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Harmonic Reduction of a Single-Phase Multilevel Inverter Using Genetic Algorithm and Particle Swarm Optimization

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Additional information is available at the end of the chapter

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Abstract

Power inverter play an important role in power system especially with its capability on reducing system size and increase efficiently. The recent research trends of power electronic system are focusing on multilevel inverter topics in optimization on voltage output, reducing the total harmonics distortion, modulation technique, and switching configuration. The research emphasizes the optimization with a fundamental switching frequency method that is the optimized harmonic stepped waveform (OHSW) modulation method. The selective harmonic elimination (SHE) calculation has adapted with genetic algorithm (GA) and particle swarm optimization (PSO) in order to speed up the calculation. Both bioinspired algorithms are compared in terms of total harmonic distortion (THD) and selective harmonic elimination for both equal and unequal sources. The overall result showed that both algorithms have high accuracy in solving the nonlinear equation. However, the genetic algorithm showed better output quality in terms of selective harmonic elimination which overall no exceeding 0.4%. Particle swarm optimization shows strength in finding the best total harmonic distortion where in seven-level cascaded H-bridge multilevel inverter ($m=0.8$) shows 6.8% only as compared to genetic algorithm. Simulation for three-level, five-level, and seven-level for each multilevel inverter at different circumstances had been done in this research. The result draws out a conclusion where the possibility of having a filterless high-efficient inverter can be achieved.

Keywords: multilevel inverter, SPWM, OSHW, PSO, GA

1. Introduction

Inverters can be classified into two main types, that is, voltage source inverter (VSI) and current source inverter (CSI). Each type has its own unique characteristic, which has been listed in the literature [1–5]. From the literature, a brief conclusion of VSI which is more popular than CSI has been made [1]. VSI transformer-less inverter popular in renewable energy (RE) application due to overall size reduction. The most commonly used inverter is high-power two-level PWM inverter. However, high-power application ideally requires low switching losses.

Over the past decade, numberless of literature has proven multilevel inverter is a practical solution on resolving high switching losses problem exist in conventional inverter for high power application [6]. Research trends nowadays are more focusing on several multilevel inverter topologies for renewable energy source application. Multilevel inverter topologies generate multilevel voltage source output which synthesizes the staircase waveform from single or multiple low DC voltage source. The low-input voltage source reduces the stress encounter by the switches with the ability to produce high-output voltage source. Cascaded H-bridge multilevel inverter (CHB-MLI) and its modified topologies is highly grab researchers attention due to the flexibility toward renewable energy.

Multilevel inverter system can be separated into two sectors which are inverter topology system and switching strategy. Inverter topology system consists of the most part include switch, power sources, topology configuration, and filter system. Power sources are mostly RE such as solar panel and wind turbine. For topology configuration, there are three main types, which have been frequently cited in the literature, that is, diode-clamped multilevel inverter (DC-MLI), capacitor-clamped multilevel inverter (CC-MLI), and cascaded H-bridge multilevel inverter (CHB-MLI) [7–14]. Filter is applied to remove harmonics and to smoothen the inverter output quality.

Switching strategy aid in manipulate the harmonic profile for the inverter output waveform. Square wave output is a conventional type. This type evolves into a quasi-square wave, which gives a better profile as compared to square wave. The current trend is pulse width modulation (PWM), which has been widely applied in current VSI devices [15]. However, researchers explored other methods on overcoming the cons of PWM where different kinds of add-on methods have been applied in conjunction with PWM such as selective harmonic elimination (SHE). SHE consists of a complex nonlinear equation on resolving the best switching timing. Hence, various calculation approaches have been tested to optimize the overall performance. The calculation method includes Newton-Raphson, Fourier transform, and even bioinspired algorithm approach such as bee, ant, particle swarm, genetic, bat, and others [16–21]. The overview for this chapter is to introduce genetic algorithm and particle swarm optimization in resolving the SHE which eliminates the low order of undesired harmonics.

2. Multilevel inverter

One of the inverters discussed in this chapter is the cascaded H-bridge multilevel inverter. Simulation is conducted under the same parameters and the same modulation methods, which

Parameters	Value
Modulation signal frequency	50 Hz
Carrier signal frequency	4000 Hz
Sampling time	$1 \times e^{-06}$ s
Total input voltage source(s)	240 V

Table 1. Simulation parameters.

are SPWM and OSHW. The simulation result will be evaluated based on the total harmonic distortion (THD) level of the inverter. SPWM is constructed with parameters shown in Table 1.

2.1. Cascaded H-bridge multilevel inverter

Two or more separate DC sources in a full bridge are placed in series to generate a staircase AC output waveform voltage. Figure 1 shows a two-level CHB-MLI topology. CHB-MLI requires

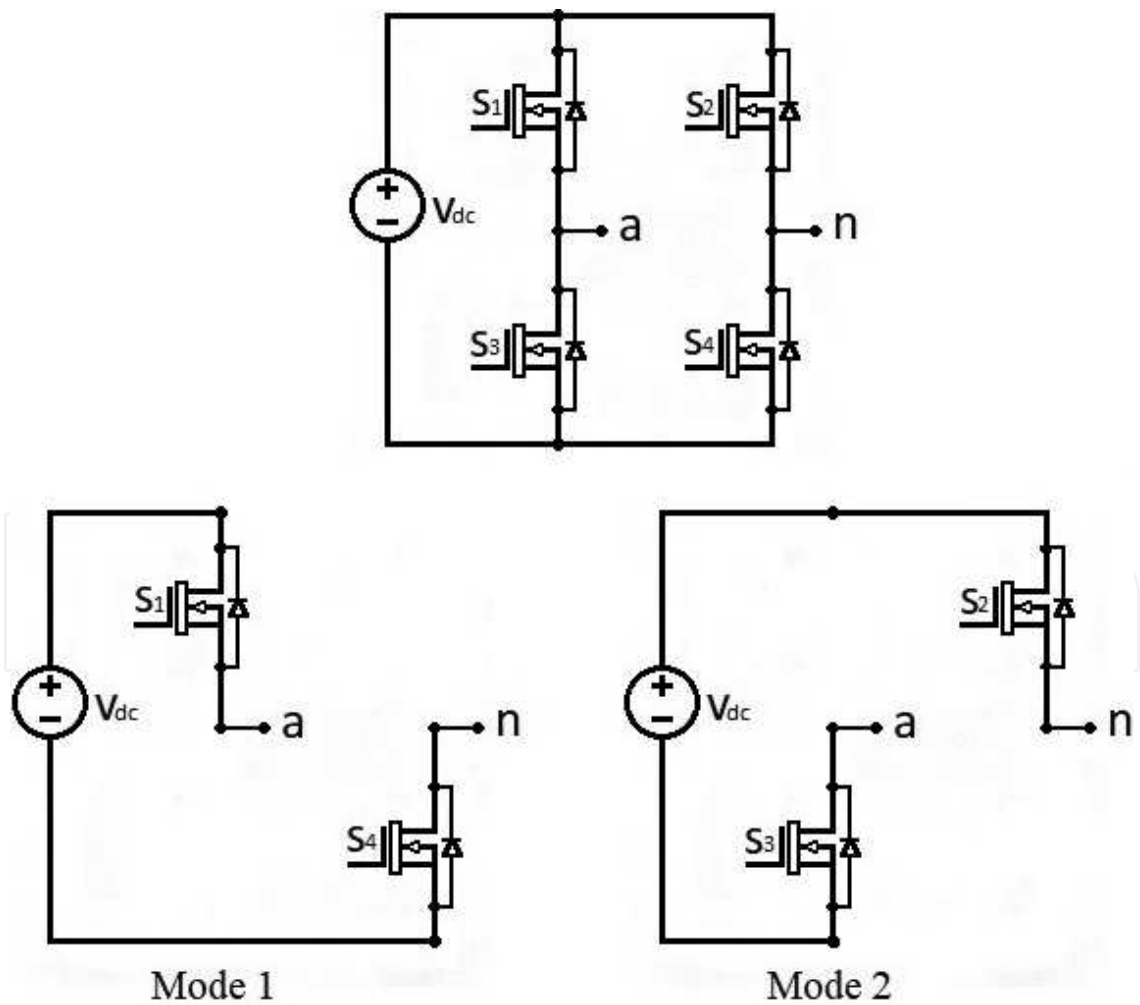


Figure 1. Two-level cascaded H-bridge multilevel inverter topology.

fewer components where each voltage level requires the same amount of components. However, the number of sources is higher since m voltage-level inverter $s = \frac{(m-1)}{2}$ sources are required. The number of sources s is also equal to the number of full-bridge modules.

The CHB-MLI switching configuration is similar to the other topology. When S1 and S4 are on and S2 and S3 are off, voltage V_{an} is equal to V_{dc} due to the current flow sequence. When S1 and S2 are on and S3 and S4 are off, the voltage output is 0. When S1 and S2 are off and S3 and S4 are on, the voltage output is 0. When S1 and S4 are off and S2 and S3 are on, the voltage output is $-V_{dc}$.

Every full-bridge module has four diodes and four switches s in turn giving the CHB-MLI $2(m-1) = 4s$ diodes and switches. When making a three-phase inverter with the topology, the number of needed components is multiplied by 3 for all components since there is no common DC bus to share.

CHB-MLI are suitable to be implemented in the photovoltaic cells, battery cells, or fuel cells [3, 16, 17]. The consideration of the number of levels for CHB-MLI is different from other. The calculation of CHB-MLI of the number of voltage levels includes the negative side of each voltage level, while other topologies do not.

The topology is implementing a combination of several H-bridges dependent on the number of levels required. Three-level cascaded H-bridge multilevel inverter is shown in **Figure 2**. The separate dc sources gain the possibility of a single-phase topology to be constructed. The numbers of levels involved are three-level, five-level, and seven-level, which are constructed throughout observing the effect on harmonic distortion.

2.2. Sinusoidal pulse width modulation

Sinusoidal pulse width modulation (SPWM) is applied with the capability of offering switching signal to the power electronic switch. The operation function is by comparing two principal component signals which are the modulation signal and the carrier signal. Modulation signal used is a sine wave signal due to the desired output wave. The carrier wave applied mostly is high-frequency triangle or Sawtooth repetition wave. This technique employs comparison between the modulation signal and the carrier signal to obtain a desired fundamental component of the voltage output waveform. **Figure 3** has shown phase disposition modulation, which uses one of the multicarrier PWM methods where the number of carriers depends on the multilevel inverter. The method is applied $(m-1)$ where m is referring to the number of sources. Both carriers are in the same phase, which gives rise to the name of phase disposition modulation.

The pulse generator operation is illustrated in **Figure 4**. The top-row black signal in the top figure is the triangle repetitive pulse, while the red signal in the top figure is the modulation wave. The bottom-row red signal in the bottom figures shows the pulse generated throughout the comparison. When the modulation signal is higher than the carrier signal, the output signal comparator would show 1. Then, when the modulation signal is less than the carrier signal, the output signal comparator would show 0. The generator switching pulse is then injected to a

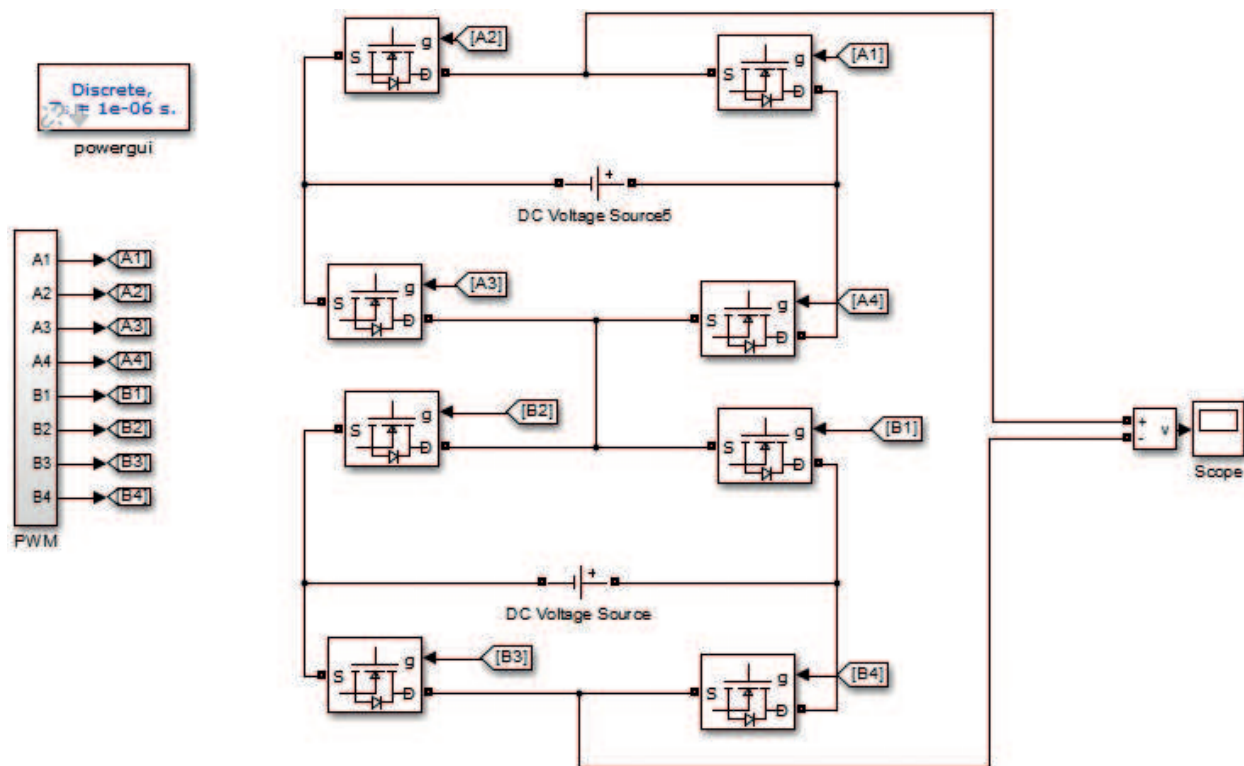


Figure 2. Three-level cascaded H-bridge multilevel inverter.

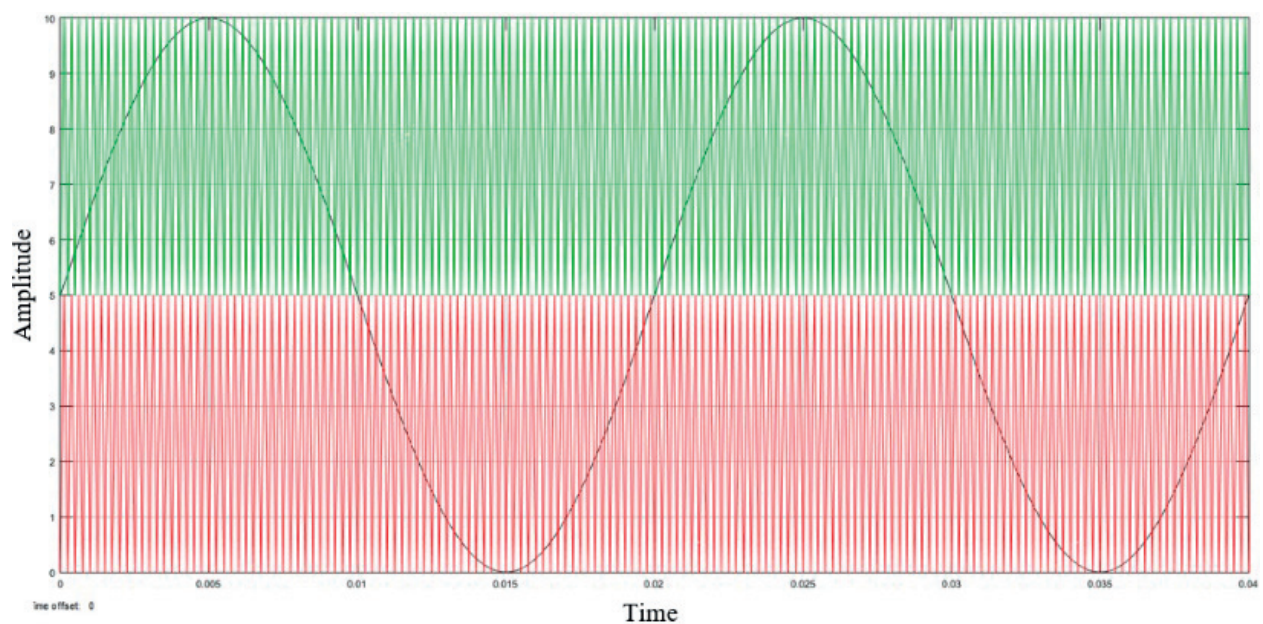


Figure 3. SPWM phase disposition modulation.

specific switch. The switching affects the output voltage where different switching sequences allow for different voltage-level configurations with different switching frequencies. Hence, the voltage levels are able to be switched according to the SPWM signal.

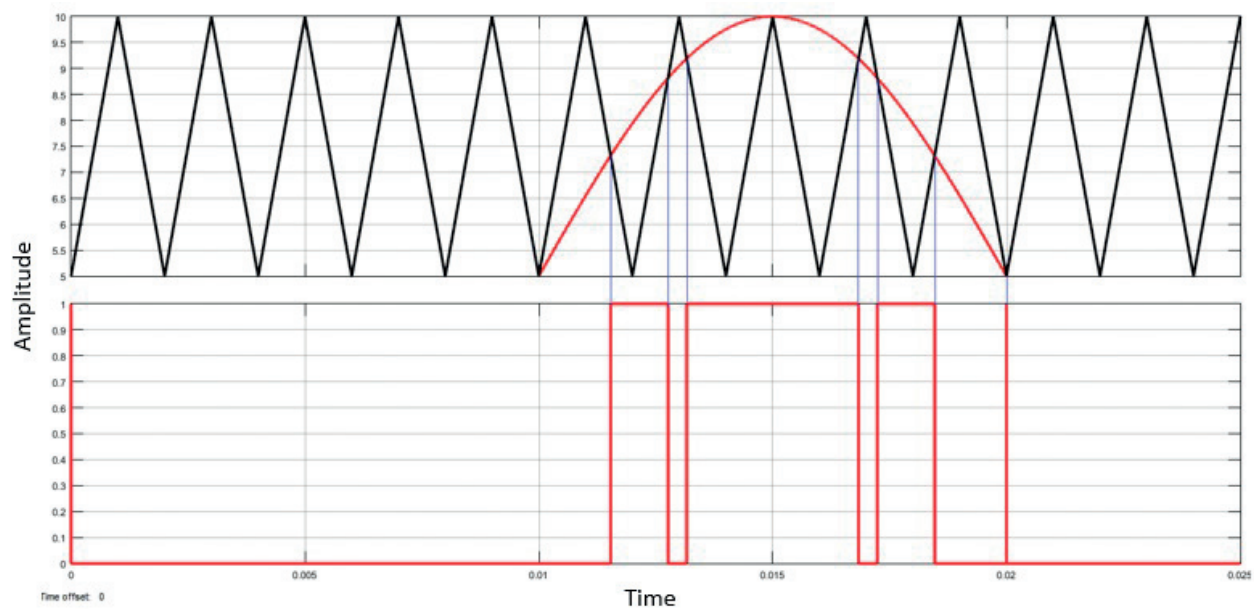


Figure 4. Comparison of modulation signal and carrier signal illustration.

2.3. Optimized harmonic stepped waveform

OHSW technique has the advantage to reduce harmonic distortion. The basic concept is applying selective harmonic elimination PWM and quarter-wave symmetric to eliminate low-order harmonics [18]. For the topology of OHSW cascaded H-bridge multilevel inverter to operate, switching angle is first calculated using MATLAB’s main interface to obtain the best switching angle. The result obtained is applied to be the pulse generation block generated in Simulink environment. Other parameters such as modulation signal and carrier signal are added in the block.

From the MATLAB calculation for the selective harmonic elimination, the switching angle for each specific voltage-level change is recorded. The recorded data is simulated from 0 to 1 of the modulation index with a step of 0.5. The result obtained is converted into a graphical form for further analysis of the pattern.

2.4. Fourier series approach voltage output

The H-bridge multilevel inverter has an individual voltage supply for each full bridge. Hence, the total voltage output for the inverter is given as Eq. (1):

$$V_{out} = V_1 + V_2 + \dots + V_n. \tag{1}$$

where n is the number of voltage source applied in the whole H-bridge multilevel inverter. **Figure 5** shows the generalized staircase waveform of a five-level multilevel inverter. From the **Figure 5**, it can be observed that the θ_1 , θ_2 , θ_3 and θ_4 showed the switching angle for the inverter. For each level, the voltage value is changed according to the switching angle time. Voltage at θ_1 switching timing is V_1 , at θ_2 switching time is V_2 , and so on. The voltage supplied

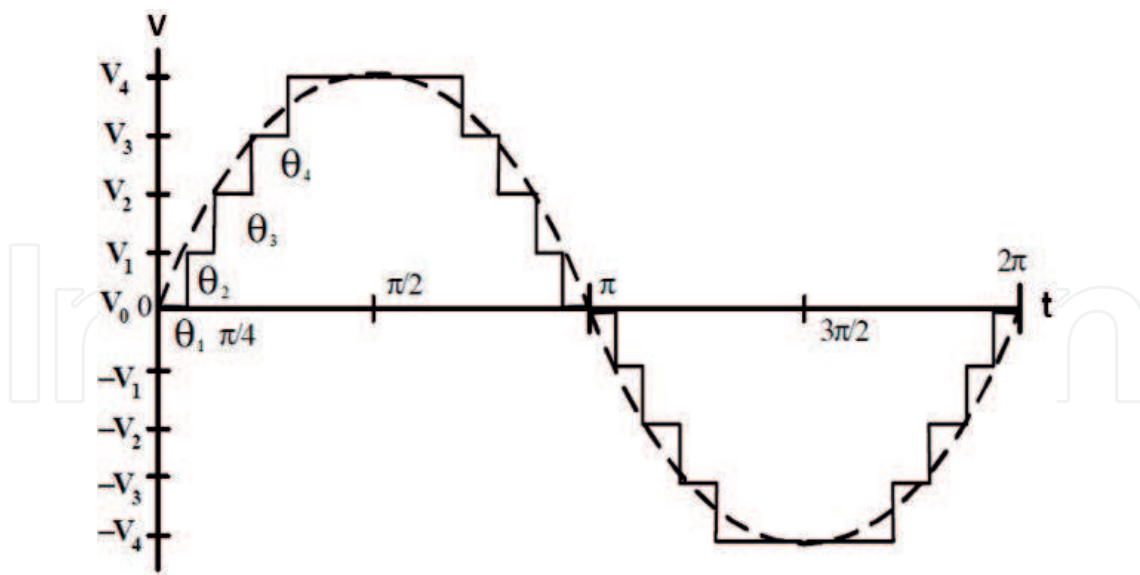


Figure 5. Generalized staircase waveform of five-level multilevel inverter.

by the separate dc sources is different in the voltage level where the amplitude or voltage of each dc source can be different. There are two variables which may manipulate the harmonic distortion for the inverter. The first variable is the amplitude of the separate DC source where the voltage level of each DC source can be equal or unequal. The second variable is the switching step where the step can be short or long. Both variables will affect the result of the total harmonic distortion of the output voltage.

For the modulation index of an H-bridge multilevel inverter, the definition is similar to the modulation index for SPWM. The equation is drawn as given in Eq. (2) assuming that all the V_{dc} are equal:

$$m = \frac{V_{out}}{4nV_{dc}}. \quad (2)$$

where V_{out} is the amplitude output voltage, V_{dc} is the amplitude dc source of the H-bridge, and n is the number of dc source in H-bridge. For the condition of unequal voltage source, the V_{dc} value is replaced with the total voltage of all the DC sources in use as shown in Eq. (3):

$$m = \frac{V_{out}}{V_1 + V_2 + \dots + V_n}. \quad (3)$$

The staircase waveform is analyzed to obtain a general equation. The quarter-wave symmetric waveform can be written in a Fourier series form shown in Eq. (4):

$$\begin{aligned} a_n &= \frac{4}{\pi} \int_0^{\frac{\pi}{2}} f(\omega t) \sin(n\omega t) d(\omega t), \text{ for odd } n \\ a_n &= 0, \text{ for even } n \\ b_n &= 0, \text{ for all } n. \end{aligned} \quad (4)$$

where

$$f(\omega t) = V_{out}(\omega t) \quad (5)$$

From Eqs. (4) and (5), the Fourier series can be concluded as Eq. (6):

$$f(\omega t) = \sum_{n=1}^{\infty} a_n \sin(n\omega t). \quad (6)$$

Let $x = \omega t$,

$$a_n = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} f(x) \sin(nx) dx. \quad (7)$$

Then

$$\begin{aligned} a_n &= \frac{4}{\pi} \left[\int_{a_1}^{a_2} E_1 \sin(nx) dx + \int_{a_2}^{a_3} E_2 \sin(nx) dx + \dots + \int_{a_k}^{\frac{\pi}{2}} E_k \sin(nx) dx + \right] \\ &= \frac{4}{n\pi} \left[-E_1 \cos(nx) \Big|_{a_1}^{a_2} - E_2 \cos(nx) \Big|_{a_2}^{a_3} - \dots - E_k \cos(nx) \Big|_{a_k}^{\frac{\pi}{2}} \right] \\ &= \frac{4}{n\pi} \left[-E_1 \cos(nx_2) + E_1 \cos(nx_1) - E_2 \cos(nx_3) \right. \\ &\quad \left. + E_2 \cos(nx_3) - \dots - E_k \cos\left(n\frac{\pi}{2}\right) + E_k \cos(nx_k) \right] \\ &= \frac{4}{n\pi} [E_1 \cos(nx_1) + (E_2 - E_1) \cos(nx_2) + \dots + (E_k - E_{k-1}) \cos(nx_k)]. \end{aligned} \quad (8)$$

Eq. (7) assumes that x is equal to ωt to simplify the calculation. Then, the resultant equation is Eq. (8). Eq. (8) shows separate DC source formulation where E_1 ($E_2 - E_1$) and $(E_k - E_{k-1})$ represents each H-bridge voltage source. There are two conditions in the simulation, that is, the equal dc source and the unequal DC source. The equation above applies for both conditions. However, for equal DC source, the equation is able to be simplified as show in Eq. (9).

Since DC source are equal

$$\begin{aligned} V_{1,2\dots k} &= E_1 = (E_2 - E_1) = (E_k - E_{k-1}) \\ a_n &= \frac{4}{n\pi} [V \cos(nx_1) + V \cos(nx_2) + \dots + V \cos(nx_k)] \\ a_n &= \frac{4V}{n\pi} [\cos(nx_1) + \cos(nx_2) + \dots + \cos(nx_k)] \\ a_n &= \frac{4V}{n\pi} \sum_{s=1}^k V \cos(nx_s). \end{aligned} \quad (9)$$

2.5. Selective harmonic elimination calculation

SHE is proposed to eliminate the unwanted harmonics. Harmonic distortion occurs due to the conversion of DC to AC. Harmonic distortion is able to be resolved by using harmonic filters such as low-pass filter to reduce the high-frequency harmonics. For medium and high voltage or power applications, the first approach and the number of switching angles are limited by switching loss and usually are used when the available voltage steps are limited.

SHE is manipulating the switching angle to reduce the harmonic distortion. In multilevel application, every single voltage level has multiple switching angles. The SHE method provides the best switching angle to decrease the harmonic frequency. The harmonic elimination is depending on the number of voltage step. In inverter with voltage output of three voltage steps, the possible harmonic elimination would be the third and fifth harmonic component only. The general staircase waveform Fourier series given in Eq. (10) is derivative of the above equation. The mathematical Fourier series formulation is shown as the possible method of eliminating the desire of low harmonic component and can be manipulated as selective harmonic elimination:

$$V_{\text{out}} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{\text{in}}}{2\pi} \times \frac{1}{n} (\cos(n\theta_1) + \cos(n\theta_2) + \dots + \cos(n\theta_k)) \sin(n\omega t). \quad (10)$$

where V_{out} = voltage output (V), V_{in} = voltage input (V), n = harmonic component, k = number of switching angles.

The number of switching angles represents the harmonic component that is required to be eliminated. The fundamental component is the desired voltage, and the rest needs to be eliminated. Hence, the number of harmonics needed to be removed is $k-1$. From the expression of Eq. (10), each peak voltage for the n th harmonics is expressed in Eq. (11):

$$V_n = \frac{4V_{\text{in}}}{n\pi} [\cos(n\theta_1) + \cos(n\theta_2) + \dots + \cos(n\theta_k)]. \quad (11)$$

Each peak voltage is calculated to obtain the switching angle. The equation showed that the voltage of each harmonic can be manipulated. The method to manipulate to remove the other undesired harmonic voltages is the basis of selective harmonic elimination (SHE) method. Eq. (12) showed the general SHE method calculation. H represents the number of harmonics step [22–26]:

$$\begin{aligned} H = 1 : \quad V_1 &= \frac{4V_{\text{in}}}{\pi} [\cos(\theta_1) + \cos(\theta_2) + \dots + \cos(\theta_n)] \\ H = 2 : \quad 0 &= \cos(2\theta_1) + \cos(2\theta_2) + \dots + \cos(2\theta_n) \\ H = 2n - 1 : 0 &= \cos[(2n - 1)\theta_1] + \cos[(2n - 1)\theta_2] + \dots + \cos[(2n - 1)\theta_n]. \end{aligned} \quad (12)$$

3. Bioinspired algorithm

Selective harmonic elimination is a series of nonlinear equations that can be solved to obtain the switching angle for the inverter. Due to the multiple possible set of data, the calculation

involved is very complicated. In order to resolve the problem, the research makes comparison between particle swarm optimization algorithm and genetic algorithm.

3.1. Genetic algorithm

Genetic algorithm (GA) employs the natural biological evolution theory as the concept to solve constrained or unconstrained optimization problems [27, 28]. The algorithms are inspired by Darwin theory of “the survivor of the fittest” [29]. GA is a method where the first-generation individual left for the competition. For every round of competition, the survivor will become the new-generation individual to continue to be in the competition. The process will keep repeating where the survivor becomes the parent of the new generation to pass over the genetic. The survivor is also known as the fittest individual. The competition continues to leave the desired genetic behind until the best fitness individual is obtained [24].

The GA algorithm starts with the injection of the initial population. The existing instantaneous individual is evaluated by fitness function to determine the best answer. If the fitness is not reaching the desired level, the individual selection will undergo crossover, which mutates new offspring to be tested on its fitness, and the old generation will be disqualified. The process is repeated until the best fitness or optimum result is achieved.

There are several advantages of GA as compared to other optimization techniques. GA is more robust as compared to the conventional artificial intelligence. Besides that the GA is also not easy to break the error due to the slight input change or reasonable noise. This method also shows advantages of larger state space search optimization technique. The genetic algorithm parameter is set by the creation function in the optimization tool of MATLAB.

The genetic algorithm application method in MATLAB is done with a series of M-file code. The calculation to resolve the nonlinear equation is done by applying genetic algorithm. Calculation process is separated into two parts, that is, constraint and fitness. Constraint file functions as the limitation of the switching angle. The switching angle of the wave should not be more than 180° . The constraint also gives a faster guideline, which ensures that the switching angle of the each switch is in the feasible range. For example, the switching angle for θ_2 is greater than θ_1 , θ_3 is greater than θ_2 , and $\frac{\pi}{2}$ is greater than θ_3 . This step is to make sure that the switching angle calculated is valid to be applied in the switching order which is $\theta_1 < \theta_2 < \dots < \theta_k < \frac{\pi}{2}$.

The next part is fitness where the nonlinear equation is listed for calculation. In this part, the change variable is modulation index, where m affects the result of switching angle. Fitness function is added in this M-file which generates fitness indices to clarify the best fit modulation index. Fitness value (fval) is a measurement of the solution from the fitness function with respect to the original objective and the amount of infeasibility. The fitness function applied is shown in Eq. (13):

$$f = \theta_0^{\pi/2} \left\{ \left(100 \frac{V_{ref} - V_1}{V_1} \right)^4 + \sum_{i=1}^n \frac{1}{n} \left(50 \frac{V_n}{V_1} \right)^2 \right\}. \quad (13)$$

where $n = 1, 3, 5, \dots, n$.

Parameters	Values
Inertia weight maximum (ω_{max})	0.9
Inertia weight minimum (ω_{min})	0.4
Acceleration constants (c_1 and c_2)	2
Swarm size	100
Number of iterations range	10–1000
θ_{min}	0
θ_{max}	0.5π

Table 2. Particle swarm optimization algorithm parameter.

The modulation index (m) is set to the range of 0 to 1. The process takes a few seconds to finish depending on the complexity of the function. The switching angle computed according to the modulation index provide and the fitness value is determined. Fitness function section for a three-level inverter for unequal DC source includes harmonic elimination on the third harmonic order by applying Eqs. (12) and (13) as mentioned before.

Both the constraint and fitness m-files are applied in the genetic algorithm optimization tool. In this stage, the fitness function section where the fitness file is created needs to be included. The number of variables in the fitness function needs to be clarified. Besides that, the boundary needs to be set for each variable to narrow the prediction. The upper bound should be 0, while the lower bound should not exceed $\pi/2$. The last process applied is the nonlinear constraint function where the constraint m-file is applied at this point.

3.2. Particle swarm optimization algorithm

Particle swarm optimization (PSO) originates from the natural behavior of a flock of birds, a school of fish, or a swarm of bee. James Kennedy and Russell Eberhart are the PSO founders which use optimized nonlinear functions [30, 31] in this technique. By applying bioinspired algorithm, constraint or unconstraint optimization can be solved efficiently and faster. PSO terminology is based on the current moving speed and direction in progress of searching the best personal and group position and in the end is located to the optimal or almost optimal solution [32]. PSO starts with declaration of parameters. The PSO algorithm for the selective harmonic elimination parameter is set in **Table 2**. The process continues with the random generation of particles by initializing their position and velocity. Fitness of position and velocity are evaluated to obtain the best fitness, P_{best} and global best, G_{best} . The process repeat is continuously updating the particles P_{best} and G_{best} until the optimum result is obtained.

4. Result and discussion

The simulation is repeated for three-, five-, and seven-level with equal and unequal DC source to test the topology performance and capability of the both algorithms in resolving such

problem. The example of simulation result is shown as follows, and the overall result is concluded.

4.1. Simulation of three-level CHB-MLI with OHSW method (equal sources)

The switching angle for each switch is calculated by applying SHE using genetic algorithm. Graph of switching angle versus modulation index is plotted and shown in **Figure 6**. The switching angle is set as a constraint where the angle θ_2 must be greater than θ_1 . The result shows validated data for the switching angle, which only happened to be located in between the range of modulation index 0.05 and 0.85. In this range, the result fulfills the constraint set. Hence, the best fit switching angle is within this range. Modulation index of 0 gives an invalid result due to highly inaccurate switching angle. From modulation index 0.05 to 0.4, the difference between θ_1 and θ_2 is small which causes the fitness function value to be high. From 0.45 to 0.85, the difference between θ_1 and θ_2 is larger. Hence, the fitness value for this region is low. From 0.9 to 1, high fitness value is shown. Fitness value is affected in terms of validation of switching angle calculated.

To further narrow down the range, graph of fitness function versus modulation index is plotted as shown in **Figure 7**. Theoretically, the lower the fitness function value, the better the chance to obtain the optimized switching angle. Hence, the range of relevant switching angle is narrowed down to the range of 0.45 to 0.8 of the modulation index.

All sets of modulation index and switching angle were tested in the simulation environment, and the results are recorded in **Table 3**. The table shows information for modulation index, total harmonic distortion, and the third harmonic of the corresponding modulation index. The result of extremely low third harmonics is highlighted which shows the region achieving

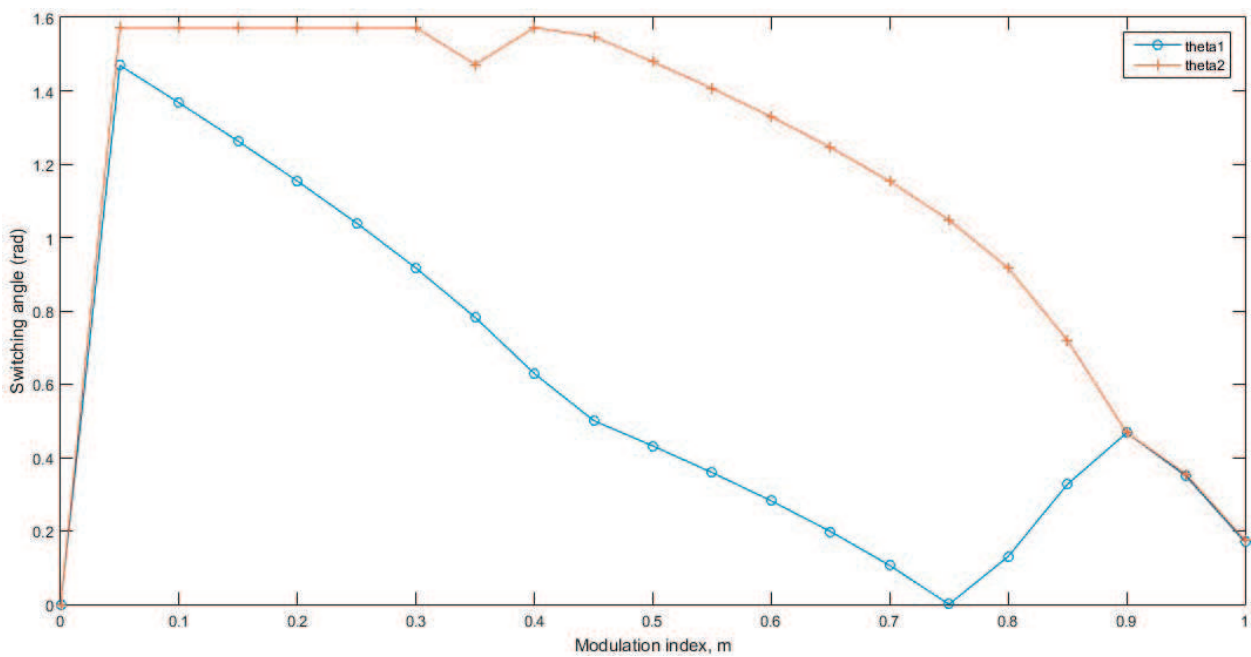


Figure 6. Three-level switching angle versus modulation index.

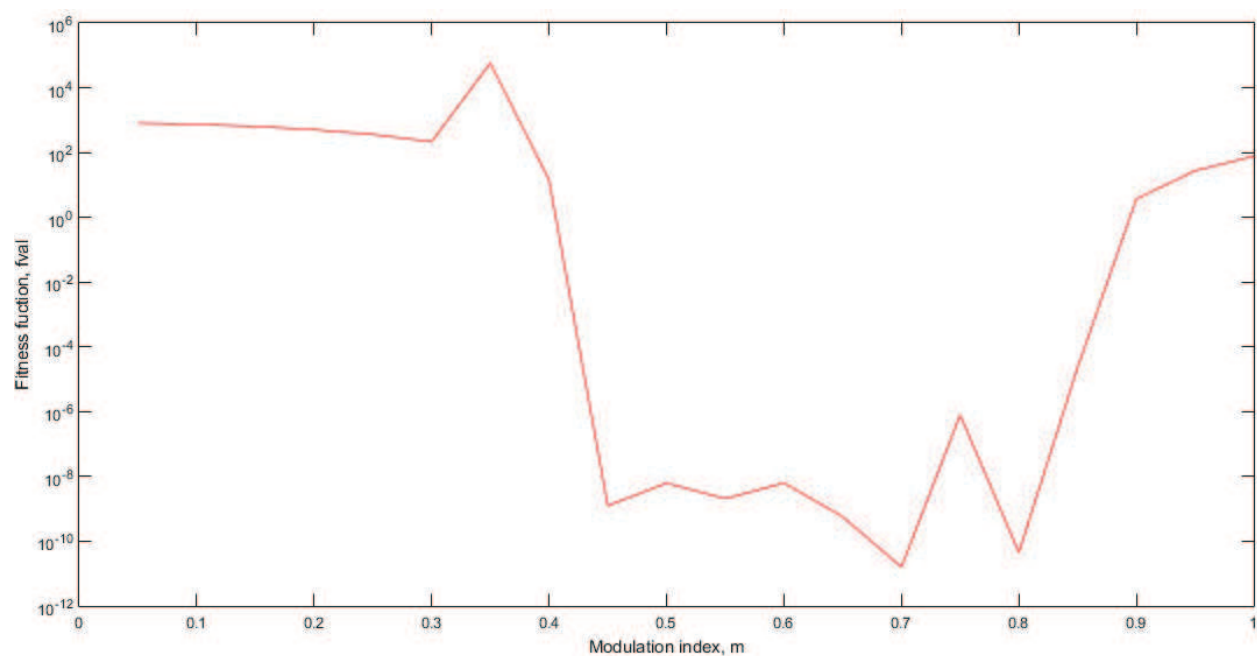


Figure 7. Graph of fitness function versus modulation index.

m	THD (%)	Third harmonic (%)
0.45	32.21	0.02
0.5	33.34	0.01
0.55	32.69	0.01
0.6	31.41	0.01
0.65	30.23	0
0.7	29.84	0
0.75	31.09	0
0.8	20.97	0
0.85	18.2	0.02

Table 3. Three-level total harmonic distortion with respective modulation index.

successful elimination of harmonics. Within the region, the lowest total harmonic distortion percentage is 18.2% with existing 0.02% of the third harmonic component present.

The result of the voltage output for $m = 0.85$ is shown in **Figure 8**. Output voltage is clearly a switched three-level voltage in a staircase sinusoidal waveform. The output undergoes FFT analysis, and the result is shown in **Figure 9**. The fundamental voltage component reaches 259.6 V_{rms} which shows the boosting character of cascaded H-bridge multilevel inverter character. The total harmonic distortion is 18.2% and clearly shows the third harmonics being reduced. The effect of selective harmonic elimination results in elimination of the third harmonics which is reduced to 0.02%.

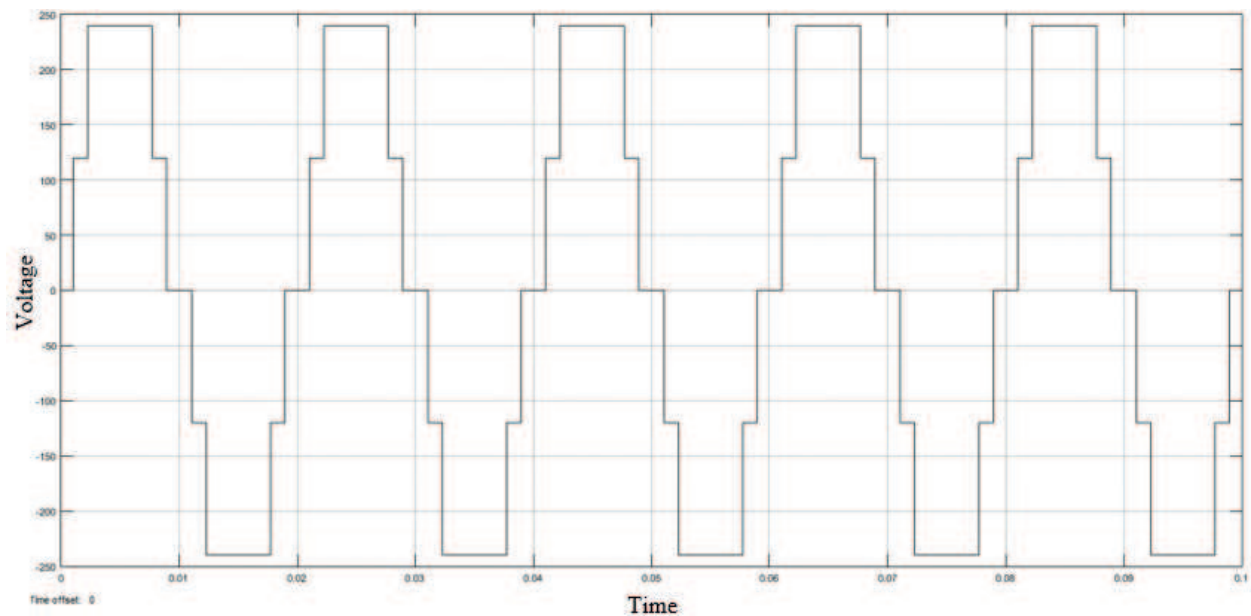


Figure 8. Three-level voltage output ($m = 0.85$).

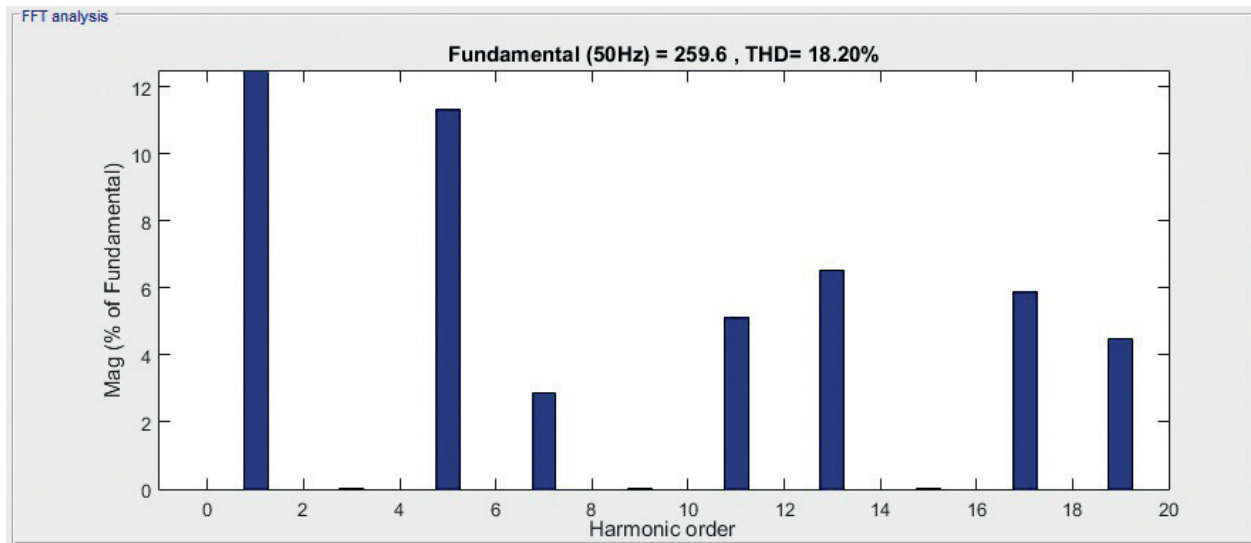


Figure 9. FFT analysis of three-level output ($m = 0.85$).

4.2. Overall result

The result simulation between SPWM and OHSW (GA) method is tabulated in **Table 4**. CHB-MLI applied optimized harmonic stepped waveform modulation method. The advantage for this method compared to SPWM is the switching frequency. SPWM in the first part of the simulation employed 4000 Hz carrier frequency which resulted in the pulse to occur at every step of the voltage. OHSW method operates at fundamental frequency. Switching frequency is mainly affecting the loss of energy and increases harmonic content. High switching frequency also results in short life span on power electronic switch. Hence, OSHW is superior to SPWM

CHB-MLI	Total harmonic distortion (%)	
	SPWM	OSHW(GA)
Three-level	26.96	18.2
Five-level	13.78	13.52
Seven-level	9.27	8.9

Table 4. Comparison between SPWM and OSHW method.

in terms of performance and durability. **Table 4** shows the THD comparison of SPWM and OSHW modulation on CHB-MLI. The result shows a huge reduction on THD for three-level but for five- and seven-level show minor reduction less than 1%. The result shown for CHB-MLI with OSHW method shows better performance as the selective harmonic elimination is applied. Genetic algorithm shows the capability of simplifying the Fourier series calculation and gets the most appropriate solution of switching angle.

The information obtained from the table show that THD percentage reduces as the number of the voltage level increases. This phenomena show that the increase of the voltage level is able to reduce the THD. This also inherits information that the decrement of THD is exponential to the number of levels. Hence, the increase of the voltage level to decrease THD is only limited to a certain number of voltage levels in terms of economical and performance aspect.

Standalone mode application mostly deals with the storage system. Hence, another set of simulation is done to test the capability of OSHW method with unequal DC source CHB-MLI. The result of the comparison of equal and unequal DC source CHB-MLI is tabulated in **Table 5**. The result shows that unequal DC source CHB-MLI performs better than equal DC source. All three-level, five-level and seven-level show lower THD percentage but the only minor differences. This result shows that OSHW modulation method is capable of reducing THD of both equal and unequal DC sources of cascaded H-bridge multilevel inverter. The result of low harmonic component elimination also shows the satisfactory level where the selected harmonics are reduced less than 1%.

Unequal DC source performs better than equal DC source CHB-ML. The problem is found to be related to modulation index step. Both GAs apply modulation step of 0.05 interval where a better solution possibly lies in the step with smaller interval. Besides that, the arrangement of

CHB-MLI (GA)	Total harmonic distortion (%)	
	Equal	Unequal
Three-level ($m = 0.85$)	18.2	18.06
Five-level ($m = 0.80$)	13.52	11.83
Seven-level ($m = 0.80$)	8.9	8.68

Table 5. Comparison between equal and unequal DC sources (genetic algorithm).

CHB-MLI (PSO)	Total harmonic distortion (%)	
	Equal	Unequal
Three-level ($m = 0.85$)	18.34	18.23
Five-level ($m = 0.80$)	12.17	12.63
Seven-level ($m = 0.80$)	9.4	6.80

Table 6. Comparison between equal and unequal DC sources (particle swarm optimization).

the voltage source is in increasing order which is also one of the factors, which smoothens the staircase waveform.

Another set of simulation applies the particle swarm optimization method with same fitness function and modulation step. The result is shown in **Table 6**. The result shows that SHE by PSO is less effective than GA. For three-level and seven-level CHB-MLI, GA produces lower THD output and then PSO type.

GA method has good prediction of switching angle for three-level CHB-MLI. But for five-level, the harmonic contained is higher than PSO method with the same level. For GA, the unequal DC source handling capability is there but not as good as compared to PSO. The result is obviously shown where PSO effectively reduces each selected harmonic.

5. Conclusion

Conventional inverter and SPWM switching method need high switching frequency. OHSW is introduced to overcome the problem. Besides that, SHE is also introduced to reduce low harmonic component. The result shows success in reducing the switching frequency with aid of GA and PSO as the nonlinear optimizer for switching angle. For seven-level CHB-MLI with OHSW by GA, 8.9% of THD, which is 0.37%, is lower compared to SPWM modulation method. The benefits for the low switching frequency are the increase of life span of the switching device and reduced power loss which is due to high switching frequency. The output waveform shows OHSW method switch on and off per cycle, which is far more less than the SPWM method. For comparison in three-level CHB-MLI (equal DC) total harmonic distortion, GA has a better output with 18.2% which is 0.14% lower than PSO. However, PSO shows more adaption for five-level CHB-MLI (equal DC) with 12.17%, which is 1.35% lower than GA. In seven-level CHB-MLI (equal DC) output voltage THD, GA is 8.9% which is 0.5% higher than PSO. However, unbalance voltage sources and GA-based CHB-MLI have better result for three-level and five-level. However, seven-level CHB-MLI showed that PSO has a better output with 6.8% of THD which is 1.88% lower than GA. However, the main intention of applying the bioinspired algorithm is to simplify the calculation of SHE in obtaining the most optimum result. The results in terms of selected low harmonic component elimination and GA is more efficient than PSO according to the result obtained where GA reduces all selected harmonics to below 0.4%, while PSO reduces to below 2.5%.

6. Future works

In this research, only single-phase CHB-MLI undergoes the optimization using OHSW. Hence, implementation of OHSW in three-phase multilevel inverter topology can be done for further detailed analysis. Three-phase system has additional switches and configuration which will be challenged on calculation complexity on the calculation of switching timing.

Besides that, implementation of different bioinspired algorithms in comparison mode will be a worthy research. The latest intelligent algorithm such as bat algorithm and bacterial foraging optimization can be applied for the switching timing calculation. As concluded from the research found, different algorithms can lead to different result accuracies. The latest intelligent algorithm is not yet being widely exposed in power electronic fields.

Furthermore, actual experimental work can be done in the future where the real work environment data can be obtained. This method is proposed to be suitably applied in the renewable energy harvest application where unstable sources frequently occur.

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