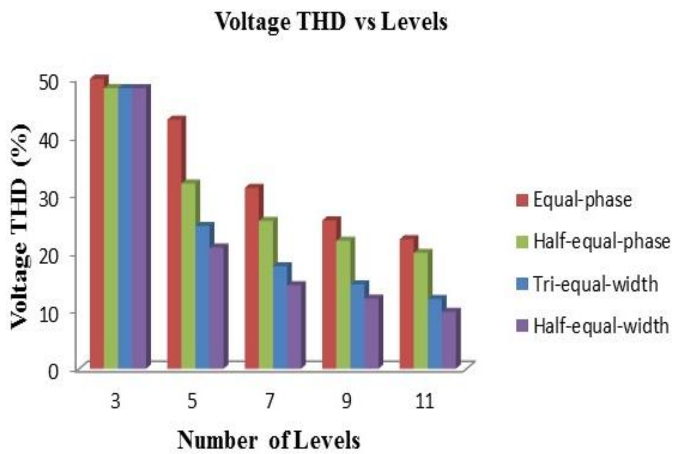

Fig. 6. Voltage THD vs number of levels.

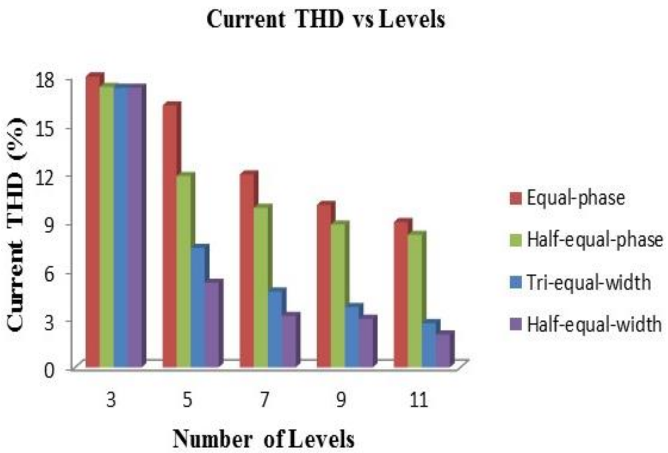

Fig. 7. Current THD vs number of levels.

Table 3. Voltage and current THD.

Number of Levels	Equal-Phase	Half-Equal-Phase	Tri-Equal-Width	Half-Equal-Width
		Voltage THD (%)		
3	80.32	48.38	48.37	48.37
5	42.93	31.92	24.61	20.88
7	31.18	25.47	17.65	14.39
9	25.57	22.05	14.53	12.08
11	22.33	19.95	12.00	09.80
		Current THD (%)		
3	32.42	17.36	17.30	17.30
5	16.21	11.84	07.39	05.23
7	11.94	09.87	04.69	03.18
9	10.05	08.84	03.73	03.00
11	08.99	08.20	02.73	02.03

4. Conclusions

In this paper, the validity of a new set of switching angle arrangement techniques for cascaded H-bridge multilevel inverter was analysed and evaluated using PSIM software. The detailed description of proposed methods namely Tri-equal-width and Half-equal-width switching angle arrangement techniques have been provided. Based on achieved results, it was observed that the simulation results of the 3-, 5-, 7-, 9-, and 11-level cascaded H-bridge multilevel inverters indicated that the voltage and current output waveform from proposed switching angle arrangement techniques such as Tri-equal-width method and Half-equal-width method was more sinusoidal as compared to Equal-phase method and Half-equal-phase method. It is also revealed from the analysis of the results that the output waveform obtained using the Half-equal-width method had the lowest total harmonic distortion with respect to other switching angle arrangement techniques using in this research work. Furthermore, the voltage and current THD decreased as the number of levels increased.

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