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Harmonics Elimination of Reduced Switch Multilevel Inverter Using Henry Gas Solubility Optimization Algorithm

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Abstract: This study introduces a pioneering method to enhance the efficiency and effectiveness of three-phase five-level reduced switch cascaded H-bridge multilevel inverters (CHB MLI) by employing the Henry Gas Solubility Optimization (HGSO) algorithm. Targeting the selective harmonic elimination (SHE) technique, the research emphasizes the optimization of switching angles to significantly reduce total harmonic distortion (THD) and align the fundamental output voltage closely with the reference voltage. Central to this exploration are three distinct objective functions (OFs), meticulously designed to assess the HGSO algorithm's performance across various modulation indices. Simulation results, facilitated by PSIM software, illustrate the impactful role these objective functions play in the optimization process. OF1 demonstrated a superior ability in generating low OF values and maintaining a consistent match between reference and fundamental voltages across the modulation index spectrum. Regarding the reduction of THD, it is crucial to emphasize that all OFs can identify the most effective switching angle to minimize THD and eliminate the fifth harmonic to a level below 0.1%. The findings highlight the potential of HGSO in solving complex optimization challenges within power electronics, offering a novel pathway for advancing modulation strategies in CHB MLIs and contributing to the development of more efficient, reliable, and compact power conversion systems.

Keywords: Henry Gas Solubility Optimization Algorithm, Multilevel Inverter, Reduced Switch, Selected Harmonic Elimination.

1 Introduction

POWER electronics has focused on multilevel inverters (MLIs) since they connect renewable energy sources to the grid [1], [2], [3]. The Cascaded H-Bridge (CHB) architecture is ideal for high-power applications due to its versatility and scalability [4], [5]. Recent CHB MLI trends emphasize efficiency, THD reduction, and power quality. CHBs are easy to implement and can run with different DC sources for each H-bridge, improving reliability and fault tolerance, but they also bring problems. The complexity of control strategies needed to balance DC connection voltages, and the increased number of power electronic components can increase expenses and maintenance [6], [7], [8].

To get the desired performance, CHB MLI modulation methods must be carefully chosen [9]. Selective Harmonic Elimination (SHE) is unique in its ability to correctly alter the output waveform and minimize THD [10], [11], [12], [13]. SHE methods determine the best

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switching angles to reduce harmonics while keeping the fundamental frequency. Due to its complexity and constant change, resolving non-linear transcendental equations is difficult when using this method. Iterative numerical methods, algebraic resolves, and bio-inspired algorithms are all used to handle these difficulties, each with pros and downsides. Although iterative numerical methods like the Newton-Raphson technique are accurate, they can be resource-intensive [14], [15]. Bio-inspired algorithms like the Genetic Algorithm (GA) [16], Particle Swarm Optimization (PSO) [17], Bee Algorithm (BA) [18], and Whale Optimization Algorithm (WOA) [19] balance precision with processing speed to meet SHE's evolving needs.

The Henry Gas Solubility Optimization (HGSO) algorithm is an innovative addition to the optimization field, drawing inspiration from Henry's Law, a physical theory that explains the solubility of gases in liquids [20]. This method emulates the inherent process of gas dissolution to address intricate optimization problems, providing a novel approach to discovering global optima in multi-dimensional domains. HGSO stands out by skillfully managing the exploration and exploitation stages, therefore preventing early fixation on suboptimal solutions, and showcasing exceptional performance in benchmark optimization tasks [20], [21]. Its application goes beyond conventional optimization problems, demonstrating potential in optimizing modulation strategies for MLIs. It can aid in the efficient calculation of switching angles for SHE methods, thereby improving the overall performance and efficiency of cascaded H-bridge multilevel inverters [22].

Based on the previously mentioned analysis of recent literature, the topologies highlighted possess different points of view concerning their structure, modularity, and overall power components. However, for three phase topology configurations, conventional topologies demand a high number of power components. Therefore, this provides an opportunity for the development of a new modular topology with reduced power components and DC sources. This study proposes a new three-phase five-level CHB MLI design with a reduced number of switches and expected to be a compact structure. The SHE technique will be applied with the help of HGSO as an optimization-based technique to obtain the optimized switching angles. Its benefits have been explored through an analysis of three different objective functions. A simulation has been created by using PSIM software to assess the feasibility of the proposed topology.

2 Methodology

2.1 Reduced Switch Cascaded H-Bridge Multilevel Inverter

Due to their natural ability to generate stepped voltage waveforms to other output voltage waveforms of higher quality, MLI topologies have been the focus of many research studies in the development of topological structures. From this perspective, an effort has been carried out to create a new, three-phase five-level CHB MLI with reduced switch for the same amount of DC sources using a single-phase structure [23]. Fig. 1 shows a generalized structure for three-phase topology made up of five-level ($0V_{DC}$, $1V_{DC}$, $2V_{DC}$, $-1V_{DC}$, $-2V_{DC}$) voltage generation modules connected in series with switching devices. The switching scheme for proposed topology is tabulated in Table 2. Referring to the table, there will be five stages of output voltage generated from $0V_{DC}$ to $-2V_{DC}$. To clearly explain the operating system, Fig. 2 depicts a generalized single-phase structure to generate stepped voltage waveform as shown in Fig. 3.

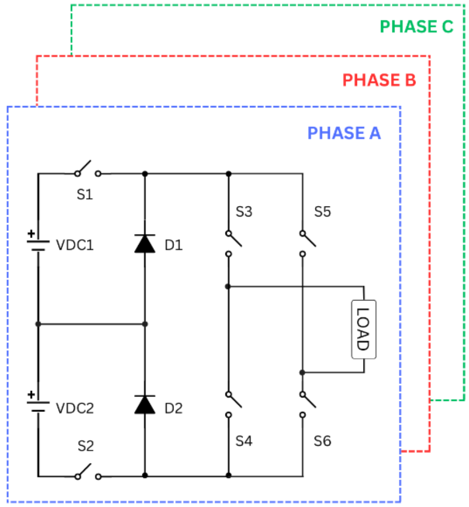


Fig. 1 Generalized structure for three-phase five-level CHB MLI.

Table 1 Switching scheme for proposed five-level CHB MLI topology.

Output Voltage	Switches					
	S1	S2	S3	S4	S5	S6
$2V_{DC}$	1	1	1	0	0	1
$1V_{DC}$	1	0	1	0	0	1
$0V_{DC}$	0	0	0	1	0	1
$-1V_{DC}$	1	0	0	1	1	0
$-2V_{DC}$	1	1	0	1	1	0

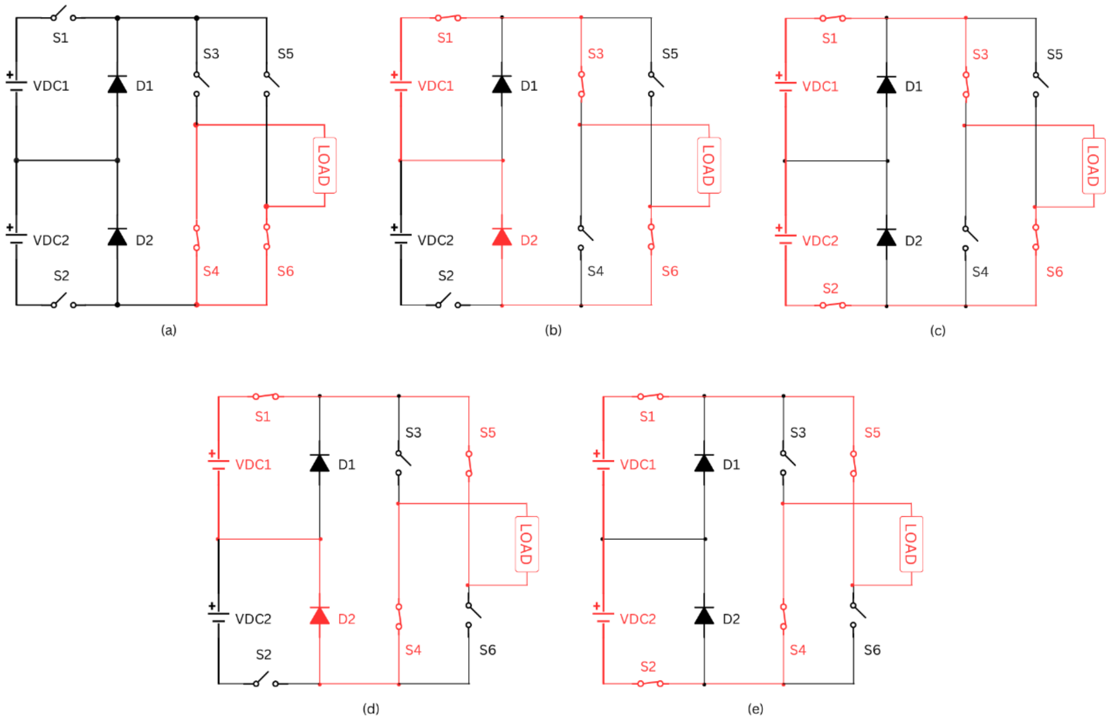


Fig. 2 The operation of five-level CHB MLI proposed topology: (a) $0V_{DC}$ (b) V_{DC} (c) $2V_{DC}$ (d) $-V_{DC}$ (e) $-2V_{DC}$

To produce $0V_{DC}$ of output voltage, the switches S4 and S6 will be turned on and short-circuiting the load. In this stage, there will be no supply sent to the load as shown in Fig. 2(a). On a positive half-cycle basis, the switches S3 and S6 from the H-bridge side will be turned on. To produce the output voltage of Vdc, the DC source VDC1 supplied to the load through switch S1 and the diode D2. The operation is shown in Fig. 2(b). Next, both the DC sources of VDC1 and VDC2 are supplied to the load through switch S1 and S2 to produce the output voltage of $2V_{DC}$. The switches S3 and S6 from the H-bridge side have remained turned on as shown in Fig. 2(c). On a negative half-cycle basis, the switches S4 and S5 will be turned on instead of the switches S3 and S6 to generate $-V_{DC}$ output voltage. Same as previous in the second stage, the load will be supplied by the DC source VDC1 through switch S1 and the diode D2 as shown in Fig. 3(d). Lastly, $-2V_{DC}$ of output voltage is generated when the load is supplied by the DC sources VDC1 and VDC2 through the switches S1 and S2. From the H-bridge side, the switches S4 and S5 remained turned on as shown in Fig. 2(e).

2.2 Selective Harmonic Elimination Switching Scheme

The SHE technique entails determining the most favorable switching angles to eliminate particular lower-order harmonics while preserving the fundamental frequency component of the voltage waveform. The process involves solving a collection of nonlinear transcendental equations that accurately reflect the harmonic components of the inverter's output voltage. Before continuing with solving the SHE problems, the staged output waveform can be expressed in Fourier Series expression as in Eq. (1).

$$V(\omega t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t) \tag{1}$$

where, a_0 is DC component, a_n is even harmonics, and b_n is odd harmonics.

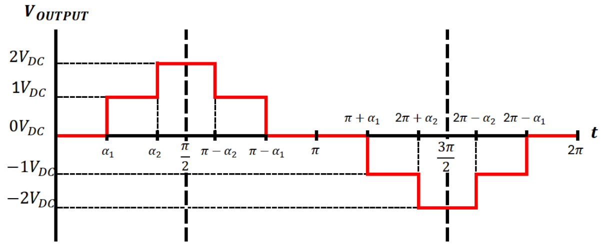


Fig. 3 Generalized output voltage waveform for five-level CHB MLI [24].

In order to eliminate unwanted low order harmonics, the optimum switching angles are required. Since the output voltage waveform produced is in stepped wave with the property of quarter wave symmetry (QWS), the

DC component, even harmonics and odd harmonics for cosine term are equals to zero. Thus, Eq. (1) can be rewritten as Eq. (2).

$$V(\omega t) = \sum_{n=1}^{\infty} b_n \, sin(n\omega t) = \sum_{n=1}^{\infty} V_n \, sin(n\omega t) \qquad (2)$$

where $\mathrm{V_n}$ is notated as magnitude of n^{th} order harmonic. According to the odd symmetry of QWS, even order harmonics are zero, then $\mathrm{V_n}$ is expressed as in Eq. (3).

$$V_n = \begin{cases} \dfrac{4V_{DC}}{n\pi} \displaystyle\sum_{i=1}^{n} cos(na_i)\,; n = odd \\ 0\,;\ n = even \end{cases} \qquad (3)$$

In order to lessen the harmonic distortion of the fundamental peak voltage, V_1, the switching angles must be within $0 \le a_1 \le a_2 \ldots \le a_n \le \pi/2$. The number of harmonics that can be eliminated in a single-phase five-level CHB MLI is $n = \frac{L-1}{2}$, where L is the number of the level. Therefore, there will be three non-linear expressions since the total number of harmonics that may be eliminated is $n - 1$ $(n = 3)$. For three-phase, triple-n order harmonics (third, sixth, nineth…) will be eliminated. Thus, general Eq. (2) for the first and fifth harmonic orders are given as in Eq. (4).

$$\begin{aligned} \frac{4V_{DC}}{\pi}(cos(a_1) + cos(a_2)) &= V_1 \\ \frac{4V_{DC}}{5\pi}(cos(5a_1) + cos(5a_2)) &= V_5 \end{aligned} \qquad (4)$$

The modulation index, M_i which is the ratio of referred fundamental voltage and supply voltage is given in Eq. (5). Arranging the equation, the V_{ref} can be expressed as Eq. (6).

$$M_i = \frac{\pi V_{ref}}{4nV_{DC}} \qquad (5)$$

$$V_{ref} = \frac{4nV_{DC}M_i}{\pi} \qquad (6)$$

Basically, to optimize the switching angles, the V_1 is set to equal to V_{ref} and any undesired individual harmonic is set to 0. Considering this the expression in Eq. (4) can be rewritten as in Eq. (7).

$$\begin{aligned} \frac{4V_{DC}}{\pi}(cos(a_1) + cos(a_2)) &= \frac{4nV_{DC}M_i}{\pi} \\ \frac{4V_{DC}}{5\pi}(cos(5a_1) + cos(5a_2)) &= 0 \end{aligned} \qquad (7)$$

2.3 Henry Gas Solubility Optimization

A population-based metaheuristic algorithm that was just introduced, the Henry Gas Solubility Optimization Algorithm (HGSO) stands out for breaking the population up into N clusters, each of which is mapped to a separate HGSO with its own set of parameters and local best. Although this clustering method improves exploration, there are two key drawbacks noted [25]. Firstly, there is a lack of flexibility in the static mapping of HGSO to clusters because it does not alter over time. Secondly, the algorithm fails to consider the possible advantages of hybridization, an approach that enhances outcomes by merging the advantages of many algorithms [25], [26]. Figure 4 depicts the pseudocode for HGSO algorithm.

```
begin
    Initialize population $X_g (g = 1.2. \ldots. N)$, number
        of gas types and all parameters
        $(g. H_i. P_{g.i}. C_i. l_1. l_2. and\ l_3,)$
    Divide the population agents into a number of gas
        types (cluster) with the same $H_i$.
    Evaluate each cluster $i$
    Get the best gas $X_{g.best}$ and the best search agent,
        $X_{best}$
    while $t < Iteration_{max}$
        For each search agent do
            Update the search agent individual
            position
        end for
        Update Henry's coefficient of each gas
        Update solubility for each gas
        Rank and select the number of worst agents
        Update the position of the worst agents
        Update the best gas $X_{g.best}$ and the best search
            agent, $X_{best}$
        $t = t + 1$
    end while
    return $X_{best}$
end
```

Fig. 4 HGSO pseudocode [27].

2.4 Formulation of the Optimization Problem

Before using an optimization procedure to solve the SHE problem, the objective function (OF) needs to be defined with the following goals in mind:

1. Eliminate the difference between reference voltage (V_{ref}) and fundamental voltage (V_1). The V_{ref} is targeted fundamental voltage depends on specific modulation index (M_i).
2. Eliminate the desired harmonics.

In this paper, two main switching angles need to be precisely optimized, and the fifth order harmonic is required to be eliminated. Thus, the generic OF can be written as in Eq. (8)[28], [29]:

$$\begin{aligned} &Minimize, f_{fit}\,(\alpha_1, \alpha_2) \\ &= \left(\varepsilon_1 \frac{V_{ref} - V_1}{V_{ref}}\right)^x + \frac{1}{5}\left(\varepsilon_2 \frac{V_5}{V_1}\right)^y \end{aligned} \qquad (8)$$

In Eq. (8), the first term represents the fundamental voltage difference between the reference and derived values and is referred to as the basic component. Additionally, the second term refers to the components used for eliminating harmonics. The ε_1 and ε_2 are the weight penalty factors associated with each phrase, respectively. This value is often chosen within the range of 1 to 100. The higher the value, the more it has the substantial effect on the overall performance. For instance, if this number is set to 100, when the value varied by 1%, the fitness function contributed by this term is increased by the factor of 100. Meanwhile, the x and y values represent the power penalty factor, which is used to apply a greater penalty if the calculated value exceeds the specified range of significance. Typically, terms with greater significance will incur a higher penalty amount. Three distinct objective functions are established based on the data presented in Table 2. The aim is to analyse the influence of various factors on the performance of HGSO in attaining the optimal switching angle using the SHE approaches.

Table 2 Objective functions parameters.

Objective Function	**Switches**				
	ε_1	ε_2	x	y	**Notes**
OF1	100	50	4	2	Term 1 is set to be more important
OF2	50	100	2	4	Term 2 is set to be more important
OF3	100	100	2	2	Both is set to equally important

3 Results And Discussion

The optimal switching angles are determined by utilizing three OFs in the HGSO algorithm. The values are determined through the application of MATLAB program. The quantity of gases is established at 50, divided into five groups. The maximum number of iterations is set to 1000. Other settings are based on HGSO original parameters given in [27]. The modulation index, ranging from 0 to 1, is utilized to compute the switching angles using a step size of 0.01. The procedure is iterated 10 times for each modulation index value. Fig. 5 displays the cumulative distribution function (CDF) for all objective functions. Cumulative distribution function (CDF) is primarily employed to assess the ability of the HGSO algorithm to generate OF values that are deemed satisfactory. A higher proportion corresponds to a superior level of ability. Upon examining this figure, within the range of permitted values for objective functions, which is 10^2 [30], [31], the acceptable percentages for OF1, OF2, and OF3 are 53.6%, 51.6%, and 45.3% correspondingly. This first evidence the superiority of OF1 compared to other OFs.

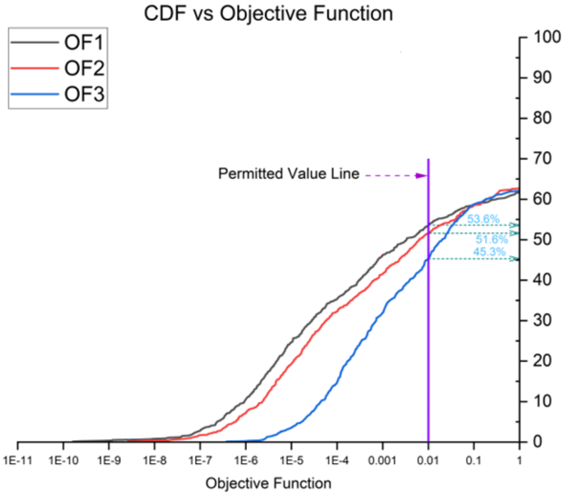


Fig. 5 Cumulative distribution function (CDF).

The modulation index is divided into three stages: the lower stage, ranging from 0 to 0.30; the middle stage, ranging from 0.31 to 0.70; and the higher stage, ranging from 0.71 to 1.00. Fig. 6 depicts the relationship between the objective function value and the modulation index. Observing this figure, during the medium stage, the minimum values for OF1, OF2, and OF3 occurred at a modulation index of 0.44 (OF = $8.35E^{-9}$), 0.56 (OF = $1.94E^{-8}$), and 0.39 (OF = $2.51E^{-6}$), respectively. At a higher stage, the minimum values for OF1, OF2, and OF3 are $1.61E^{-10}$ $(M_i = 0.71), 2.62E^{-9}(M_i = 0.80)$, and $3.79E^{-5}$ $(M_i = 0.87)$, correspondingly.

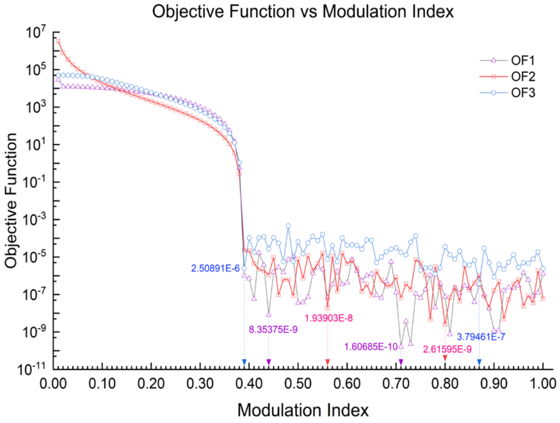


Fig. 6 Objective function value versus modulation index.

This study aims to observe how different factors affect the performance of HGSO in achieving the optimal switching angle utilizing the SHE techniques. The first observation is on the difference between reference and fundamental voltage. Fig. 7 displays the proportion of fundamental voltage achieved at each modulation index for the OF. Upon examination of the figure, it is evident that the fundamental voltage, V_1, obtained from OF1 is consistently aligned with V_{ref} across all modulation index stages. The percentage for V_1, derived from OF2 and OF3, shows minimal discrepancy up to a modulation index of 0.4, and subsequently aligns with V_{ref}.

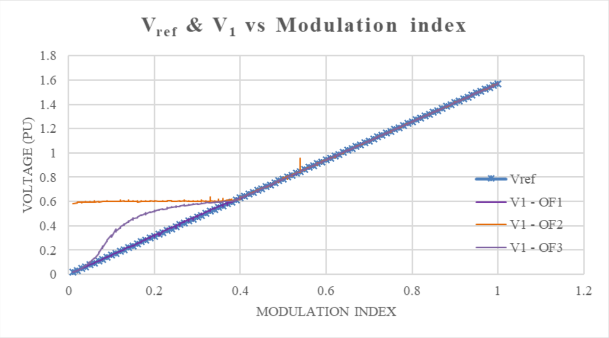


Fig. 7 Fundamental and reference voltages versus modulation index.

The second observation relates to THD. Fig. 8 illustrates the THD performance as a function of the modulation index for OF1, OF2, and OF3. The modulation index of 0.61 (middle stage index) results in the lowest THD values of 16.45%, 16.44%, and 16.43% correspondingly. The lowest THD values for OF1, OF2, and OF3 are 0.91, with values of 11.02%, 11.01%, and 11.01% respectively, within a higher range of modulation index. OF3 has the lowest THD in both the medium and upper stages of the index, in comparison to the THD values derived from OF1 and OF2.

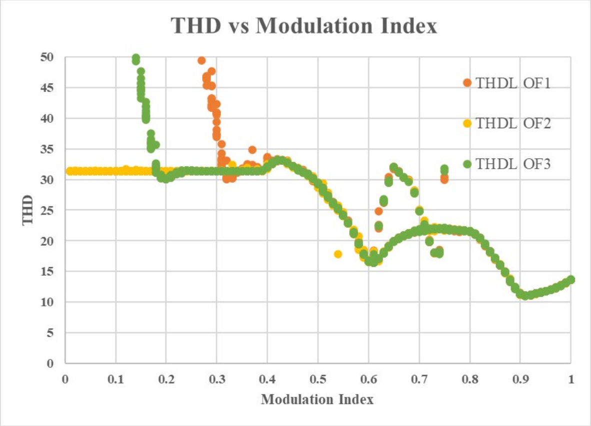


Fig. 8 THD versus modulation index.

To facilitate additional examination, the switching angles associated with the minimum THD generated across all modulation indices have been chosen and organized in Table 3. The suggested three-phase, five-level CHB MLI utilizes these switching angles to observe the harmonic contents. Fig. 9 presents a graphical representation of the harmonics associated with each of the chosen modulation index values. In a three-phase system, it is widely acknowledged that triplen harmonics are non-existent. Hence, the harmonic that is specifically targeted for elimination in this investigation is solely the fifth harmonic. Table 3 presents the values of fifth harmonics alongside the THD value for each chosen modulation index.

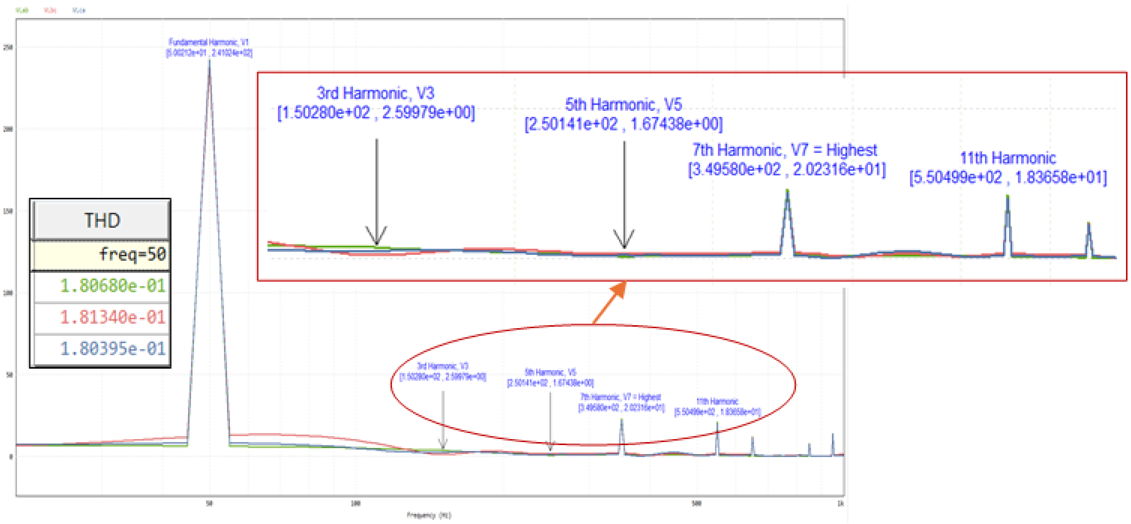
Table 3 The optimal switching angle value for OF1, OF2, and OF3.

Objective Function	M_i	α_1	α_2	5th Harmonics	THD (%)	
					Simulation	Calculation
OF1	0.61	41.80	77.82	**$1.80E^{-04}$**	18.08	16.45
	0.91	23.24	59.24	**$4.28E^{-05}$**	12.42	11.02
OF2	0.61	41.81	77.73	$6.88E^{-04}$	18.03	16.43
	0.91	23.27	59.28	$2.84E^{-04}$	12.41	11.01
OF3	0.61	41.83	77.78	$4.04E^{-04}$	18.05	16.43
	0.91	23.25	59.31	$9.91E^{-04}$	**12.40**	**11.00**

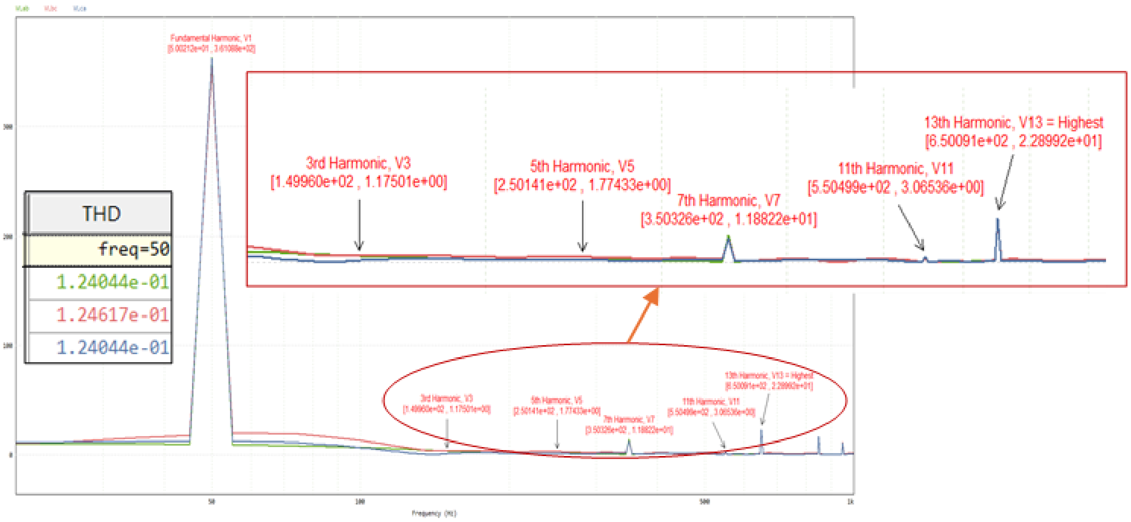
Upon examination of each individual harmonic depicted in Fig. 9, it is observed that the fifth harmonic exhibits a substantial reduction, amounting to less than 0.1%. The angels generated from OF1, OF2, and OF3 exhibited the most significant reduction with a modulation index of 0.91. In the context of modulation index 0.61, it was observed that the application of angles OF2 resulted in the lowest value of the fifth harmonic, followed by OF3 and OF2. The angles achieved through optimization using various objective functions exhibit the capability to achieve the lowest THD and eliminate the desired harmonics (with a simulation value below 0.1%).

4 Conclusions

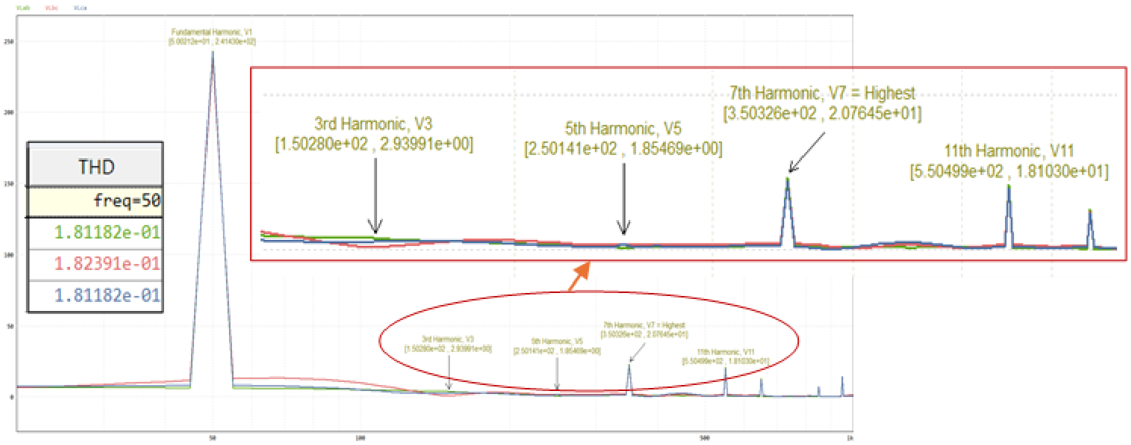
This paper presented an innovative approach to optimizing a three-phase five-level reduced switch CHB MLI using the HGSO algorithm, with a focus on the SHE technique. The study showcased the effectiveness of the HGSO algorithm in minimizing THD and aligning the fundamental output voltage with the reference voltage across different modulation indices, achieved through careful execution of three separate OFs. The findings of the study revealed that OF1 had superior



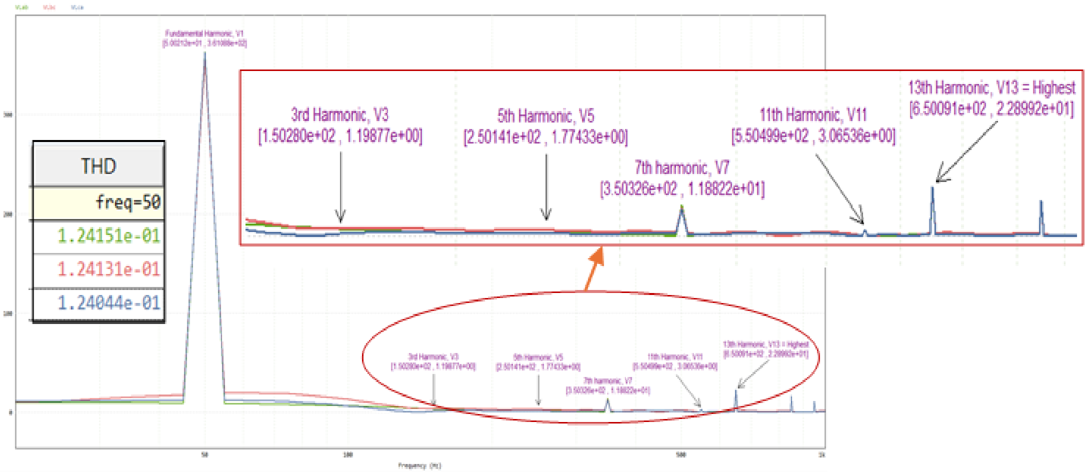
(a) OF1 (Mi=0.61)



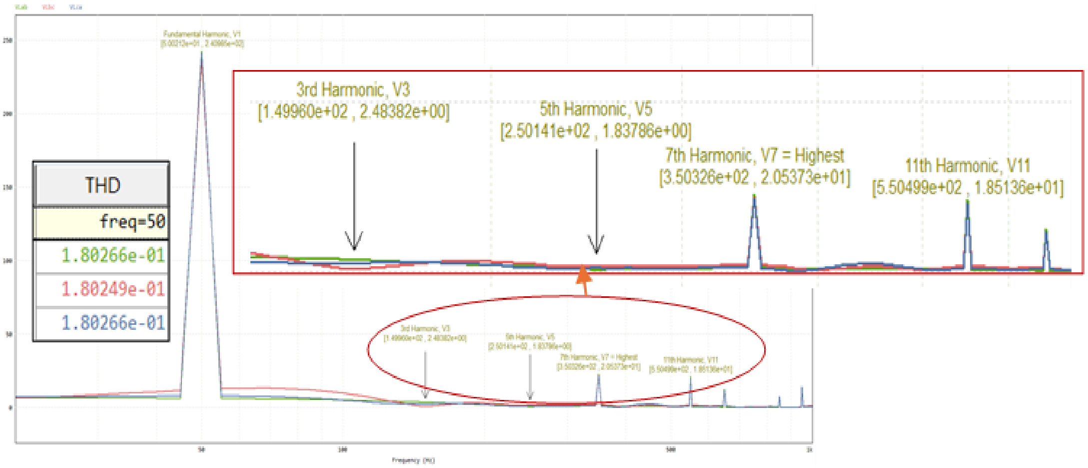
(b) OF1 (Mi=0.91)



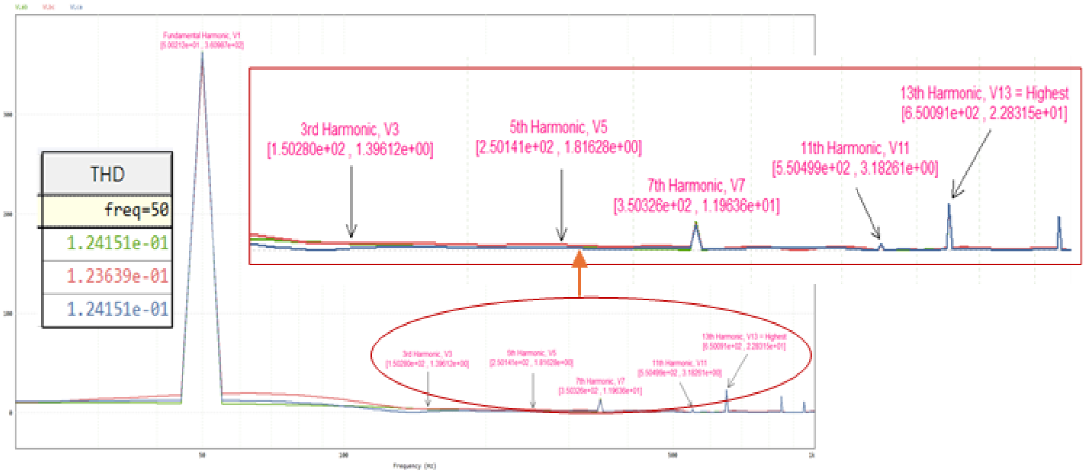
(c) OF2 (Mi=0.61)



(d) OF2 (Mi=0.91)



(e) OF3 (Mi=0.61)



(f) OF3 (Mi=0.91)

Fig. 9 Individual harmonic graph and THD value for selected Modulation Index (a) OF1 ($M_i = 0.61$) (b) OF1 ($M_i = 0.91$) (c) OF2 ($M_i = 0.61$) (d) OF2 ($M_i = 0.91$) (e) OF3 ($M_i = 0.61$) (f) OF3 ($M_i = 0.91$)

performance compared to other OFs in terms of attaining lower OF values and sustaining a consistently close alignment between reference and fundamental voltages across the entire modulation index spectrum. In the context of minimizing THD, it is important to highlight that all OFs have the capability to determine the optimal switching angle that may effectively reduce THD and eliminate the fifth harmonic to a level below 0.1%.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The experiment and simulation were designed by Murni Nabila and Zainuddin. The optimization algorithm was simulated by Mohd Hafiz, Baharuddin, and M. Fitra. The analysis of results was conducted by Zainuddin, Ernie, and Md Hairul Nizam. All authors participated in data interpretation, as well as in the writing and revision of the article.

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