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New modified CHB multilevel inverter topology with elimination of lower and higher order harmonics

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ABSTRACT

The main objective of this study is the improvement of output voltage waveform quality generated by a new modified Cascaded H-bridge (CHB) multilevel inverter using Selective Harmonic Elimination (SHE) method and passive LC filters. A PWM technique with SHE is used to control fundamental harmonic and eliminate harmonics of chosen lower-order in CHB multilevel inverter. A passive LC filter is added to the inverter in order to eliminate the high-order harmonics. The switching angles are drawn by solving a non-linear equations system using Hybrid Genetic Algorithm (HGA). In order to evaluate the performance of the HGA in solving the non-linear equations of the system presented in this study, the proposed optimization algorithm was compared to the well-known particle swarm optimization method. Different cases including 5- and 7-level inverters with different values of modulation indices are reported. The simulation findings are validated through experimental results.

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KEYWORDS
New modified CHB multilevel inverter; selective harmonic elimination; hybrid genetic algorithm; particle swarm optimization; passive LC filter

1. Introduction

Multilevel inverters are a type of power converters that can generate a desired AC output voltage, synthesized from multiple DC sources. This configuration can be achieved by connecting several individual converters in series. By increasing the number of converters and DC sources, the AC output voltage becomes more similar to a sinusoidal waveform. There are three main categories of multilevel inverters, Diode-clamped, flying capacitor and cascade H-bridge inverters [1]. The cascade H-bridge multilevel inverters are easy to control, and they have a simple modular structure, the number of voltage levels could be increased by connecting additional H-bridge modules in series without changing the inverter's structure.

The cascade multilevel inverters provide a lot of advantages such as low Total Harmonic Distortion (THD), low electromagnetic interference [2], low voltage stress on semiconductor switches and an output voltage similar to a sinusoidal waveform which make them widely used in high and medium power applications like high voltage direct current transmission systems and Flexible AC Transmission systems [3,4]. The use of unequal DC sources in cascade multilevel inverters will increase the number of output voltage levels, therefore, improving the performance of the inverter [5].

Several modulation methods were used to control multilevel inverters like Space Vector Pulse Width Modulation (SVPWM) and Sinusoidal PWM (SPWM) [6,7], a more effective and efficient modulation strategy called Selective Harmonic Elimination PWM (SHEPWM) is also used in the control of multilevel inverters, the method provides numerous advantages such as reducing low-order harmonics and the possibility of driving the semiconductor switches at low frequencies. In This work, a passive LC filter is added to the Cascaded H-bridge (CHB) multilevel inverter in order to eliminate high-order harmonics.

Genetic Algorithm (GA) is a powerful algorithm that can solve almost all optimization problems, it mimics the process of natural evolution, it is frequently used to reach a near global optimum solution [8,9]. Hybrid Genetic Algorithms (HGA) have been developed to eliminate the fine tuning problem of a local search (LS) in GA. It is a combination of LS and GA [10,11]. In this work, a HGA with LS method has been applied to determine the optimal switching angles for the proposed CHB multilevel inverter. The performance of the proposed topology is verified by the simulation and experimental results of single-phase 5- and 7-level inverters.

In order to assess the performance of the proposed optimization method and to present it in a fair context with other optimization methods, it is compared to particle swarm optimization (PSO) [12] which is very powerful optimization algorithm based and inspired by social behaviour of bird flocking or fish schooling.

The paper is organized as follows. The structure of the proposed CHB multilevel inverter is presented in

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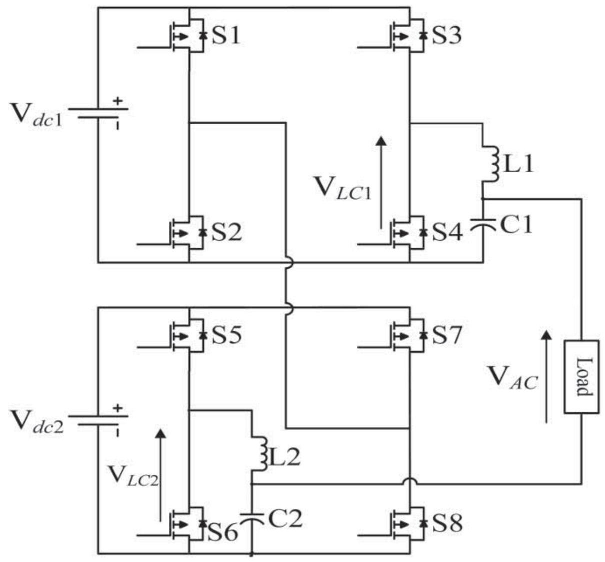

Figure 1. Proposed single-phase CHB multilevel inverter.

Section 2. In Section 3, a HGA-based SHE strategy is explained. Simulation and experimental results of the control strategy for the proposed inverter are presented in Section 4. Finally, the conclusions are summarized in Section 5.

2. Proposed CHB multilevel inverter

Cascade H-bridge multilevel inverter is one of the most important topologies in power converters due to its various advantages, the topology requires least number of semiconductor switches, gate-drives and protection circuits comparing to diode-clamped and flying capacitors type multilevel inverters. The asymmetrical configuration for multilevel inverters provides more voltage output levels for the same number of semiconductor switches than the symmetrical configuration, therefore improving the AC output voltage quality [13,14].

Figure 1 illustrates the structure of the proposed single-phase inverter, it consists of two H-bridge modules connected in series, V_{dc1} and V_{dc2} are the isolated DC voltage sources for the H-bridge modules, $V_{AC} = V_{LC1} - V_{LC2}$ is the AC output voltage obtained via a two LC filter.

In this study the inverter is operated in two configurations 5- and 7-level in order to observe the impact of adding more voltage levels on the quality of the generated AC voltage waveform, and also adding and removing the filters to observe their effect on the output voltage. The 5-level configuration can be achieved by using equal DC sources ($V_{dc1} = V_{dc2}$) , whereas the7-level is obtained by using the asymmetrical configuration by setting $V_{dc2} = 2V_{dc1}$, Table 1 present the output voltage values of different switching states for 5- and 7-level inverters.

Table 1. Output voltage level (*p.u.*) with corresponding conducting switches of 5- and 7-level inverters.

5-level inverter	7-level inverter
2 (S2,S3,S6,S7)	3 (S2,S3,S6,S7)
1 (S2,S3,S6,S8)	2 (S2,S4,S6,S7)
0 (S2,S4,S6,S8)	1 (S2,S3,S6,S8)
−1 (S1,S4,S6,S8)	0 (S2,S4,S6,S8)
−2 (S1,S4,S5,S8)	−1 (S1,S4,S6,S8)
	−2 (S2,S4,S5,S8)
	−3 (S1,S4,S5,S8)

Considering the inverter direct output fundamental, the LC filter transfer function is given by:

$$T = \frac{V_{C1}}{V_{LC1}} = \frac{1}{1 - x^2 + jxy}, \qquad (1)$$

where $x = \omega\sqrt{LC}$, $y = R\sqrt{C/L}$, ω is the fundamental angular frequency and R represents the internal inductors resistance.

The transfer function magnitude of the filter is expressed by:

$$|T| = \frac{1}{\sqrt{(1 - x^2)^2 + x^2y^2}}. \qquad (2)$$

The maximum value T_{max} of T can be expressed by:

$$\begin{cases} T_{max} = T_{\omega_{max}} = \dfrac{1/y^2}{\sqrt{1/y^2 - 0.25}} \\ \omega_{max} = \dfrac{\sqrt{2}}{RC}\sqrt{1 - 0.5y^2} \end{cases}. \qquad (3)$$

The maximum angular frequency ω_{max} exists if $y < 1.4142$. The filter transfer function will present a peak value and then decreases to zero. Consequently, the fundamental, as well as harmonics, are amplified, which leads to the undesirable situation, as illustrated in Figure 2.

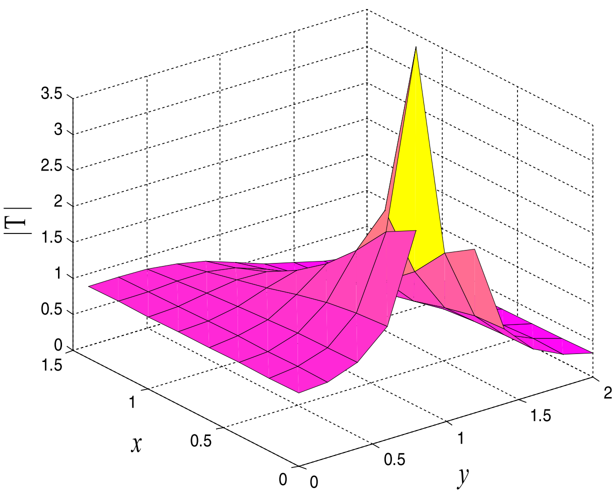

Figure 2. Transfer function of the LC filter for the fundamental.

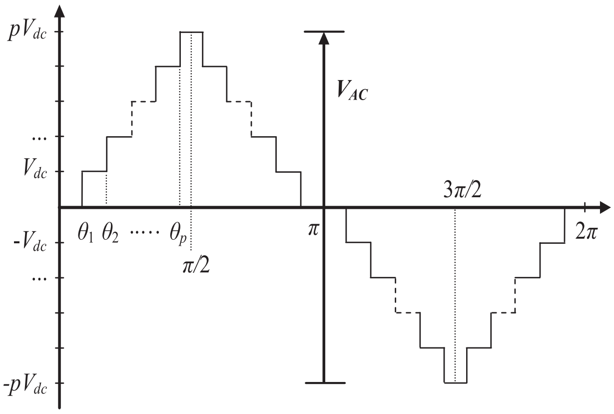

Figure 3. Generalized output voltage waveform of a CHB multilevel inverter.

3. Selective harmonic elimination with HGA

3.1. General formulation of SHE in proposed inverter

The SHE is based on the Fourier analysis of the generated voltage V_{AC} at the output of the proposed CHB multilevel inverter (Figure 3). This voltage is symmetric in a half and a quarter of a period. As a result, the even harmonic components are null. The Fourier series expansion for the V_{AC} voltage is thus:

$$V_{AC} = \sum_{n=1,3,5\ldots}^{\infty} V_n \sin(n\omega t),$$

$$\text{with} V_n = \frac{4V_{dc}}{n\pi} \sum_{i=1}^{p} \cos(n\theta_i), \tag{4}$$

where V_n is the amplitude of the harmonic term of rank n, $p = (N-1)/2$ is the number of switching angles per quarter waveform θ_i is the ith switching angle and N is the number of levels of the output voltage.

The p switching angles in (4) are calculated by fixing the amplitude of the fundamental term and by cancelling the $p-1$ other harmonic terms. These switching angles can be determined by solving the following system of non-linear equations:

$$\begin{cases} \sum_{i=1}^{p} \cos(\theta_i) = \frac{p\pi}{4} r \\ \sum_{i=1}^{p} \cos(n\theta_i) = 0 \text{ for } n \in \{3, 5 \ldots 2p-1\} \end{cases}, \tag{5}$$

where $r = V_1/pV_{dc}$ is the modulation index. The solution of (5) must also satisfy the following constraint:

$$0 < \theta_1 < \theta_2 < \cdots < \theta_p < \pi/2. \tag{6}$$

An objective function is then needed for the optimization procedure, which is selected as a measure of effectiveness of eliminating selected order of harmonics while maintaining the fundamental component at a pre-specified value. Therefore, this objective function is defined as:

$$(\theta) = F(\theta_1 \ldots \theta_p) = \left(\sum_{i=1}^{p} \cos(\theta_i) - \frac{p\pi}{4} r \right)^2 + \sum_{n=3,5\ldots}^{2p-1} \sum_{i=1}^{p} \cos(n\theta_i). \tag{7}$$

The optimal switching angles are obtained by minimizing Equation (7) subject to the constraint (6), and consequently the required harmonic profile is achieved. The main challenge is the non-linearity of the transcendental set of Equation (5), as most iterative techniques suffer from convergence problems and other techniques such as elimination using resultant theory [15] and Walsh function [16] are complicated. It is, therefore, worth considering more techniques and simple techniques such as HGA.

3.2. Solution using HGA

GA can reach the region near an optimum point relatively quickly as a global search technique. HGA have been developed to eliminate the fine tuning problem of a LS in GA. It is combination of GA and one LS technique [10,11].

In this work, a HGA with LS method has been applied to determine p switching angles by using the

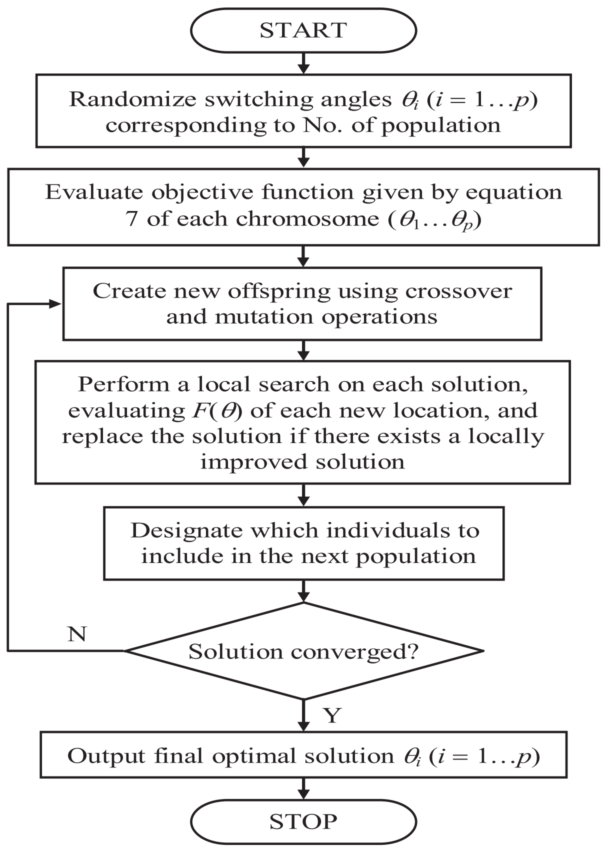

Figure 4. Flowchart of HGA for SHE.

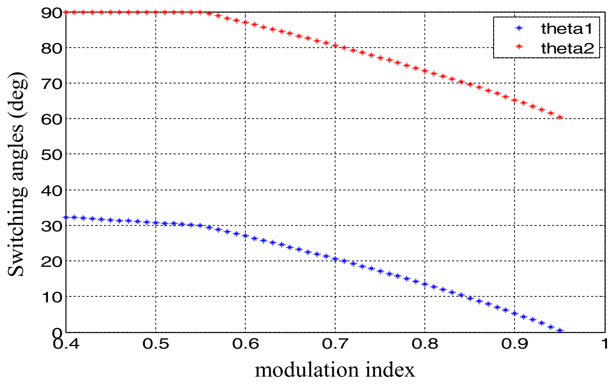

Figure 5. Optimal switching angles versus *r* for 5-level inverter.

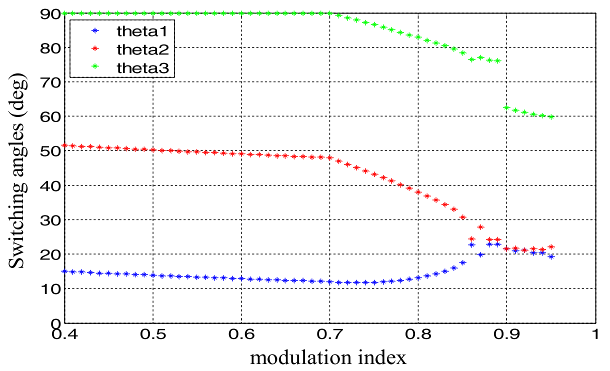

Figure 6. Optimal switching angles versus *r* for 7-level inverter.

MATLAB GA-Toolbox. This toolbox aims to find a minimum of the objective function $F(\theta)$. The value of the $F(\theta)$ is improved by using Hybrid Function which operates after the terminating of the GA. The determined final point from GA is used for Hybrid Function as an initial point. In this paper, *fmincon* which is a LS technique is preferred as hybrid function. *fmincon* is used to determine a minimum of a multivariable function with non-linear constraints. A flowchart of the HGA algorithm for SHE is shown in Figure 4.

This algorithm was used to find the switching angles (θ_1, θ_2) to eliminate the 3rd harmonic for 5-level inverter (i.e. $p = 2$), and $(\theta_1, \theta_2, \theta_3)$ to eliminate the 3rd and 5th harmonics for 7-level inverter (i.e. $p = 3$). The results for the two inverters are plotted, respectively, in Figures 5 and 6 versus r, where $0.4 \leq r \leq 0.95$ with a step of 0.01. The THD corresponding to the solutions given in Figures 5 and 6 is represented by Figure 7.

4. Simulation and experimental results

A laboratory prototype of a proposed single-phase CHB multilevel inverter was built using IRF840 (500 V, 8A) MOSFETs as the switching devices, and IR2112 as MOSFET gate drivers, 4N25 optoisolators for protection, and two laboratory variable power supplies. Atmel SAM3X8E microcontroller was used to generate control signals. SDS1000 siglent digital storage oscilloscope was used to capture voltage signals. Fast Fourier Transform (FFT) and THD calculations were performed by a computer linked to the SDS1000 digital oscilloscope via USB connection. Figure 8 shows the experimental setup used in this study.

Figures 9 and 10 show, respectively, simulated and experimental output voltages generated by the HGA-based SHE and the corresponding FFT without LC filter (unfiltered output voltage) and with LC filter (filtered output voltage) of 5-level inverter for $r = 0.86$ (i.e. $\theta_1 = 7.054°$, $\theta_2 = 67.05°$) with $V_{dc1} = V_{dc2} = 15\,\mathrm{V}$ and the filter parameters $y = 0.2$, whereas the simulated and experimental output voltages generated by the PSO for the same modulation index r (i.e. $\theta_1 = 8.745°$, $\theta_2 = 68.745°$) and the filter parameters are presented, respectively, in Figures 11 and 12.

The waveforms representing the experimental results in Figures 10 and 12 are practically identical to the results obtained by simulation in Figures 9 and 11, respectively.

The filtered output voltages generated by both methods (HGA and PSO) are perfectly sinusoidal. From the experimental results of unfiltered FFT output voltage, it is seen that the 3rd harmonic is efficiently eliminated as obtained in the simulations. All high-frequency

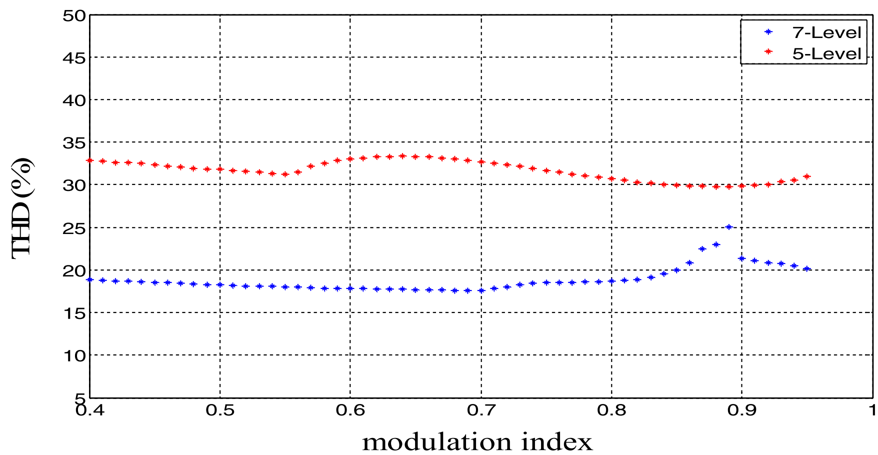

Figure 7. THD versus *r* for optimal switching angles.

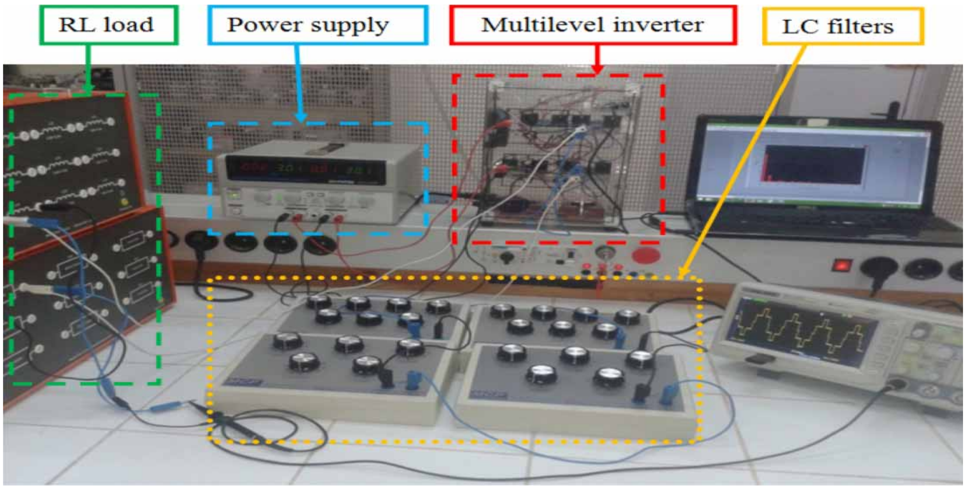

Figure 8. Experimental setup.

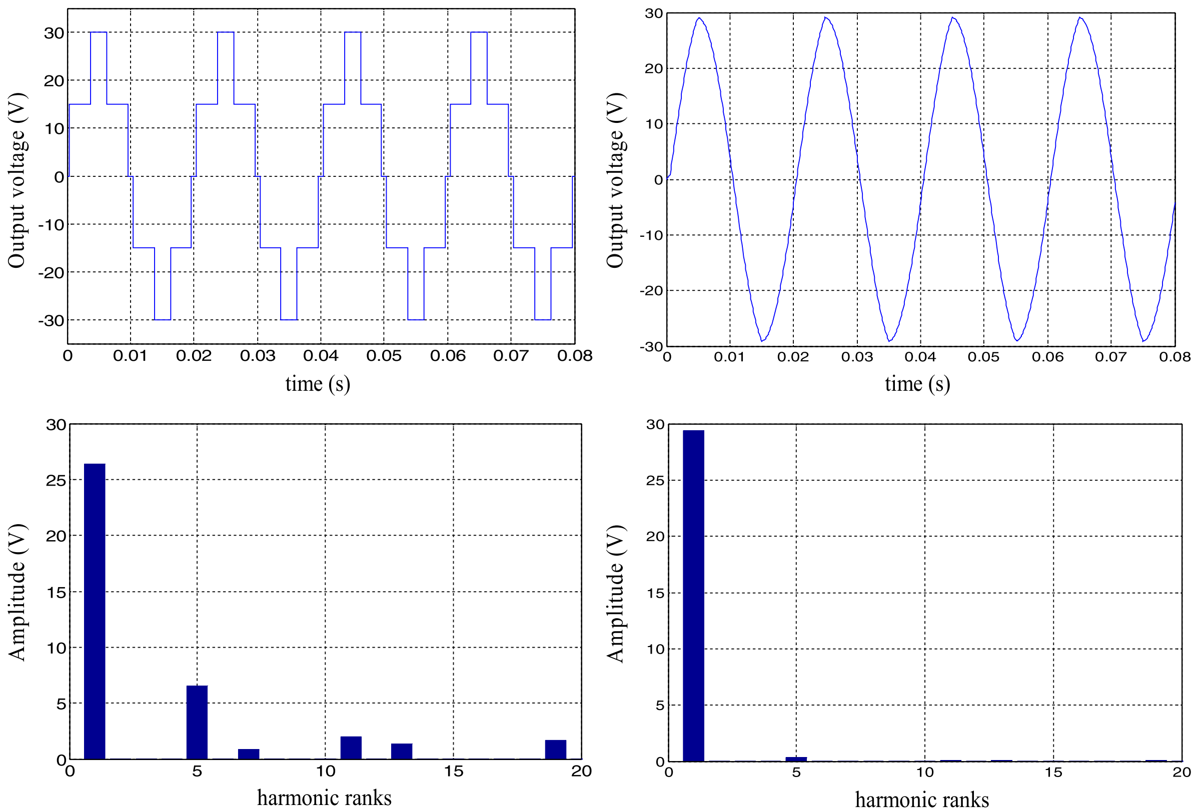

Figure 9. Simulated output voltages and the corresponding FFT of 5-level inverter without LC filter (left) and with LC filter (right) for $r = 0.86$, $V_{dc1} = V_{dc2} = 15$ V and $y = 0.2$ using HGA.

harmonics of filtered FFT output voltage are cancelled which proves the efficiency of the proposed inverter.

The same remark is for Figures 13 and 14 showing, respectively, simulated and experimental unfiltered output voltage and filtered output voltage generated by the HGA of 7-level inverter for $r = 0.8$ (i.e. $\theta_1 = 18.27°$, $\theta_2 = 29.65°$, $\theta_3 = 77.85°$) with $V_{dc2} = 2V_{dc1} = 20$ V and the filter parameters $y = 0.25$ and also for the results presented in Figures 15 and 16, the two figures show, respectively, simulated and experimental results of the unfiltered and filtered output voltages generated by the PSO for the same modulation index r (i.e. $\theta_1 = 13.22°$, $\theta_2 = 38.00°$, $\theta_3 = 82.90°$) and filter parameters.

From the results of 7-level unfiltered FFT output voltage, it is clear that the low-order harmonics 3rd and 5th are totally eliminated, and all high-order harmonics are eliminated of filtered FFT output voltage.

Table 2 presents the THD during experimental testing, and it is found that there is a significant improvement of the THD using the passive filter, and also by increasing the number of voltage levels. It can also be seen from the presented results that the proposed optimization method (HGA) performed better than the

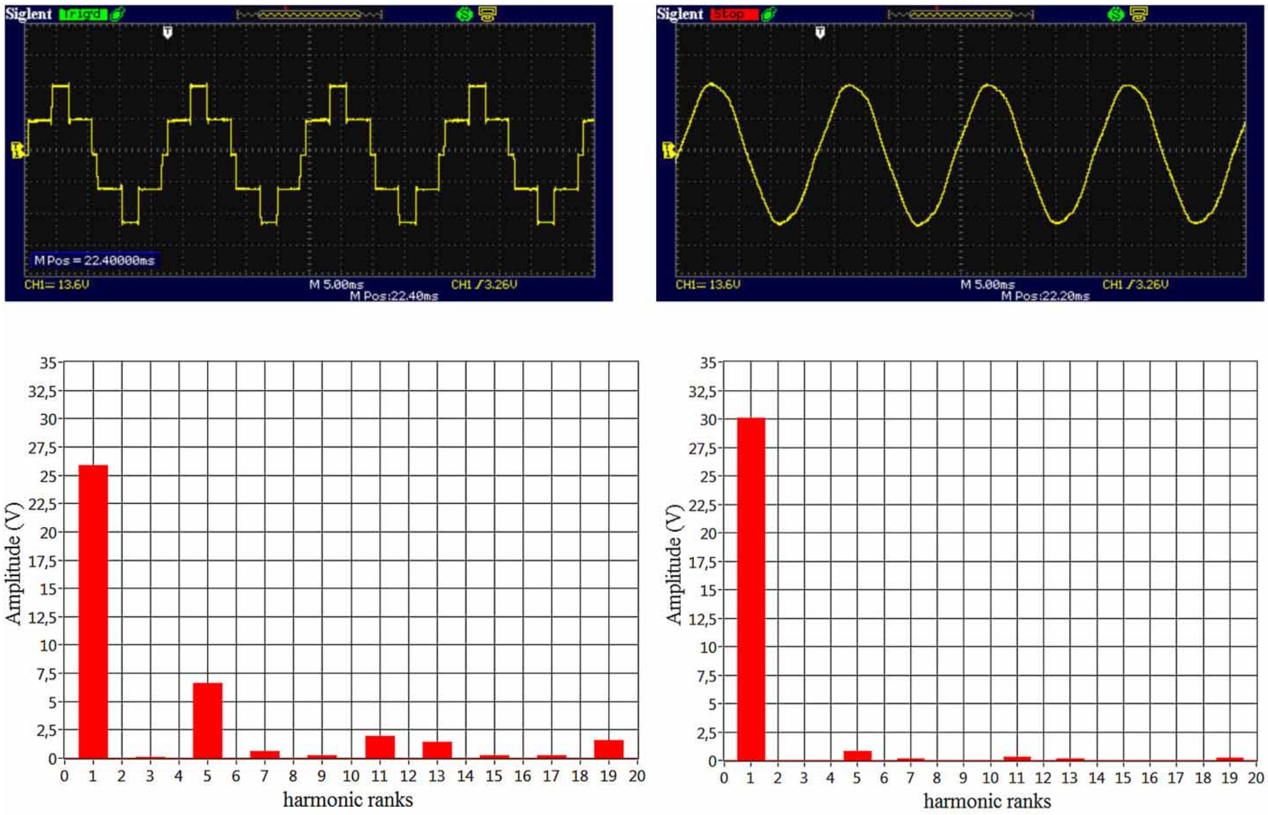

Figure 10. Experimental output voltages and the corresponding FFT of 5-level inverter without LC filter (left) and with LC filter (right) for $r = 0.86$, $V_{dc1} = V_{dc2} = 15$ V and $y = 0.2$ using HGA.

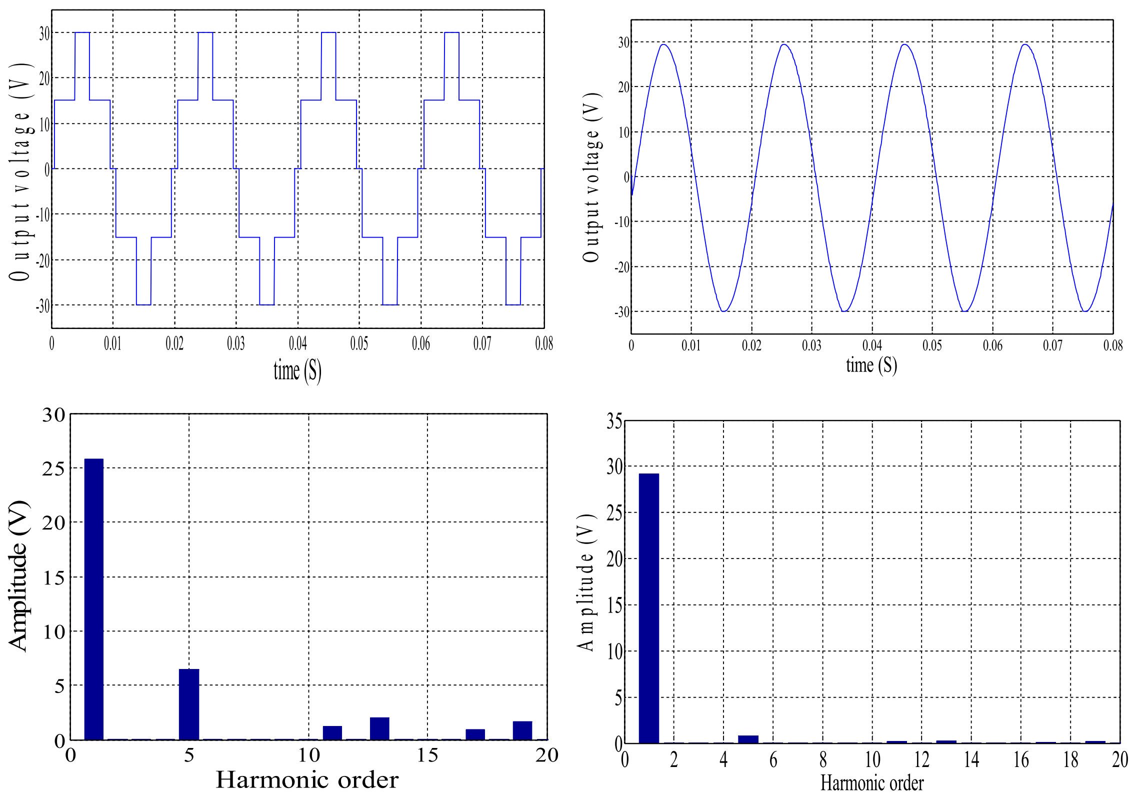

Figure 11. Simulated output voltages and the corresponding FFT of 5-level inverter without LC filter (left) and with LC filter (right) for $r = 0.86$, $V_{dc1} = V_{dc2} = 15$ V and $y = 0.2$ using PSO.

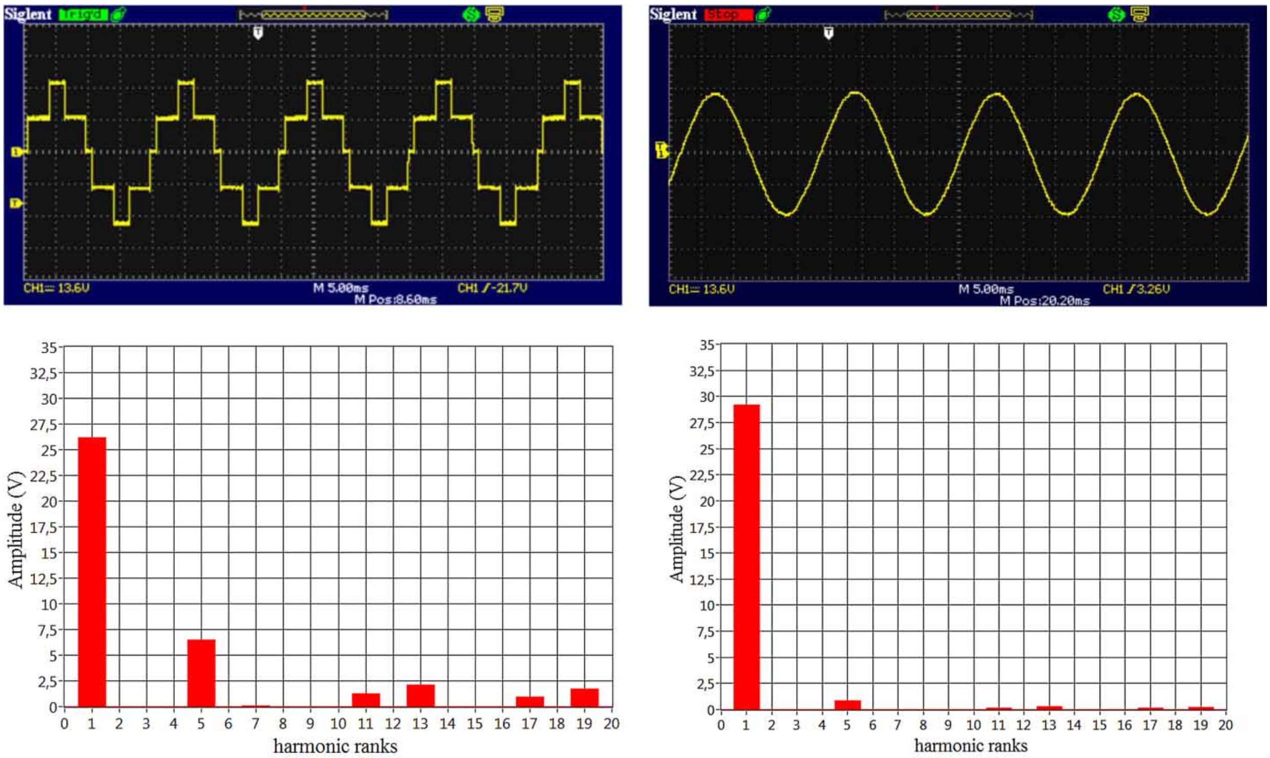

Figure 12. Experimental output voltages and the corresponding FFT of 5-level inverter without LC filter (left) and with LC filter (right) for $r = 0.86$, $V_{dc1} = V_{dc2} = 15$ V and $y = 0.2$ using PSO.

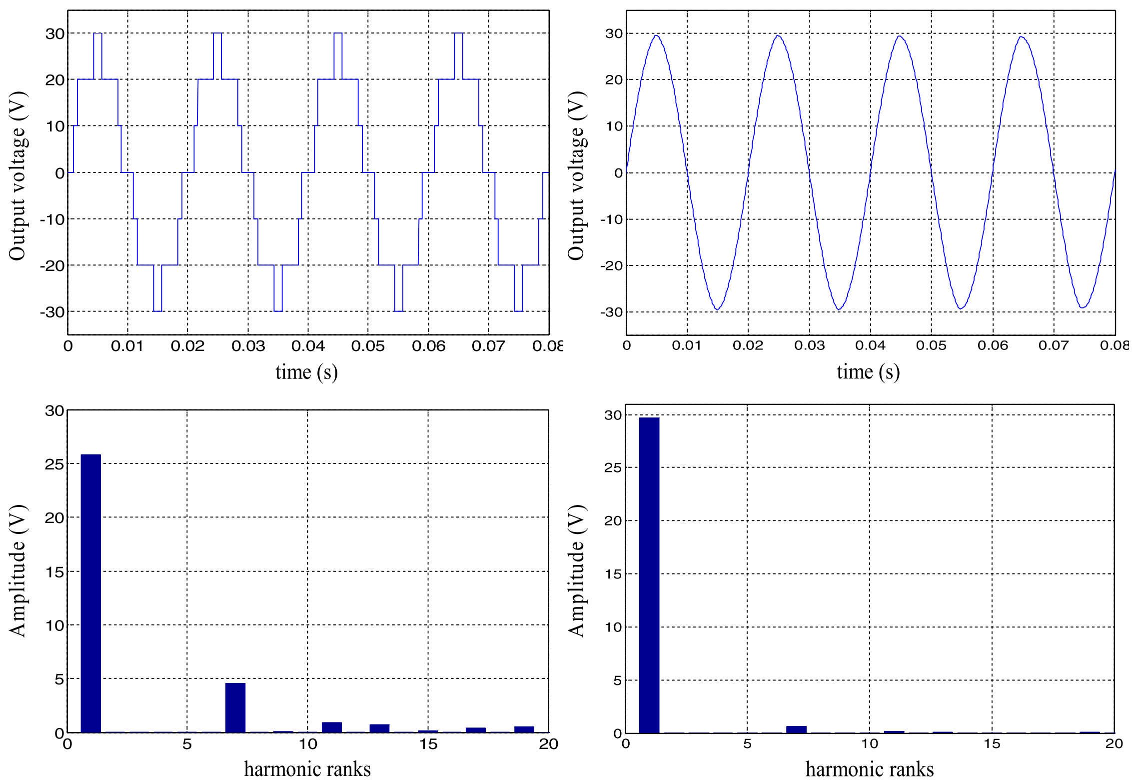

Figure 13. Simulated output voltages and the corresponding FFT of 7-level inverter without LC filter (left) and with LC filter (right) for $r = 0.8$, $V_{dc2} = 2V_{dc1} = 20$ V and $y = 0.25$ using HGA.

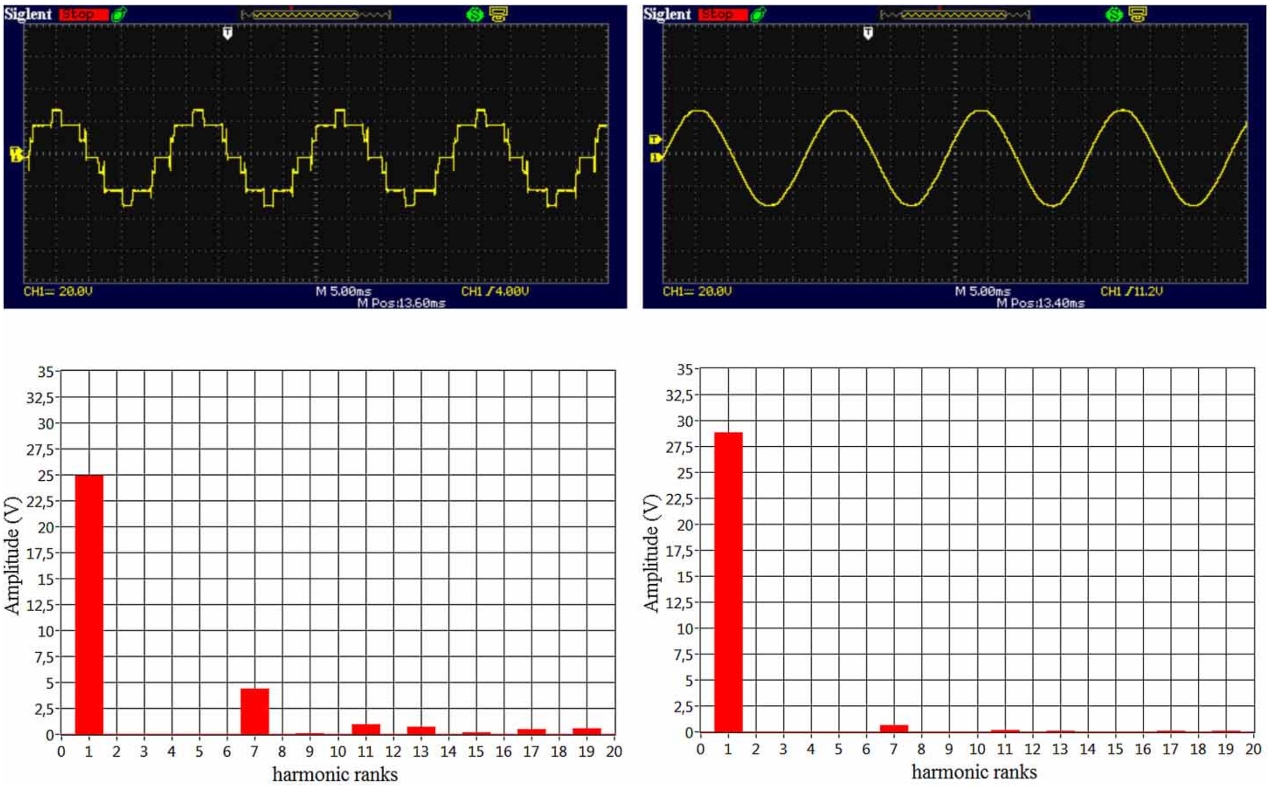

Figure 14. Experimental output voltages and the corresponding FFT of 7-level inverter without LC filter (left) and with LC filter (right) for $r = 0.8$, $V_{dc2} = 2V_{dc1} = 20$ V and $y = 0.25$ using HGA.

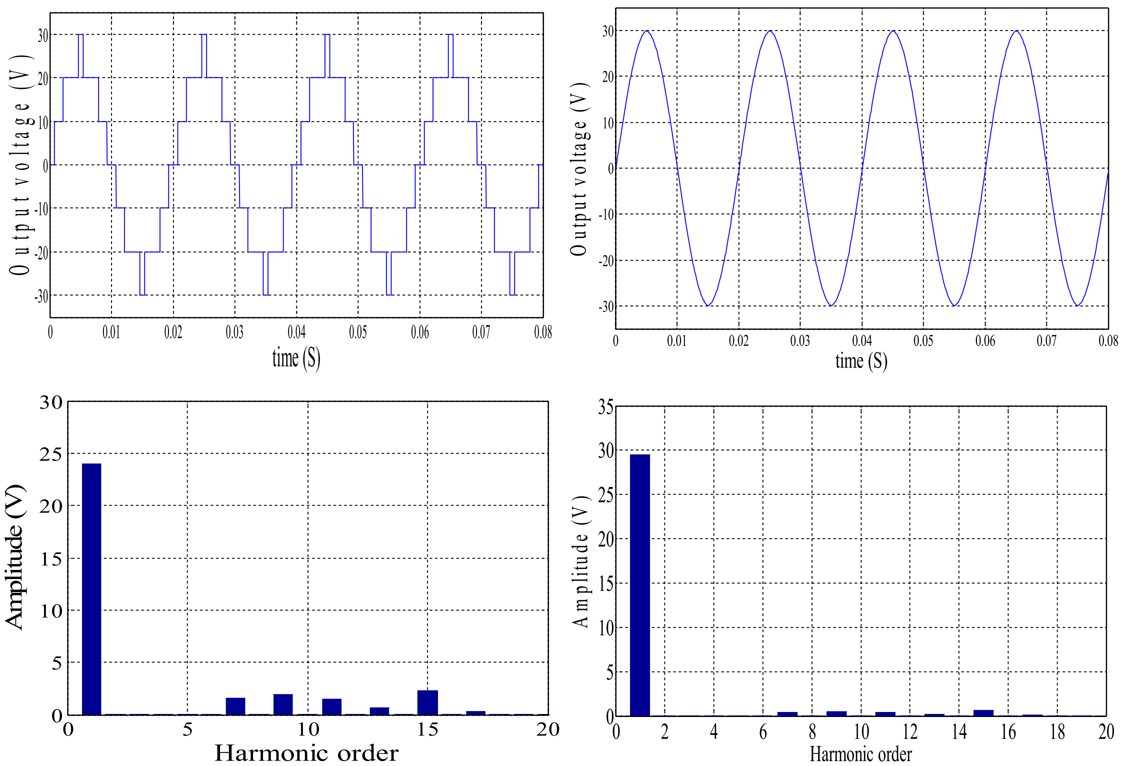

Figure 15. Simulated output voltages and the corresponding FFT of 7-level inverter without LC filter (left) and with LC filter (right) for $r = 0.8$, $V_{dc2} = 2V_{dc1} = 20$ V and $y = 0.25$ using PSO.

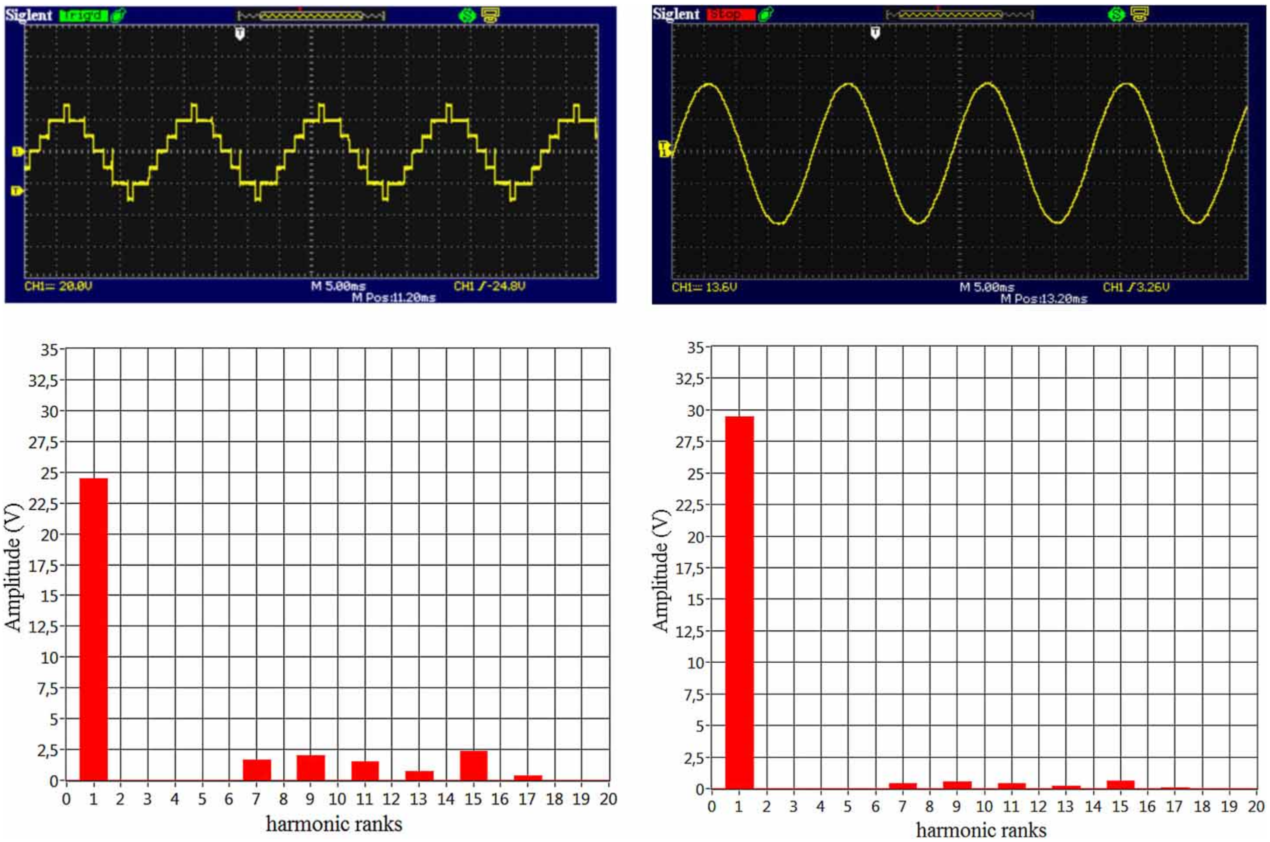

Figure 16. Experimental output voltages and the corresponding FFT of 7-level inverter without LC filter (left) and with LC filter (right) for $r = 0.8$, $V_{dc2} = 2V_{dc1} = 20$ V and $y = 0.25$ using PSO.

Table 2. Experimental measurement of THD.

	Unfiltered output voltage		Filtered output voltage	
	HGA	PSO	HGA	PSO
5-level	27.42%	29.83%	2.9%	3.41%
7-level	18.26%	18.68%	1.33%	1.54%

PSO algorithm generating output voltage waveforms with less THD.

5. Conclusion

In this paper, a single-phase CHB multilevel inverter is developed by combining SHE and a passive LC filter to eliminate the output voltage harmonics. The overall system model requires solving a set of non-linear transcendental equations for the optimal switching angles calculation. The proposed CHB multilevel inverter architecture and the harmonic elimination control strategy based on HGA make the system very efficient. The reduced switching frequency of the semiconductor switches provides more reliability and increases system components life time. The use of the LC passive filler cancelled significantly the higher order harmonics in the output voltage waveform. The obtained results from experimental tests show a good agreement with the results obtained in simulation. In order to evaluate the performance of the proposed optimization method (HGA) a comparison was carried out with PSO method, obtained the results show the superiority of the HGA over PSO with the HGA generating output voltage waveforms with less THD.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

[1] Alishah RS, Nazarpour D, Hosseini SH, et al. Novel topologies for symmetric, asymmetric, and cascade switched-diode multilevel converter With minimum number of power electronic components. IEEE Trans Ind Electron. 2014;61(10):5300–5310. doi:10.1109/TIE.2013.2297300

[2] Gnana Sundari M, Rajaram M, Balaraman S. Application of improved firefly algorithm for programmed PWM in multilevel inverter with adjustable DC sources. Appl Soft Comput. 2016;41(Supplement C):169–179. doi:10.1016/j.asoc.2015.12.036

[3] Dahidah MSA, Konstantinou G, Agelidis VG. A review of multilevel selective harmonic elimination PWM: formulations, solving algorithms, implementation and applications. IEEE Trans Power Electron. 2015;30(8):4091–4106. doi:10.1109/TPEL.2014.2355226

[4] Sotoodeh P, Miller RD. A new multi-level inverter with FACTS capabilities for wind applications. 2013 IEEE Green Technologies Conference (GreenTech); 2013.

[5] Babaei E, Sheermohammadzadeh S, Sabahi M. Improvement of multilevel inverters topology using series and parallel connections of DC voltage sources. Arab J Sci

Eng. 2014;39(2):1117–1127. doi:10.1007/s13369-013-0696-9

[6] Trabelsi M, Ben-Brahim L, Yokoyama T, et al. An improved SVPWM method for multilevel inverters. 2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC); 2012.

[7] Haris M, Pathak MK, Agarwal P. Comparison of SPWM multilevel inverter fed PMSM drive with two level inverter fed drive. International Conference on Recent Advances and Innovations in Engineering (ICRAIE-2014); 2014.

[8] Deniz E, Aydogmus O, Aydogmus Z. GA-based optimization and ANN-based SHEPWM generation for two-level inverter. 2015 IEEE International Conference on Industrial Technology (ICIT); 2015.

[9] Kampouropoulos K, Andrade F, Garcia A, et al. A combined methodology of adaptive neuro-fuzzy inference system and genetic algorithm for short-term energy forecasting. Adv Electr Comput Eng. 2014;14(1):9–14.

[10] Dahidah MSA, Agelidis VG, Rao MV. Hybrid genetic algorithm approach for selective harmonic control. Energy Convers Manage. 2008;49(2):131–142. doi:10.1016/j.enconman.2007.06.031

[11] Deniz E, Aydogmus O, Aydogmus Z. Implementation of ANN-based selective harmonic elimination PWM using hybrid genetic algorithm-based optimization. Measurement (Mahwah NJ). 2016;85:32–42. doi:10.1016/j.measurement.2016.02.012

[12] Al-Othman AK, Abdelhamid TH. Elimination of harmonics in multilevel inverters with non-equal dc sources using PSO. Energy Convers Manage. 2009;50(3):756–764. doi:10.1016/j.enconman.2008.09.047

[13] Taleb R, Benyoucef D, Helaimi M, et al. Cascaded H-bridge asymmetrical seven-level inverter using THIPWM for high power induction motor. Energy Procedia. 2015;74:844–853. doi:10.1016/j.egypro.2015.07.820

[14] Taleb R, Meroufel A, Massoum A. Control of a uniform step asymmetrical 13-level inverter using particle swarm optimization. Autom — J Control Meas Electron Comput Commun. 2014;55(1). doi:10.7305/automatika.2014.01.117

[15] Taleb R, Derrouazin A. USAMI control with a higher order harmonics elimination strategy based on the resultant theory. Energy Procedia. 2014;50(Supplement C):1045–1055. doi:10.1016/j.egypro.2014.06.124

[16] Tsorng-Juu L, Connell RMO, Hoft RG. Inverter harmonic reduction using Walsh function harmonic elimination method. IEEE Trans Power Electron. 1997;12(6):971–982. doi:10.1109/63.641495