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Mathematical modeling and engineering design of multi-level inverter based on selective harmonic elimination

***Abstract:** SHE is a well-studied alternative to common PWM methods. This work shows how to use a Newton Raphson method to selectively reduce higher or lower order harmonics while preserving the needed fundamental voltage in asymmetrical multilevel inverter. This strategy can be used with any number of levels in asymmetrical multilevel inverter. For example, a 9-level and 27-level asymmetrical multilevel inverter is analyzed in this research, and the optimal angles are determined to eliminate the 3rd, 5th and 7th harmonics for nine level inverter and to eliminate twelve odd harmonic from 3rd harmonic to 25th harmonic for twenty seven level inverter.*

Streszczenie.** SHE jest dobrze zbadaną alternatywą dla popularnych metod PWM. Ta praca pokazuje, jak wykorzystać metodę Newtona Raphsona do selektywnej redukcji wyższych lub niższych harmonicznych przy jednoczesnym zachowaniu wymaganego napięcia podstawowego w asymetrycznym falowniku wielopoziomowym. Ta strategia może być stosowana z dowolną liczbą poziomów w asymetrycznym falowniku wielopoziomowym. Na przykład w tych badaniach analizowany jest 9-poziomowy i 27-poziomowy asymetryczny wielopoziomowy falownik, a optymalne kąty są określane w celu wyeliminowania 3, 5 i 7 harmonicznej dla 9-poziomowego falownika oraz wyeliminowania 12 nieparzystych harmonicznych od 3 do 25 harmonicznej. harmonicznych dla dwudziestu siedmiu poziomów falownika.* (Modelowanie matematyczne i projektowanie inżynierskie wielopoziomowego falownika w oparciu o selektywną eliminację harmonicznych***)

Keywords: selective harmonic elimination, THD, 9-level inverter, 27-level inverter.
Słowa kluczowe: selektywna eliminacja harmonicznych, 9-stopniowy przekształtnik

Introduction

In recent years, multilevel inverters have become increasingly popular in high-power applications [1] and in variable-speed drives. It has found their way into a wide range of common applications, including fans, pumps, and other mechanical devices because their current ratings are lower at higher power levels [2]. Multilevel converters are also used in active filters [3].

A variety of multilevel inverter topologies have been investigated and presented [4]. Among them are: neutral point clamped inverters [5], flying capacitors inverters [6], and cascaded inverters [7], the neutral-point-clamped inverter has been widely employed in the industry [8]. The cascaded inverters topology, on the other hand, show several advantages Because e it has more levels and a lower voltage rate, the popular voltage all across motor windings is reduced. [9] In addition this topology is straightforward, and its modular design allows it to be easily expanded to accommodate any number of outpu

t voltage levels are possible. The number of switches required in all popular multilevel converter topologies is determined by the output level required [10]. However, as the number of power switches increase, the complexity of the inverter circuit and control increase, as well as the price. Asymmetrical multilevel inverter can be utilized to give a high number of output levels without adding additional power switches [11].

The THD of the output voltage waveform must be kept below the acceptable limits when building an effective multilevel inverter. In order to obtain reduced THD, selective harmonic elimination (SHE) has been extensively researched. [12, 13]. The use of silicon carbide (SiC) switches in the inverter design can produce sinusoidal voltages with decreased total harmonic distortion [14].Fourier theory is used to analyze the output voltage waveform, which results in a series of nonlinear equations. If these equations have a solution, it indicates the switching angles required for a specific fundamental component and harmonic profile. To solve these sets of equations, iterative approaches such as the Newton-Raphson method have been applied [15]. This approach is derivative-dependent and may result in local optima, careful initial value selection alone ensures conversion [16]. Also, it presents another strategy based on turning the transcendental problem into polynomial equations [17]. To eliminate certain harmonics, the resultant theory is employed to compute the switching angles. However Because the number of inverter levels rises, this technique appears to be undesirable.in addition to the degree of the polynomials in the mathematical model which is likely to cause numerical difficulties as well as a significant computing burden.

In this paper, a Newton Raphson technique will be provided It resolves the same problem in a more simple manner and any number of levels without requiring lengthy analytical expression derivation. Newton Raphson is a search approach that mimics biological evolutionary processes to locate the maximum number of functions. In the literature, there is a few instances of Newton Raphson applications for power electronics [18-21].

Circuit topology

The asymmetrical structure employed in this research refers to the cascaded H-bridge (CHB) inverter structures with unequal dc voltage sources [22],[23]. When compared to the symmetrical CHB topology, this topology has the benefit of fewer power electronic Cascade inverter [25]. This can be accomplished by feeding the cascaded bridge inverter with Different dc voltage sources in a 1:3 ratio for nine -level and 1:3:9 for Twenty Seven -level. The polarity of H-bridge will be in three statuses, negative, positive or zero depending on the sequence of switching as shown in Fig1

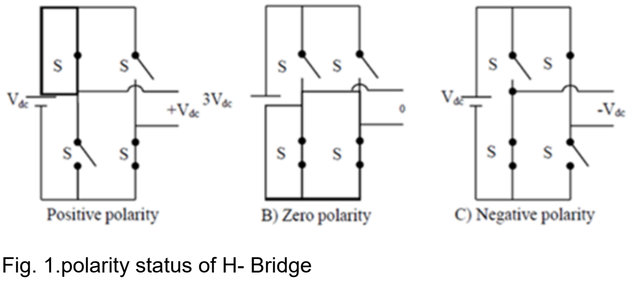

Fig. 1.polarity status of H- Bridge

1. Nine Level Asymmetrical CHB

Fig. 2 depicts a 9 -level asymmetrical inverter made up of two H-bridge. Each H-bridge composed of four power switches and a different single dc voltage source. By using different switching sequences for each H-bridge, the output voltage HB1 can be equal to Vdc, 0, and -Vdc with suitable switching sequences used for both H-bridges. In contrast, the output voltage HB2 can be set to 3Vdc, 0Vdc, or -3Vdc. As a result, the inverter's output voltage has nine different values: Vdc, 2Vdc, 3Vdc, 4Vdc, 0, -Vdc, -2Vdc, -3Vdc, and -4Vdc, as shown in Table 1

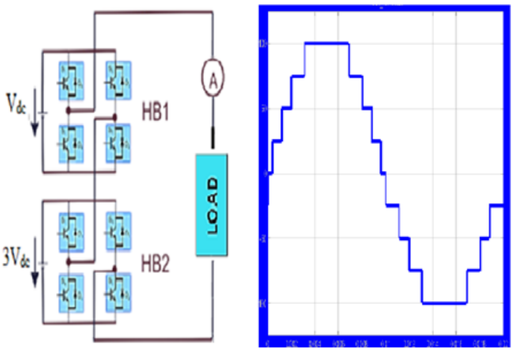

Fig. 2. Nine-level inverter output voltage

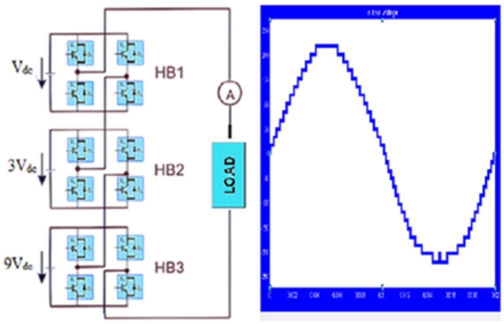

Fig. 3. Twenty-seven level inverter output voltage

2. Twenty Seven Level Asymmetrical CHB

Fig.3 depicts a Twenty Seven -level asymmetrical CHB inverter made up of three H-bridges; four switches and an unequal single dc voltage source. Using different switching sequences for each H-bridge. The output of HB1 can be equal to Vdc, 0, and -Vdc by using suitable switching sequences for both cells. In contrast, the output of HB2 can be set to 3Vdc, 0Vdc, or -3Vdc and the last output voltage HB3 can be set to 9 Vdc to -9 Vdc. As a result, the inverter's output voltage has nine different values: Vdc, 2Vdc, 3Vdc, 4Vdc….13 Vdc, 0, -Vdc, -2Vdc, -3Vdc….-13 Vdc, as shown in.Table.2.

Table 1. Nine-level inverter output voltage with polarities

Output voltage	H-bridge1	H-brige2
4 VDC	Positive	Positive
3 VDC	Zero	Positive
2 VDC	Negative	Positive
1 VDC	Positive	Zero
0 VDC	Zero	Zero
-1 VDC	Negative	Zero
-2 VDC	Positive	Negative
-3 VDC	Zero	Negative
-4 VDC	Negative	Negative

Table 2. Twenty-seven level inverter output voltage with polarities

Output voltage	H-brige1	H-brige2	H-brige3
13 VDC	Positive	Positive	Positive
12 VDC	Zero	Positive	Positive
11 VDC	Negative	Positive	Positive
10 VDC	Positive	Zero	Positive
9 VDC	Zero	Zero	Positive
8 VDC	Negative	Zero	Positive
7 VDC	Positive	Negative	Positive
6 VDC	Zero	Negative	Positive
5 VDC	Negative	Negative	Positive
4 VDC	Positive	Positive	Zero
3 VDC	Zero	Positive	Zero
2 VDC	Negative	Positive	Zero
1 VDC	Positive	Zero	Zero
0 VDC	Zero	Zero	Zero
-1 VDC	Negative	Zero	Zero
-2 VDC	Zero	Negative	Zero
-3 VDC	Positive	Negative	Zero
-4 VDC	Negative	Negative	Zero
-5 VDC	Zero	Positive	Negative
-6 VDC	Positive	Positive	Negative
-7 VDC	Negative	Positive	Negative
-8 VDC	Zero	Zero	Negative
-9 VDC	Positive	Zero	Negative
-10 VDC	Negative	Zero	Negative
-11 VDC	Zero	Negative	Negative
-12 VDC	Positive	Negative	Negative
-13 VDC	Negative	Negative	Negative

Proposed SHE Modulation

Despite the fact that there are other modulation strategies, the SHE method is extensively used in higher power applications [26]; in both two-level and multilevel inverter topologies. The goal of SHE modulation in this work is to create a staircase waveform with optimum voltage waveform steps in order to eliminate specific order harmonics. For a nine-level inverter, For SHE modulation, the Fourier equation of the inverter output voltage is:

(1) $$\mathrm{Vinv}(\omega\tau) = \frac{4\mathrm{vdc}}{n\pi}\sum_{n=1,3,5,7}^{\infty}[\cos(n\theta1) + \cos(n\theta2) + \cos(n\theta3) + \cos(n\theta4)] * \sin(n\omega\tau)$$

Where θ1-θ4 are the switching angles in the first quarter waveform at each level and must satisfy the following criteria:

θ1< θ2< θ3< θ4<π/2. The following equations can be used to calculate the switching angles:

(2)
$$\begin{aligned}
&\cos(\theta1) + \cos(\theta2) + \cos(\theta3) + \cos(\theta4) = \quad 4M\\
&\cos(3\theta1) + \cos(3\theta2) + \cos(3\theta3) + \cos(3\theta4) = 0\\
&\cos(5\theta1) + \cos(5\theta2) + \cos(5\theta3) + \cos(5\theta4) = 0\\
&\cos(7\theta1) + \cos(7\theta2) + \cos(7\theta3) + \cos(7\theta4) = 0
\end{aligned}$$

For 27 level For SHE modulation, the Fourier equation of the inverter output voltage is:

(3)
$$Vinv(\omega\tau) = \frac{4vdc}{n\pi}\sum_{n=1,3,5,7,9,11,13,15,17,19,21,23,25}^{\infty}[\cos(n\theta1) + \cos(n\theta2) + \cdots. + \cos(n\theta13) +] *3)$$

With the switching angle set from θ1 to θ13, the condition is the same as in the 9-level SHE modulation approach, where θ1< θ2< θ3< θ4< θ5< θ6< θ7< θ8< θ9< θ10< θ11< θ12< θ13<π/2. To get the correct switching angles for the selected 27-level asymmetrical CHB inverter, sets of transcendental equations are required. The first equation represents the fundamental voltage, while the second equation is utilized to remove selected low-order harmonics. The resulted harmonic equations are as follows:

(4)
$$\begin{gathered}
\cos(\theta1) + \cos(\theta2) + \cos(\theta3) + \cdots. + \cos(\theta13) = \quad 13M\\
\cos(3\theta1) + \cos(3\theta2) + \cos(3\theta3) + \cdots \cos(3\theta13) = 0\\
\cos(25\theta1) + \cos(25\theta2) + \cos(25\theta3) + \cdots. + \cos(25\theta13)\\
= 0
\end{gathered}$$

The Newton Raphson method can be used to solve the sets of nonlinear equations in (1) and (3). One of the quickest iteration algorithms, begins with a reasonable approximation and eventually converges at the zero of the specified set of equations. The switching angles are calculated by using Matlab in this study. The total harmonic distortion (THD) of the set of switching angles is then evaluated in order to choose the best solution.

(5) $\theta^j = [\theta_1^j, \theta_2^j, \theta_3^j, \dots . \theta_N^j]$

(6) $F^j = \begin{bmatrix} cos(\theta_1^j) - \cos(\theta_2^j) + \cdots \pm \cos(\theta_N^j) \\ cos(3\theta_1^j) - cos(3\theta_2^j) + \cdots \pm cos(3\theta_N^j) \\ cos(N\theta_1^j) - cos(N\theta_2^j) + \cdots \pm cos(N\theta_N^j) \end{bmatrix}$

(7) $\frac{dF^j}{d\theta} = \begin{bmatrix} -sin(\theta_1^j) + \sin(\theta_2^j) - \cdots \pm \sin(\theta_N^j) \\ -3\, sin(3\theta_1^j) + 3\, sin(3\theta_2^j) - \cdots \pm 3sin(3\theta_N^j) \\ -N\, sin(N\theta_1^j) + N\, sin(N\theta_2^j) - \cdots \pm N sin(N\theta_N^j) \end{bmatrix}$

(8($T = [\frac{NM}{\pi}\ 0\ 0\ 0\ 0 \dots . 0]$

Where T harmonic amplitude matrix, N number of level and M modulation index

(9) $F(\theta) = T$

By solving the nonlinear equation using Matlab, the optimum THD of a 9-level CHB inverter which is obtained at switching angles of 7.25°, 21°, 36° and 55.93° for θ1, θ2, θ3 and θ4, respectively, in order to cancel the 3rd, 5th and 7th harmonics, while the optimum THD of a 27-level CHB inverter is obtained at switching angles of 4.25°, 7.27°, 11.75°, 16.2°, 21.35°, 27°,31.9°, 37.5°, 43.79°, 49.3°, 57.6°, 70.2° and 89.4° for θ1, θ 2, θ3, θ4, θ5, θ6, θ7, θ8, θ9, θ10, θ11, θ12 and θ13, respectively, in order to cancel twelve odd harmonic from 3rd harmonic to 25th harmonic for twenty seven level inverter .

Simulation results

Switching techniques were used to confirm the selected structures. MATLAB/Simulink is used to model both 9-level asymmetrical cascade inverter and Twenty Seven -level asymmetrical cascade inverter topologies. The simulations are run by using a set of switching angles to eliminate specific harmonic contents, as shown in Table 3.The used topology firstly applied for nine-level asymmetrical cascade inverter consists of two Different dc voltage sources, each of which is Vdc and 3Vdc. Figures 6(a) and 6(b) show the inverter output voltage and voltage THD, respectively. The voltage THD of the 9-level CHB inverter is 9.95%; according to simulation data. The harmonic contents of the 3rd, 5th, and 7th harmonics are removed. The same topology is used for Twenty Seven -level asymmetrical cascade inverter consists of three unequal dc voltage sources, each of which is Vdc, 3Vdc and 9Vdc. Figures 6(a) and 6(b) show the inverter output voltage and voltage THD, respectively. The voltage THD of the nine-level cascade inverter is 3.82%, which is lower than the voltage THD of the 9-level cascade inverter, according to simulation data. The harmonic contents of the 3rd, 5th, 7th, 9th, 11th, 13th, 15th, 17th, 19th, 21st, 23rd and 25th harmonics are removed.

Table 3 switching angle for Nine and Twenty seven inverter

NO level	Switching angles in degree
9 level	7.25, 21, 36, 55.93
27 level	4.25, 7.27, 11.75, 16.2, 21.35, 27, 31.9, 37.5, 43.79, 49.3, 57.6, 70.2, 89.4

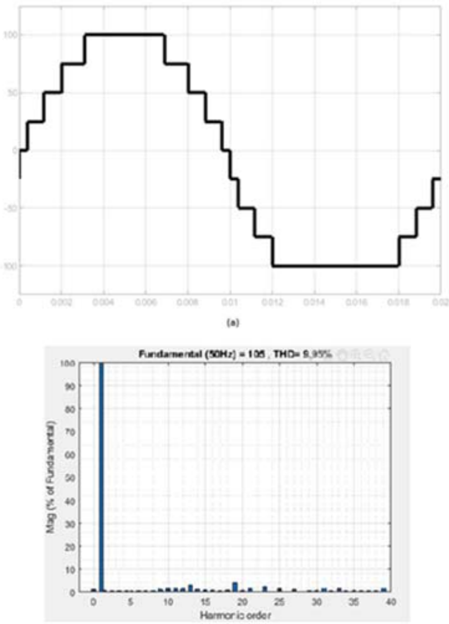

Fig. 5 The nine-level asymmetrical cascade inverter.
(a) The voltage output (b) voltage THD

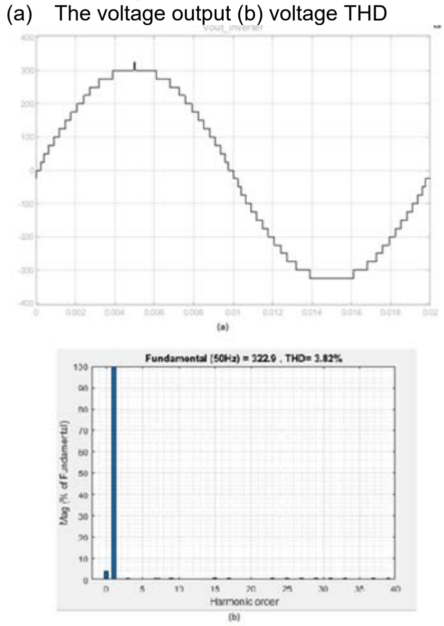

Fig. 6. The Twenty Seven -level asymmetrical cascade inverter
(a) The voltage output (b) voltage THD

In the Fig 5 b, we notice that the third, fifth and seventh harmonics have been canceled
In the figure 6 b, we notice that the 3rd, 5th, 7th, 9th, 11th, 13th, 15th, 17th, 19th, 21st, 23rd and 25th harmonics have been canceled

Conclusion

For two CHB inverter topologies, this study shows selective harmonic elimination using the Newton-Raphson method. CHB inverters with 9 levels and 27 levels of asymmetric were designed. The proposed SHE for a single-phase CHB inverter was simulated by MATLAB/Simulink. In both cases, the proposed switching angles are capable of removing some low order harmonic components. Also, a lowering THD in the output voltage was obtained. The THD of the Twenty-seven level asymmetrical cascade inverter is much lower than that of the nine-level asymmetrical cascade inverter, according to the results.

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