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OUTPUT VOLTAGE WAVEFORM IMPROVEMENT OF MODIFIED CASCADED H-BRIDGE MULTILEVEL INVERTER USING SELECTIVE HARMONIC ELIMINATION TECHNIQUE BASED ON HYBRID GENETIC ALGORITHM

FAYÇAL CHABNI, RACHID TALEB, M'HAMED HELAIMI

Key words: Modified cascaded H-bridge (CHB) multilevel inverter, Selective harmonic elimination (SHE), Hybrid genetic algorithm, LC filter.

The main objective of this work is to improve the quality of voltage waveform generated by a modified cascaded H-bridge (CHB) multilevel inverter topology using selective harmonic elimination (SHE) control strategy and also using LC filters. This study presents a new topology of multilevel inverters that combines the conventional architecture of a cascade H-bridge inverter and LC filters. The SHE method is used to eliminate harmonics of chosen lower-order while controlling the amplitude of fundamental harmonic in CHB multilevel inverter. LC filters are added to the inverter in order to eliminate the high-order harmonics. Optimal switching angles are obtained by solving a non-linear equations system using hybrid genetic algorithm (HGA). 5 and 7 level configurations for the new topology are presented in this work. The obtained simulation results are validated through experimental results.

1. INTRODUCTION

Multilevel dc to ac power converter configuration can be achieved by connecting several individual converters in series. By increasing the number of converters and dc sources, the ac output voltage become 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 electrical transmission systems. Several modulation methods were used to control multilevel inverters such as space vector and sinusoidal pulse width modulation (PWM) [3–5], 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 [6, 7]. In this work, a passive LC filter is added to the CHB multilevel inverter in order to eliminate high-order harmonics.

Genetic algorithm (GA) is a very powerful algorithm that can solve almost all optimization problems, it mimics the process of natural evolution, and it is frequently used to obtain optimal solutions [8–10]. The hybrid genetic optimization algorithm has been developed to solve the fine-tuning problem of a local search in GA. It is combination of local search and GA [11–13]. In this work, a HGA with local search method has been applied to determine the optimal switching angles for the proposed CHB multilevel inverter. Computer simulations using MATLAB software and experiments using a small scale laboratory were carried out to evaluate the results obtained by the proposed converter for 5 and 7 level configurations.

This paper is organized as follows: The structure of the proposed CHB multilevel inverter is presented in Section 2. In Section 3, a HGA based SHE strategy is explained. The results obtained from simulations and experiments of the control strategy are presented in Section 4. The conclusion is presented in Section 5.

2. PROPOSED CHB MULTILEVEL INVERTER

Cascade H-bridge multilevel topology requires least number of semiconductor switches, gate-drives and protection circuits comparing to other types and configurations of multilevel power converters. 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 voltage waveform quality [14, 15].

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.

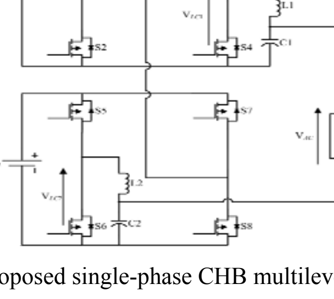

Fig. 1 – Proposed single-phase CHB multilevel inverter.

Hassiba Benbouali University, Faculty of Technology, Department of Electrical Engineering, Laboratoire Génie Electrique et Energies Renouvelables (LGEER), Chlef, Algeria, E-mail: chabni.fay@gmail.com, rac.taleb@gmail.com, halimi1976@yahoo.fr

In this study the inverter is operated in two configurations 5 level and 7 level in order to observe the impact of adding more voltage levels on the quality of the output ac 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 the 7 level is obtained by using the asymmetrical configuration by setting $V_{dc2} = 2V_{dc1}$, Table 1 present the output voltage values (per unit) 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 transfer function of LC filter can be expressed as follows:

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

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:

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

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

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

The maximum angular frequency ω_{max} exists if $y < 1.4142$. The filter transfer function will present a maximum value and then decreases to zero. Consequently, the fundamental and harmonic components are amplified, which leads to the undesirable effects, as it is shown in Fig. 2.

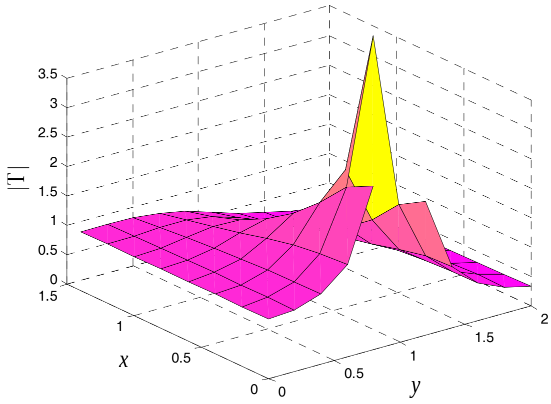

Fig. 2 – Transfer function of the LC filter for the fundamental.

3. SELECTIVE HARMONIC ELIMINATION WITH HGA

3.1. GENERAL FORMULATION OF SHE IN PROPOSED INVERTER

The SHEPWM is based on the Fourier analysis of the voltage waveform presented in Fig. 3. Since the voltage waveform generated by the power converter is symmetric in a half and a quarter of a period, the even harmonics are equal to zero. The Fourier 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 firing angles per quarter waveform, N is the number of generated voltage levels and θ_i is the switching angle of rank i.

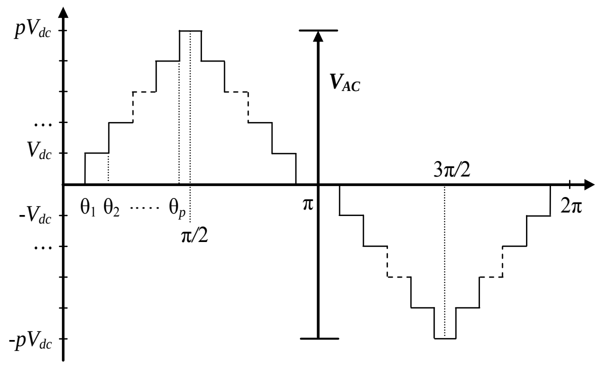

Fig. 3 – Generalized output voltage waveform of a CHB multilevel inverter.

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

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

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

$$0 < \theta_1 < \theta_2 < \dots < \theta_p < \pi/2. \qquad (6)$$

An objective function is then needed for the optimization procedure; the function must be formulated in such way that allows the elimination of targeted harmonics while maintaining the fundamental component at desired amplitude. The objective function is defined as follows:

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

The optimal switching angles are obtained by minimizing the objective function presented in (7) while respecting the constraint presented in (6). The biggest problem is the non-linearity of the equations presented in (5); multiple computational techniques were used to solve SHE problems such as Newton-Raphson method [16, 17] and or the resultant theory [18–20], these methods are either complicated or require an initial guess of the optimal solutions, which can be very difficult especially for a large number of switching angles. It is, therefore, worth considering more techniques and simple techniques such as hybrid genetic algorithms (HGA).

3.2. SOLUTION USING HYBRID GENETIC ALGORITHMS

The hybrid genetic optimization algorithm has been developed to solve the fine-tuning problem of a local search in GA. The HGA is mixture of genetic optimization algorithm and a local search (LS) method [11–13]. In this work, a hybrid genetic algorithms with local search method has been applied to determine the optimal switching angles by using the MATLAB optimization toolbox. The value of the presented objective function is minimized 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 study, *fmincon* which is a local search method is preferred as hybrid function; *fmincon* is used to find a minimum value of the proposed cost function. A flowchart of the HGA algorithm for SHE is shown in Fig. 4.

This algorithm was used to find the optimal firing angles (θ_1, θ_2) to eliminate the 3[rd] harmonic for 5 level inverter (*i.e.* p = 2), and (θ_1, θ_2, θ_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 Figs. 5 and 6 versus r, where $0.4 \le r \le 0.95$ with a step of 0.01. The THD corresponding to the solutions given in Figs. 5 and 6 is represented by Fig. 7.

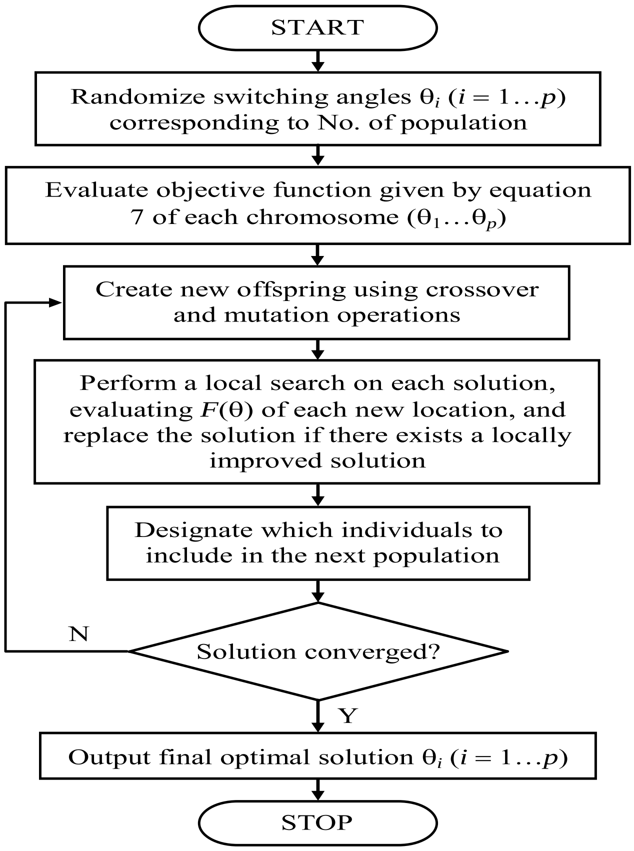

Fig. 4 – Flowchart of HGA for SHE.

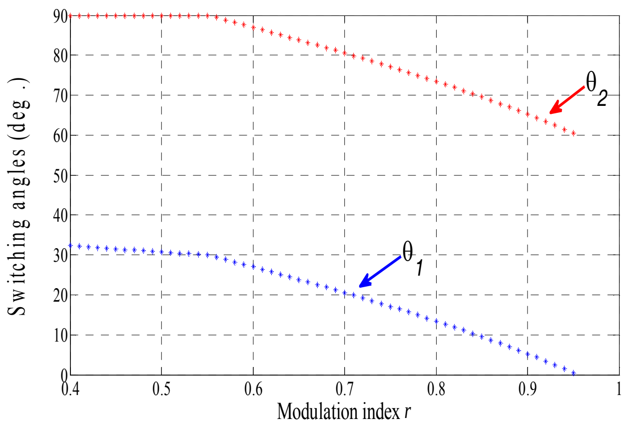

Fig. 5 – Optimal switching angles versus r for 5-level inverter.

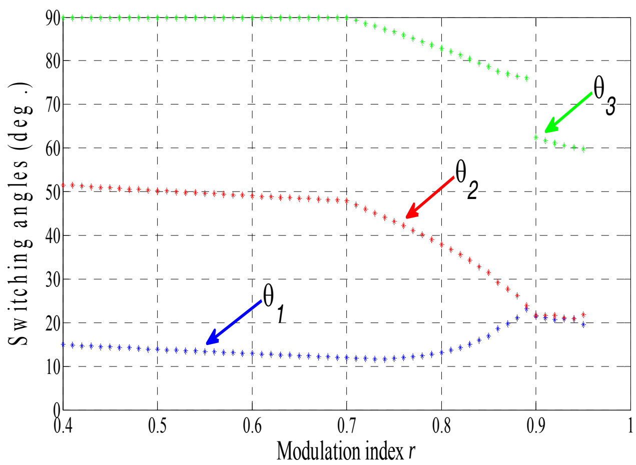

Fig. 6 – Optimal switching angles versus r for 7 level inverter.

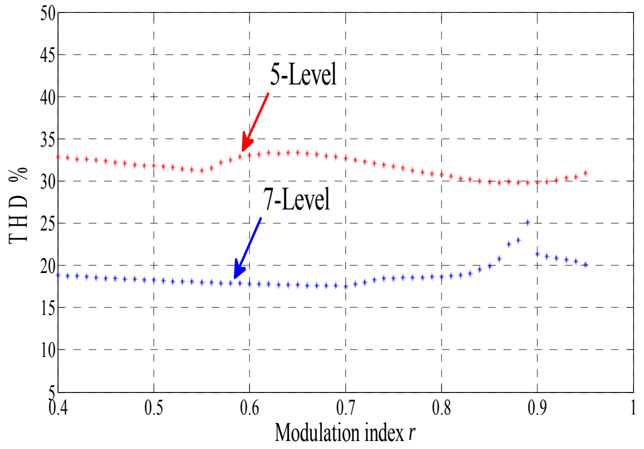

Fig. 7 – THD *versus* r for optimal switching angles.

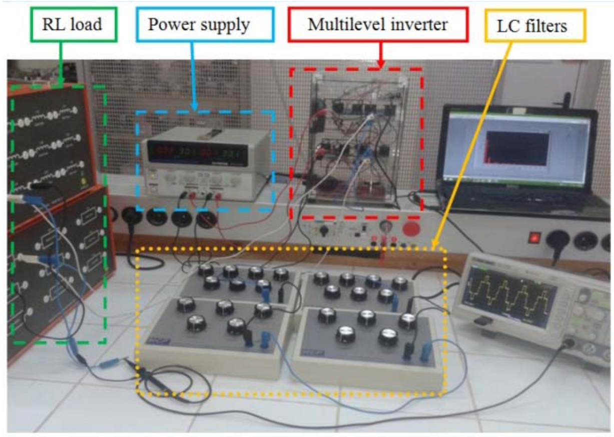

Fig. 8 – Experimental setup.

4. SIMULATION AND EXPERIMENTAL RESULTS

A laboratory prototype of the proposed single-phase CHB multilevel inverter was built using IRF840 (500 V, 8 A) MOSFETs as the switching devices, and IR2112 as MOSFET gate drivers, 4N25 optoisolators for protection, and two laboratory variable dc 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 computer linked to the SDS1000 digital oscilloscope via USB connection. Figure 8 illustrates the laboratory prototype of the proposed multilevel converter built for this study.

Figures 9 and 10 show respectively simulated and experimental output voltages inverter 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.* $\theta_1 = 7.054\ ^{o}$, $\theta_2 = 67.05\ ^{o}$) with $V_{dc1} = V_{dc2} = 15$ V and the filter parameters $y = 0.2$.

The waveform representing the experimental results in Fig. 10 is practically identical to the one obtained by simulation in Fig. 9. The filtered voltage waveform is very close to a sinusoidal form. From the experimental results of unfiltered FFT output voltage, it is seen that the 3rd harmonic is efficiently eliminated as obtained in the simulation. All high frequency harmonics of filtered FFT output voltage are cancelled which proves the efficiency of the proposed inverter.

The same remark is for Figs. 11 and 12 showing respectively simulated and experimental unfiltered output voltage and filtered output voltage of 7-level inverter for $r = 0.8$ (i.e. $\theta_1 = 18.27\ ^{o}$, $\theta_2 = 29.65\ ^{o}$, $\theta_3 = 77.85\ ^{o}$) with $V_{dc2} = 2V_{dc1} = 20$ V and the filter parameters $y = 0.25$.

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 when increasing the number of voltage levels and using an LC filter.

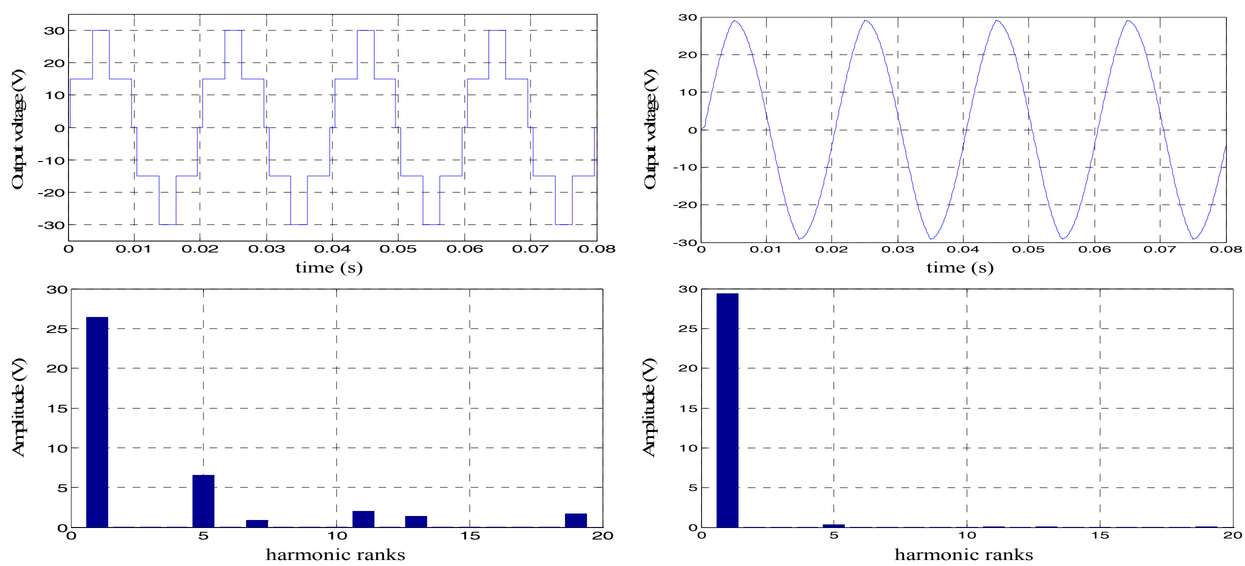

Fig. 9 – Simulated output voltages and the corresponding FFT of 5 level inverter without LC filter (left) and with LC filter (right) for $r = 0.86$, $V_{dc1} = V_{dc2} = 15$ V and $y = 0.2$.

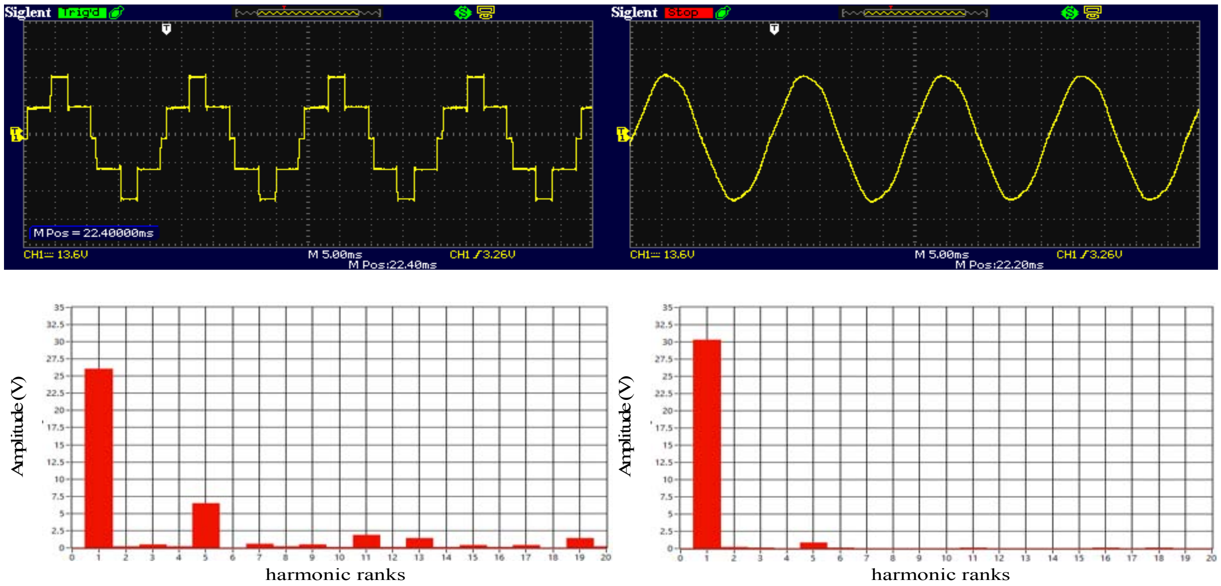

Fig. 10 – Experimental output voltages and the corresponding FFT of 5 level inverter without LC filter (left) and with LC filter (right) for $r = 0.86$, $V_{dc1} = V_{dc2} = 15$ V and $y = 0.2$.

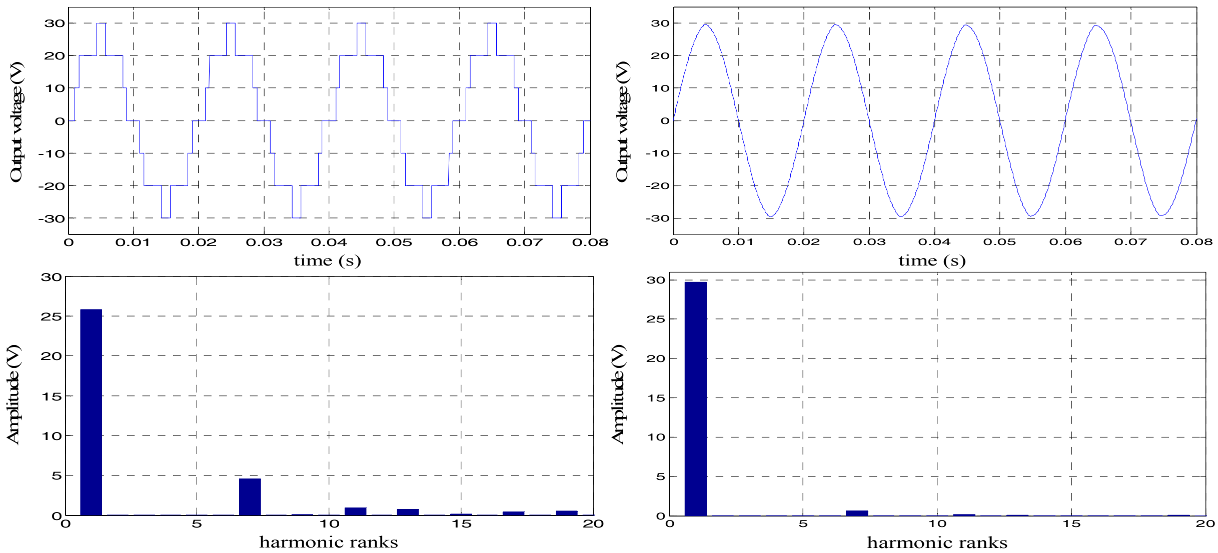

Fig. 11 – Simulated output voltages and the corresponding FFT of 7 level inverter without LC filter (left) and with LC filter (right) for $r = 0.8$, $V_{dc2} = 2V_{dc1} = 20$ V and $y = 0.25$.

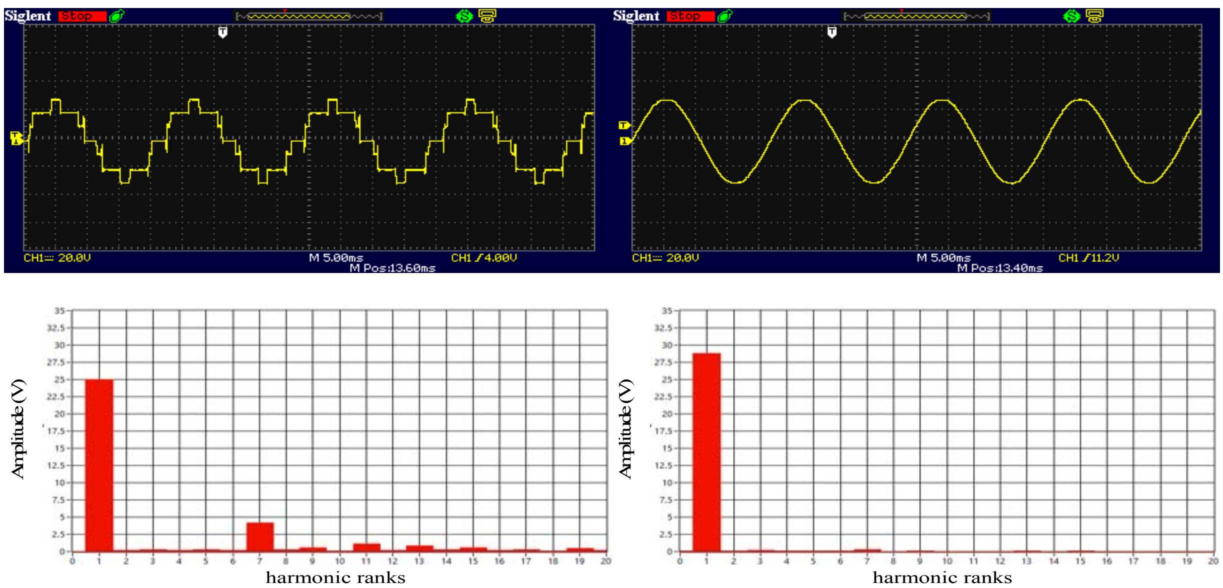

Fig. 12 – Experimental output voltages and the corresponding FFT of 7 level inverter without LC filter (left) and with LC filter (right) for $r = 0.8$, $V_{dc2} = 2V_{dc1} = 20$ V and $y = 0.25$.

Table 2

Experimental measurement of THD

	Unfiltered output voltage	Filtered output voltage
5 level	27.42 %	2.9 %
7 level	18.26 %	1.33 %

5. CONCLUSIONS

In this paper, a single-phase CHB multilevel inverter is developed by combining selective harmonic elimination and a passive LC filter to eliminate the output voltage harmonics. The overall system model requires solving a set of nonlinear equations for the optimal switching angles calculation. The proposed CHB multilevel inverter architecture and the harmonic elimination control strategy based on hybrid genetic algorithms make the system very efficient. The low switching frequency provided by the SHE control method will increase the reliability of the system and components life time. The use of the LC passive filler canceled significantly the higher order harmonics in the output voltage waveform. Results and waveforms obtained from experimental tests match perfectly the simulation results.

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