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A COMPARATIVE ANALYSIS OF GA-BASED SHEPWM IN A THREE-PHASE CASCADE H-BRIDGE AND A REDUCED SWITCH NINE-LEVEL INVERTER

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Abstract- Selective harmonic elimination (SHE) Pulse width modulation is considered to be one of efficient method which is capable of providing precise control over the harmonic spectrum of a given voltage and current waveforms that are produced by the power electronic converters. Now a days the more emphasis is on the design of converters is mainly with the objective of reduction of harmonics. This makes more suitability for high-power converters running at low switching frequency that includes the multilevel converters. This paper aims to examine the SHEPWM modulation technique for multilevel converters to limit the content of harmonics. Main aim is to develop and design the simulation of the modulation technique based on genetic algorithm for various levels inverters. To validate the effectiveness of the proposed GA-based optimization, extensive simulations studies have been carried out using MATLAB/SIMULINK. Furthermore, the scalability of the SHE multilevel inverter design is investigated, showcasing its ability to handle various output voltage levels efficiently. The simulation studies and the model developed results are compared to showcase the GA-optimized SHE outperforms in terms of THD reduction and also shown the improved voltage quality for 5, 7 and 9-level Cascaded Hybrid multilevel inverter (CHB-MLI). In addition to these results obtained for modified (Reduced Switch) 9-level multilevel inverter model has been compared with the conventional 9-level CHB-MLI.

Keywords: Pulse Width Modulation, Selective Harmonic Elimination, Genetic Algorithm, Cascaded Multilevel Inverter.

1. INTRODUCTION

Emerging applications of multilevel inverters makes use of PWM based techniques on various MLI topologies which is the growing area of study in the world of electrical power conversion. Reduced harmonics, fewer switches with lower switching loss with capacity to operate at higher voltages with higher efficiency, more electromagnetic compatibility are all the advantages of standard MLI topologies over conventional inverters with transformers. There are number of significant developments in this area in recent years in both industrial and commercial applications [1-3]. Due to the existence of undesirable harmonics, each MLI creates a staircase or non-sinusoidal output voltage waveform. These are the diode-clamped (DCMC), flying capacitor multilevel converter (FCMC), and cascaded H-bridge (CHBMC) variants [4]. To achieve a desired output voltage with reduced harmonics the inverter needs an effective control strategy which can produce the required output voltage of desired magnitude, phase and frequency. Modulation is the process of controlling the inverter output voltage by varying the ON and OFF times of the inverter switches while maintaining a constant DC input voltage [5, 6].

The modulation schemes in symmetric and Asymmetric inverters [7, 8] are mainly classified based on high-switching [9, 10] and low-switching techniques [12, 13]. As compared with low switching modulation, higher switching modulation is not suitable for high or medium power multilevel inverter because of phase-shift and level-shift using SPWM [11]. The THD is higher, switching losses are more and voltage balancing in a high-level structure is not easy. The SVM method has computational complexity is a major drawback. The aforementioned drawbacks are overcome by low switching modulation such as the SHEPWM method because it produces low switching loss, effectively removing lower-order harmonics, highly efficient and is more suitable for high-power applications [14, 16]. Abio inspired [17, 18] computational heuristic search method is employed in the present research work to identify the switching angles in SHEPWM's nonlinear transcendental equation.

In contrast to the standard Newton-Rapson approach [15], which fails to find a feasible solution over the complete range of the modulation index (MI) and results in reduction of harmonics rather than eliminating them. A metaheuristic algorithm [19, 20], or soft computing algorithms [21] such as Genetic Algorithms GA [22, 23]

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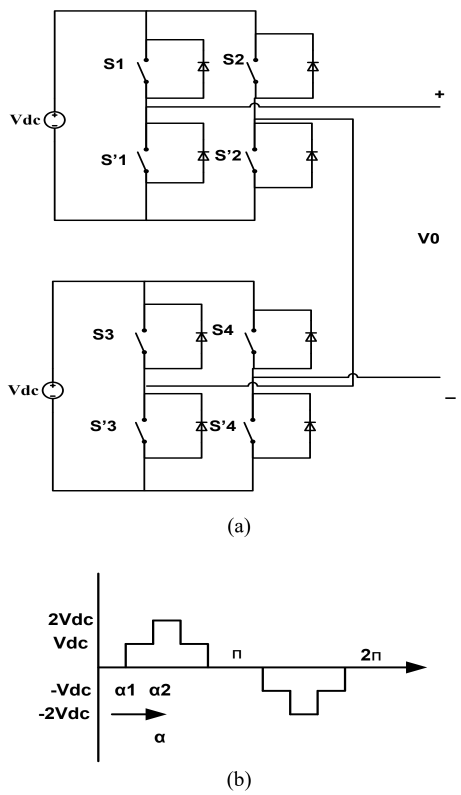
offers the optimization by finding a feasible solution for the entire MI. The main aim of this study is to use SHEPWM based on GA to reduce the 3rd, 5th, 7th, 9th and 11th order harmonics by using three-phase CHB-MLI [24, 25]. The different level CHB-MLI capable of retaining the necessary fundamental frequency and also in the simulation results demonstrates the SHEPWM based on GA effectively reduces the total harmonic distortion (THD).

2. CASCADED H-BRIDGE MULTILEVEL INVERTER

A Cascaded H-Bridge MLI is created by serially connecting *N* stages of H-Bridge inverter units and produces a sinusoidal staircase voltage waveform. A simple H-bridge has four various switch configurations, and each of these four switch configurations generates three distinct voltage levels, namely +Vdc, 0 Vdc, and -Vdc. Multiple voltage levels may be generated by cascading a number of basic H-bridge inverters, which can create a staircase waveform with *N* voltage levels. A five-level CHB-MLI with a symmetric DC voltage and its phase and fundamental voltage waveform are depicted in Figure 1a and 1b, which generates five voltage levels such as ±2Vdc, 0 and ±Vdc. Each H-bridge inverter is built with the help of four switches connected in a variety of combinations. The 5-level inverter consists of two H-bridges and are connected in cascade, and their switching are (Sw_1, Sw_2, Sw'_1, Sw'_2, and Sw_3, Sw_4, Sw'_3, Sw'_4). The phase voltage and its switching state required for the five-level CHB-MLI are shown in Table 1.



(a)

(b)

Figure 1. a) Schematic diagram of Cascaded-MLI, b) Phase and fundamental voltage waveform

From Table 1, we can understand that to achieve the voltage level of 2Vdc, both the symmetric DC sources are connected to the H-bridge with switches Sw_1, Sw'_2, Sw_3, and Sw'_4 enabled. Sw_1 and Sw'_2 or Sw_3 and Sw'_4 are turned ON along with the first H-bridge DC source, hence the output voltage level is equal to +Vdc.

Table 1. Switches states of a 5-level Cascaded H-Bridge-MLI

	DC source connected to H-Bridge		First H-Bridge Switches status (H1)				Second H-Bridge Switches status (H2)			
Phase voltage level (V)	V_{H1}	V_{H2}	Sw_1	Sw_2	Sw'_1	Sw'_2	Sw_3	Sw_4	Sw'_3	Sw'_4
+2Vdc	√	√	1	0	0	1	1	0	0	1
+1Vdc	√	X	1	0	0	1	1	1	0	0
0Vdc	X	X	1	1	0	0	1	1	0	0
-1Vdc	√	X	0	1	1	0	1	1	0	0
-2Vdc	√	√	0	1	1	0	0	1	1	0

When only the pair of switches Sw_1 and Sw_2, or Sw_3 and Sw_4, are turned ON, the phase voltage is equal to zero. Sw_1, Sw'_1 and Sw_3, Sw'_3 switch pairs are mutually exclusive. Similarly, by connecting identical inverters in a cascading fashion, a higher voltage level can be achieved.

3. SELECTIVE HARMONIC ELIMINATION

The SHE is utilized for low switching frequency approaches, where it employs certain switching angles to eliminate undesirable harmonics from the output voltage. It is typically used to eliminate harmonic content and enhance power quality in three-phase and single-phase inverters. Figure 1b illustrates the basic operation of this modulation technique. Equation (1) illustrates how the Fourier series analysis may be used to determine the magnitude of any odd harmonic present in the output signal [13].

$$v(t)=\sum_{n=3,5,7}^{\infty} A_n \sin(n\omega t) \quad (1)$$

where, A_n represents the magnitude of harmonics of nth order and ω represents the switching frequency of fundamental voltage($2\pi f$). Equation (2) represents harmonics of odd order, and the harmonics with an even order become zero by using Equation (3). The mathematical equation of A_n are [13].

$$A_n=\frac{4V_{dc}}{\pi}\sum_{i=1,2,3..}^{s}\frac{\cos(n\alpha_i)}{n} \quad \text{For Odd} \quad (2)$$

$$0 \le \alpha_1 < \alpha_2 < \cdots < \alpha_s \le \frac{\pi}{2} \quad \text{For Even} \quad (3)$$

If n =1 (A_1) denotes the component of fundamental voltage. From Equation (1), the peak value of the nth harmonic is expressed as Equation (4) [13].

$$A_n=\frac{4V_{dc}}{\pi}\left[\cos(n\alpha_1)+\cos(n\alpha_2)+\cos(n\alpha_3)\right] \quad (4)$$

For example, A_n 9-level inverter requires four switching angles (s = 4), and it can eliminate 5th, 7th and 11th order harmonics. To calculate the switching angles, the mathematical expression is formed from Equations

(1) and (2), the expanded expression as shown in Equation (5) [13].

$$\begin{aligned}
&\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) + \cos(\alpha_4) = sm_a \\
&\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) + \cos(5\alpha_4) = 0 \\
&\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) + \cos(7\alpha_4) = 0 \\
&\cos(11\alpha_1) + \cos(11\alpha_2) + \cos(11\alpha_3) + \cos(11\alpha_4) = 0
\end{aligned} \tag{5}$$

where, m_a is the modulation index (*MI*) as given below in Equation 6 [13].

$$ma = \frac{A_1}{A_{1\max}} = \frac{A_1}{\frac{4sV_{dc}}{\pi}} \tag{6}$$

where, A_1 represents the intended fundamental voltage, $A_{1\max}$ represents the maximum fundamental voltage, and '*S*' represents the number of distinct DC sources [3, 4]. Each cascade H-bridge inverter consists of a symmetrical dc source voltage (V_{dc}) and the maximum value of the CHB-MLI output voltage level is equal to sV_{dc}. A square wave with an amplitude sV_{dc}, which happens whenever switching angles α_1, α_2, ... α_5 reduced to 0, which results in:

$$V_{1\max} = \frac{4sV_{dc}}{\pi} \tag{7}$$

In the present paper, the lower order odd harmonics are eliminated by implementing the GA based SHEPWM for CHB-MLI.

4. GENETIC ALGORITHM

The Genetic Algorithm is an evolutionary approach that uses genetics and natural selection to produce near-optimal solutions. It was developed by James Watson and Maurice Wilkins in the 1960s. The search process is initiated by the algorithm with a population that has been produced randomly and is achieved over a series of iterations. In order to accomplish the optimization, it consists of the following three distinct operators that enable the population flow from one generation to the next: The three important processes are selection, crossover, and mutation.

i) Selection Operator: The goal here is to ensure that the people who have the best chance of passing on their genes to future generations are the ones who receive the preference in the selection process.

ii) The Crossover Operator: This denotes the act of mating between different individuals. The selection operator is used to choose two individuals, and randomization is used to determine the crossover locations. After that, the genes at these crossover locations are switched, which results in the formation of an entirely new person (offspring).

iii) Mutation Operator: Mutation is used to maintain the genetic differences between chromosomes in a population from one generation to the next. Fitness function plays an important role in genetic operator in order to find best offspring from the population [22].

$$f\left(\theta_i^j\right) = 100\left|m_a V_{1\max} - \frac{|V_1|}{V_{1\max}}\right| + \sum_{n}^{\sigma} = 5,7,11\frac{|V_1|}{V_{1\max}} \tag{8}$$

The fitness function, denoted by the symbol $f(\theta_i^j)$ in Equation (8), is used in the genetic algorithm (GA) to minimize the lower-order harmonics while maintaining the fundamental component (A_1) of the phase voltage waveform in the three-phase, nine-level CHB-MLI.

5. IMPLEMENTATION OF GENETIC ALGORITHM BASED SHEPWM FOR CHB-MLI

The steps followed during the implementation of GA are mentioned in the previous section. According to the procedure involved, the fitness function plays a significant role in finding the optimal solutions within a broad search area. In the first step of the genetic algorithm, the parameters are initialized. This includes the size of the population, the number of chromosomes, the upper bound and lower bound values, the crossover value, the mutation rate, and the number of iterations. The number of variables depends on the equation *S*= (*n*-1)/2, where '*S*' represents the number of chromosomes (switching angles) and *n* represents the number of inverter levels. For example, A_n 9-level inverter requires four switching angles, and a 7-level inverter requires three switching angles. After the parameters initialization, a fitness value (FV) is computed for each chromosome. The equation for calculating fitness is presented in Equation (7). For example, the 9-level CHB-MLI are used to minimize the 3rd, 5th and 7th order harmonics, then fitness function is equal to Equation (9) [13].

$$FV = \left(100\times\frac{V_{1\max} - V_1}{V_{1\max}}\right)^4 + \frac{1}{5}\left(50\times\frac{V_5}{V_1}\right)^2 + \frac{1}{7}\left(50\times\frac{V_7}{V_1}\right)^2 \tag{9}$$

The term "fitness function" refers to a function that has to be optimized or reduced. Each chromosome's fitness is calculated using Equation (8). The modulation index, ma in the equation ranges from 0.1 to 1. For various values of the modulation index, THD values will vary. Flow chart for the implementation of GA is as shown in Figure 2.

6. RESULTS AND DISCUSSION

The proposed GA has been simulated and tested using the following parameters. Population size = 100, coding type is binary, structure of chromosomes number of generations is 300, selection method is roulette wheel, permutation method is used for inversion mutation and the mutation rate is equal to 0.1 or 10%. The type of crossover is one-point crossover and its cross rate is 0.5 and termination criterion is 300 iterations. Simulations (MATLAB Code/M-Function) were conducted on various level of cascaded multilevel inverter using SHEPWM based on GA. Simulations are performed using modulation index ranging from 0.1 to 1.00 in increments of 0.1. The obtained switching angles of different MI results are used in the MATLAB/Simulink model of three-phase 5, 7 and 9-level CHB-MLI. In addition to this the modified (reduced switch) 9-level model is developed and results are compared with 9-level CHB-MLI.

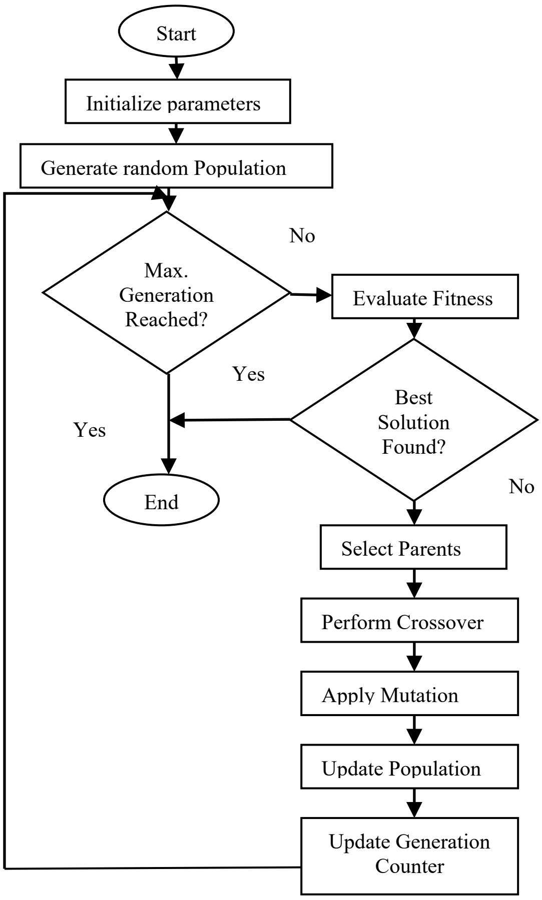
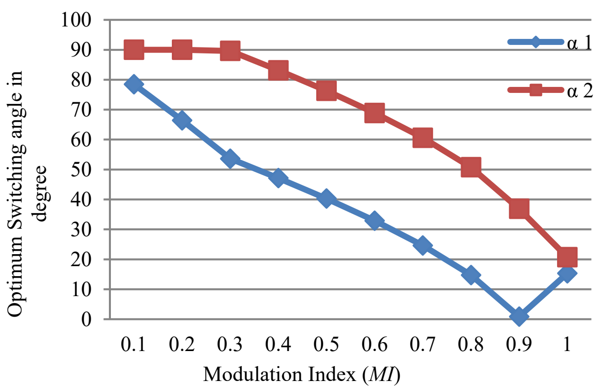


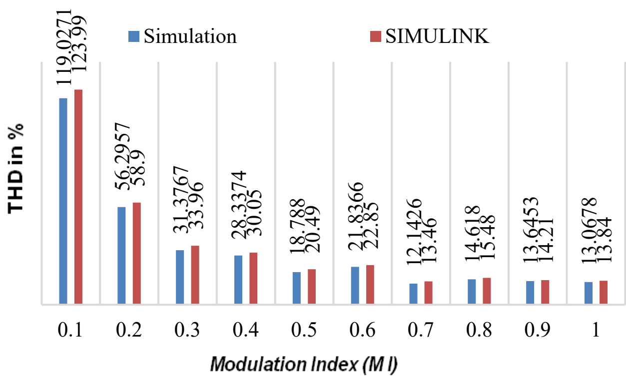
Figure 2. Flow chart for GA implementation

6.1. 5-Level Inverter

In the instance of GA-based switching, Figure 3a shows the best switching angles for various MI. The Figure 3b shows the comparison of THD content for different modulation index in5-level program simulation and Simulink CHB-MLI model. From Figures 3a and 3b, it is observed that as the modulation index increases, the corresponding switching angle reduces with THD reduction. From Figure 3b it is observed that when the modulation index (*MI*) is equal to 0.7, the amount of THD achieved shows the lowest value of 12.14% and 13.46% in program simulation and Simulink CHB-MLI model respectively. It is also observed that the variation of THD values in simulated and the model is within ±10% tolerance.



(a)

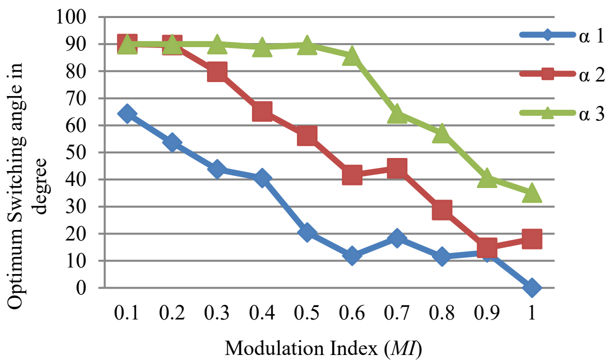


(b)

Figure 3. 5 level GA based SHEPWM CHB-MLI based on GA, a) Switching angles, b) THD Values

6.2. 7-Level Inverter

Figure 4a presents the optimal switching angles for different modulation index in GA technique. The Figure 4b shows the comparison of THD content for different modulation index of 7-level program simulation and Simulink CHB-MLI model. It is observed from Figure 4a and 4b that as the modulation index increases, the corresponding switching angle reduces resulting in THD reduction, similar to that of 5- level CHB-MLI. But from Figure 4b, it is observed that the lowest THD content has been achieved for *MI*= 0.8 in case of 7 level GA based SHEPWM CHB-MLI i.e., 7.04% and 8.77% in program simulation and Simulink model, respectively.



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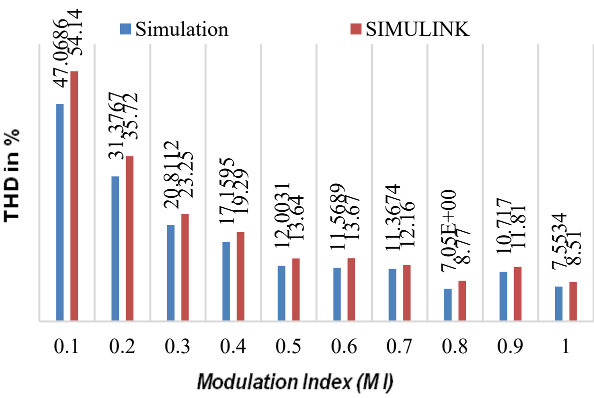


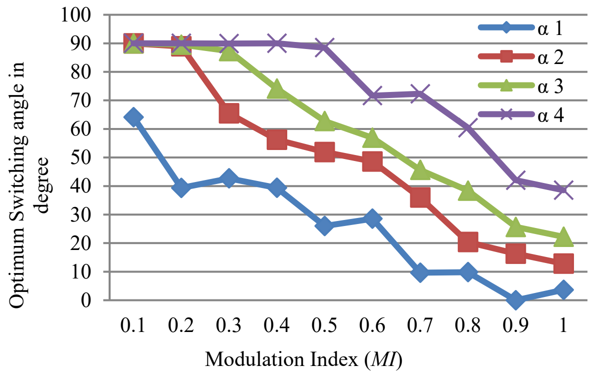
(b)

Figure 4. 7 level GA based SHEPWM CHB-MLI based on GA (a) Switching angles (b) THD Values

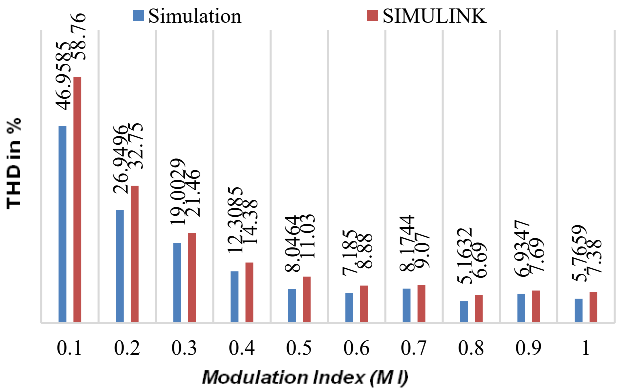
6.3. 9-Level Inverter

Figure 5a shows the ideal switching angles for various *MI* using the GA approach. The Figure 5b shows the comparison of THD values for different modulation index for 9-level program simulation and Simulink CHB-MLI model. From Figure 5a and 5b it is observed that as the modulation index increases, the corresponding switching angle reduces with THD content reduction, similar to that of 5-level MLI. However, from Figure 5b, it is observed that the lowest THD is achieved for *MI*= 0.8 in case of 7-level GA based SHEPWM CHB-MLI. i.e., 5.16% and 6.69% in program simulation and model, respectively.

From Figures 3b, 4b and 5b, it is observed that THD values are decreased as the number of levels of the MLI increases. For *MI*=0.8, the THD value is found to be 14.61% ,7.047% and 5.16% from the program simulation and 15.48%, 8.77% and 6.69% for 5, 7, 9 levels from the model simulation, respectively.



(a)



(b)

Figure 5. 9 level GA based SHEPWM CHB-MLI based on GA, a) Switching angles, b) THD Values

6.4. Comparative Analysis of 5, 7 and 9-level CHB-MLI

Table 2 summarize the comparative analysis of proposed GA based SHEPWM CHB-MLI from the developed Simulink model. The following observations were made from the derived results:

1) 3rd, 5th and 9th harmonics are almost equal to zero
2) Harmonics THD content decreases as the number of levels increased
3) Phase and line voltage levels are increases as the *MI* increases in all level MLI
4) The Phase and Line voltages are almost nearly equal to designed values (Phase voltage is 230V and Line voltage= 400
5) when *MI*=0.8.

It is also observed that in 9-level SHEPWM CHB-MLI, when *MI*=0.8 the Phase voltage is 231.3V and Line voltage=399.8 V and 5th, 7th, 9th and 11th harmonics are almost near to zero. Its shows that the designed 9-level SHEPWM CHB-MLI is most efficient compared to 5 and 7-level SHEPWM CHB-MLI.

6.5. Modified/Reduced Switch 9-Level CHB-MLI

In addition to 9-level CHB-MLI, a decreased switch (modified) 9-level MLI is constructed in this study, and the results are compared to 9-level CHB-MLI. The schematic design of the 9-level reduction switch MLI is shown in Figure 6. The 9-level reduced switch multilevel inverter necessitates eight switches and four switching angles (α_1, α_2, α_3 and α_4), which were obtained using a genetic algorithm. Figure 7 shows the Phase voltage graphs obtained at *MI*=0.8 of 9-level CHB-MLI and reduced switch MLI Simulink model.

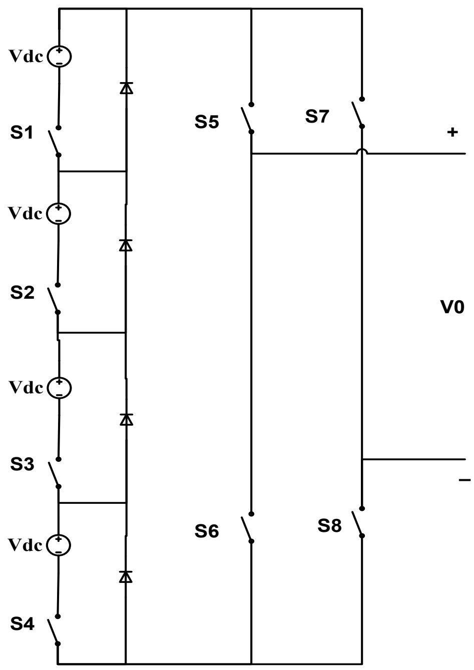


Figure 6. Schematic diagram of 9-level reduced switch MLI

Figures 8 and 9 shows the line voltage FFT Analysis Graphs obtained at *MI*=0.8 of 9-level CHB-MLI and reduced switch MLI Simulink model. Figure 10 shows the comparison of THD values for different modulation index of 9-level SHEPWMCHB-MLI and modified (reduced switch) MLI Simulink model. It is also observed that THD values of 9-level reduced switch inverter is either less or sometimes it is almost equal when *MI* is higher as to compared to 9-level CHB-MLI. It is also found that lowest THD is achieved for *MI*= 0.8 i.e., 6.69% and 6.86% in CHB-MLI and reduced switch MLI model, respectively.

Table 2. Comparisons of Simulink model results of 5, 7 and 9 level GA based SHEPWM CHB-MLI

Inverter Level	Number of Switch	*MI*	Lower order harmonics					RMS Voltage (V)		%THD	
			3rd	5th	7th	9th	11th	Phase	Line	Phase	Line
Five level CHB-MLI	8	0.7	0	0	5.678	0	3.959	208.9	352.2	27.22	13.46
		0.75	0	0	0.8553	0	6.21	221.2	377.2	22.19	13.02
		0.8	0	0	7.796	0	10.43	234.2	403.2	18.37	15.48
Seven level CHB-MLI	12	0.7	0.1584	0.2212	0.206	0.3395	2.51	195.1	332.6	22.12	12.16
		0.75	0.1679	0.1062	0.3191	0.3123	2.348	207	355.7	15.49	9.01
		0.8	0.2523	0.07386	0.3326	0.1268	1.552	220.1	379.4	12.4	8.77
Nine level CHB-MLI	16	0.7	0.3514	0.162	0.1198	0.1935	0.2111	204	350.3	16.85	9.07
		0.75	0	0.3476	0	0.2793	0.0584	217.6	375	12.95	8.15
		0.8	0.2177	0.1053	0.2	0.1231	0.1756	231.3	399.8	9.64	6.69

Table 3. Comparing Results of 9-level Modified/Reduced Switch and Conventional GA based SHEPWM MLI

Inverter Level	Number of Switch	*MI*	Lower order harmonics					RMS Voltage (V)		%THD	
			3rd	5th	7th	9th	11th	Phase	Line	Phase	Line
Nine level Reduced switch	8	0.7	0	0.2813	0	0	0	193.5	331.7	17.08	9.11
		0.75	0	0.1862	0	0	0	206.1	355.2	12.81	8.14
		0.8	0	0	0	0	0	219	378.4	9.66	6.86
Nine level CHB-MLI	16	0.7	0.3514	0.162	0.1198	0.1935	0.2111	204	350.3	16.85	9.07
		0.75	0	0.3476	0	0.2793	0.0584	217.6	375	12.95	8.15
		0.8	0.0738	0.093	0.1136	0.1586	0.1717	231.3	399.8	9.64	6.69

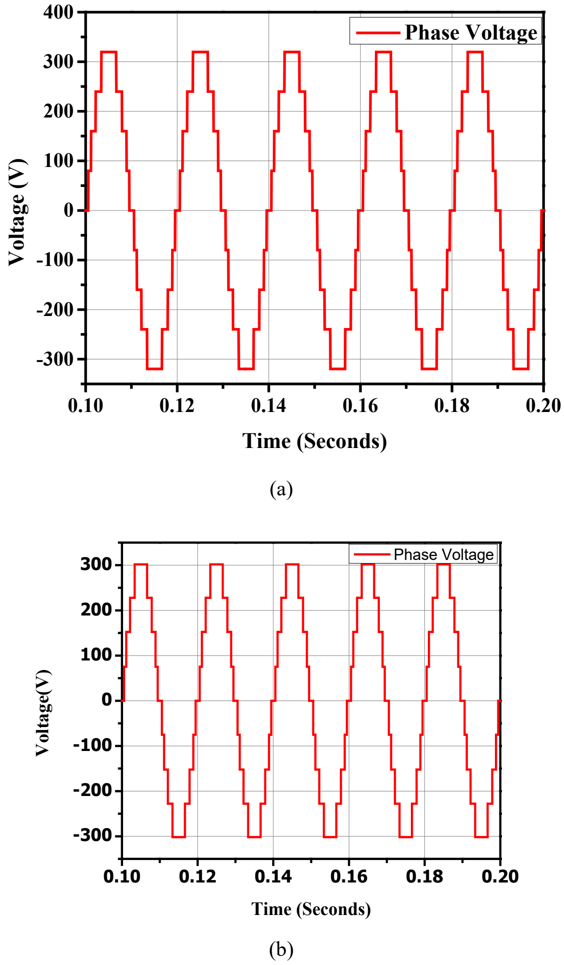


Figure 7. a) Phase voltage of 9-level CHB-MLI at *MI*=0.8, b) Phase voltage of 9-level reduced switch MLI at *MI*=0.8

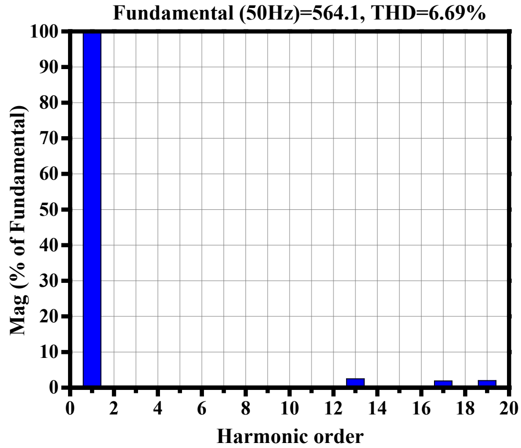


Figure 8. FFT analysis of 9-level CHB-MLI with *MI*=0.8

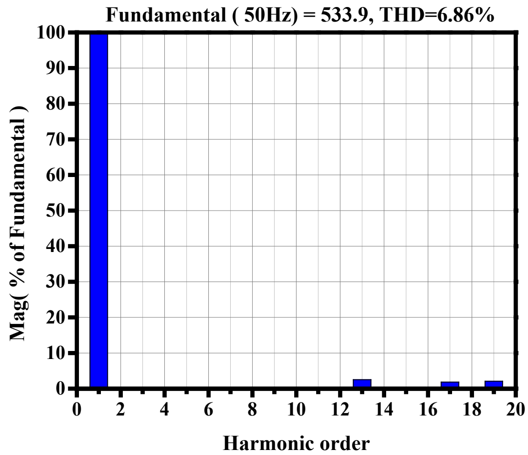


Figure 9. FFT analysis of 9-level reduced switch with *MI*=0.8

Comparing the obtained results of 9-level SHEPWM based conventional CHB-MLI and 9-level SHEPWM based reduced switch MLI, the following observations are made from Table 3 are:

i) Only eight switches are required to design 9-level reduced switch GA based SHEPWM MLI, whereas 16 switches are required to design SHEPWM CHB-MLI. This results in reduced the switching losses.

ii) Lower order harmonics of 9-level reduced switch are less and sometimes almost equal as compared to SHEPWM CHB-MLI.
iii) There is a negligible difference of THD values of 9-level reduced switch MLI as compared to SHEPWM
iv) CHB-MLI. e.g.: For *MI*= 0.8 THD values of line voltage is 6.69% in CHB-MLI and 6.87% with reduced switch MLI respectively.
v) There is a marginal reduction of RMS voltage (Line and phase) with9-level reduced switch MLI as compared to SHEPWM CHB-MLI.

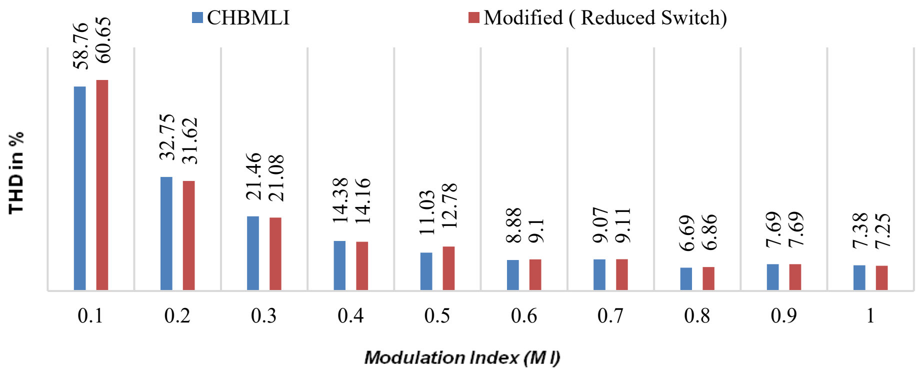


Figure 10. THD values of 9-level CHB-MLI and modified (reduced switch) Simulink model

However, this variation is within the 10%. Based on the FFT analysis result obtained from the reduced MLI configuration, it is found that the content of harmonics has been reduced and also maintains the desired output voltage. Therefore, due to the reduction in losses, the efficiency of the inverter will increase and also the THD content comparable with the conventional 9-level CHB-MLI. Therefore, it is preferable to use reduced switches CHB-MLI in place of conventional cascaded multilevel inverters.

7. CONCLUSION

A Simulink model was used to compare the proposed GA based SHEPWM three-Phase CHB-MLI with the Reduced Switch GA based SHEPWM MLI. The results obtained from the comparison provide the valuable insights into the performance and efficiency of these multilevel inverter configurations. The comparative study demonstrates that the GA-based SHEPWM approach is highly effective in achieving harmonic elimination and reducing harmonic distortion in multilevel inverters. The three-phase, nine-level SHEPWM CHB-MLI configuration outperformed the five- and seven-level configurations in terms of harmonic content, thereby enhancing efficiency. In addition to this, the 9-level reduced switch MLI with GA-based SHEPWM showed promise as a viable alternative to CHB-MLI in terms of requiring fewer switches to achieve the desired voltage level. reducing the number of switches while maintaining satisfactory harmonic performance and the desired voltage levels. These findings provide valuable guidance for engineers and researchers while selecting appropriate multilevel inverter configurations for specific applications, considering factors like harmonic performance, switch count, and overall efficiency. The results confirm the potential of the proposed approaches to contribute to the development of more efficient and reliable multilevel inverter systems for various industrial applications.

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