Harmonic Elimination in Uniform Step Nine-Level Inverter Using Differential Evolution: Experimental Validation

Rim Feyrouz Abdelgoui, Rachid Taleb, Abderrahim Bentaallah, and Fayçal Chabni

***Abstract*—This study presents the application of differential evolution algorithm to compute optimal switching angles for a single-phase nine-level inverter to improve the output voltage quality. The topology of the proposed inverter in this article is a simple cascade converter composed of two H-bridge cells with non-equal DC voltage sources in order to generate multiple voltage levels. Selective harmonic elimination pulse width modulation strategy is used to improve the generated AC output voltage waveform. The differential evolution optimization algorithm is used to solve non-linear transcendental equations necessary for the (SHPWM). Computational results obtained from computer simulations presented a good agreement with the theoretical predictions. A laboratory prototype based on STM32F407 microcontroller was built in order to validate the simulation results. The experimental results show the effectiveness of the proposed modulation method.**

***Index Terms*—Multi-level inverters; selective harmonic elimination; differential evolution; optimization; STM32F407 microcontroller.**

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I. Introduction

The cascade multilevel power inverters have received a lot of attention because of their simple and modular structure; these converters can offer a lot of advantages such as low switching losses [1]-[3] and better electromagnetic compatibility [4]-[5], low voltage stress on the switching devices [6]. The architecture can be formed by simply connecting multiple H-bridge cells in series, by adding more cells, the output voltage waveform become close to a sinusoidal waveform. Several modulation strategies such as Sinusoidal Pulse width modulation (SPWM) [7] and space vector pulse width modulation (SVPWM) [8] have been proposed for the control of multilevel inverters. A more efficient method called selective harmonic elimination pulse width modulation (SHEPWM) is also used; the method offers a lot of advantages such as operating the inverters switching devices at a low frequency which extends the lifetime of the switching devices. The main disadvantage of this method is that a set of non-linear equations must be solved to obtain the optimal switching angles to apply this strategy.

Multiple computational methods have been used to solve the optimal switching problem for multilevel inverters, and Newton-Raphson (N-R) algorithm [9] is one of the most used methods for solving SHEPWM equations, this method dependents on initial guess of the angle values in such a way that they are sufficiently close to the global minimum(desired solution). If the angles are unsuitable, non-convergence can result. Another method to compute the optimal switching angles is by using optimization algorithms such as genetic algorithm (GA) [10]-[11], particle swarm operation (PSO) [12]-[14] and bee algorithm (BA) [15]. The main advantage of these methods is that they are free from the requirement of good initial guess.

Differential evolution (DE) is one of the most powerful optimization methods. The algorithm has been drawing a lot of attention since its introduction in 1997. The DE is a simple yet powerful algorithm; it is composed of three main operations mutation, crossover and selection. The algorithm uses the difference of solution vectors to create new candidate solutions using the above-mentioned operators. This work investigates the use of (DE) as an optimization tool to implement the (SHEPWM) for a nine level inverter.

This article presents a simple and fast optimal solution of harmonic elimination of a nine level inverter with non-equal DC sources using the DE algorithm. The algorithm is used to solve a set of non-linear equations in order to obtain the optimal switching angles with the goal of eliminating low order harmonics (3^{rd}, 5^{th}, 7^{th}).

This paper is organized as follows: the next section explains briefly the structure of the proposed multilevel inverter and its control, the third section covers the application of the differential evolution algorithm for the selective harmonic elimination, this section details the procedures to obtain the optimal switch-

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ing angles and the formulation of the objective function, the fourth section presents the simulation results obtained from the mathematical model of the system and the optimization method. The effectiveness of the selective harmonic elimination using DE is verified using a small scale laboratory nine-level inverter based on STM32F407 Microcontroller unit. The conclusion is presented in the last section.

II. Topology

The cascaded multilevel inverter topology depends on one simple principle which is based on the addition of the voltage that is generated by each individual cell (H-bridge) in order to obtain a staircase output voltage waveform.

Table 1. Switching logic of a nine level H-bridge inverter

	Switches state							
Voltage levels (*p.u*)	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
4	on	off	off	on	on	off	off	on
3	off	on	off	on	on	off	off	on
2	off	on	on	off	on	off	off	on
1	on	off	off	on	off	on	off	on
0	off	on	off	on	off	on	off	on
-1	off	on	on	off	off	on	off	on
-2	on	off	off	on	off	on	on	off
-3	off	on	off	on	off	on	on	off
-4	off	on	on	off	off	on	on	off

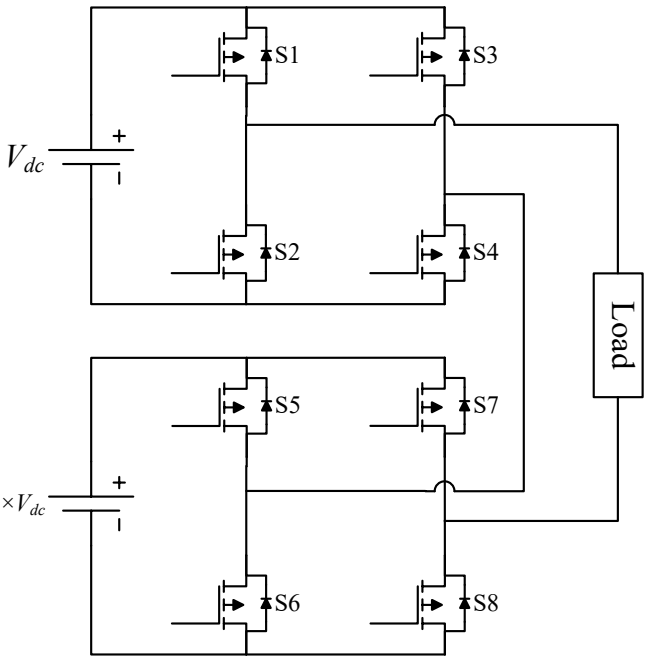

Fig. 1. Schematic of the proposed converter

Fig. 1 reveals the proposed single-phase asymmetrical nine-level inverter. It is shaped by two H-bridges that are connected indifferent series with each bridge can be powered by power supplies that are electrically isolated in order to generate the wanted waveform.

Every module can generate three voltage levels +V which is the positive voltage of the DC source, 0V and –V which represents the DC source negative voltage, and as it is demonstrated in Fig.1 when wanting to obtain nine voltage levels from the proposed inverter, the DC voltage source that is connected to the lower cell must be three times its value of the DC source that is this time connected to the upper cell ($V_{dc2}=3\times V_{dc1}$). Table 1. Shows the switching states of all the possible combinations for the asymmetrical nine-level inverter.

III. Selective Harmonic Elimination Using Differential Evolution

The number of voltage levels that can be generated by CMLIs is generally presented by *2P + 1* where P represents the number of voltage levels or switching angles in a quarter waveform of the signal with P-1 is representing the number of undesired harmonics that can be removed from the generated waveform.

When using a nine-level inverter, four is the number of voltage levels in the quarter waveform. This means that the number of harmonics that can be eliminated is three. Fig. 2 shows the voltage waveform in a quarter of period for a nine-level inverter where the switching angles θ_1, θ_2, θ_3, and θ_4 must be computed in a designed way allowing the control of the fundamental component and the elimination of undesired harmonics.

There are four voltage levels (in the quarter waveform) and three undesired harmonics for the staircase output voltage waveform of the multilevel inverter as illustrated in Fig. 2.

In order to control the peak value of the output voltage to be V_1 along with eliminating the 3rd, 5th, and 7th harmonic and considering the voltage waveform has quarter and half-wave symmetry characteristics thus the resulting Fourier series expansion is given as:

$$V(\omega t)=\sum_{n=1,3,5,\ldots}^{\infty}\left[\frac{4V_{dc}}{n\pi}\sum_{i=1}^{p}\cos(n\theta_i)\right]\sin(n\omega t) \tag{1}$$

Where *n* is rank of harmonics, $n = 1, 3, 5, \ldots$, and $p = (N - 1)/2$ is the number of switching angles per quarter waveform., and θ_i is the i^{th} switching angle, and N is the number of voltage levels per half waveform.

$$\begin{cases} H_1=\cos(\theta_1)+\cos(\theta_2)+\cos(\theta_3)+\cos(\theta_4)=((\dfrac{N-1}{2})\times\dfrac{r}{4}) \\ H_3=\cos(3\theta_1)+\cos(3\theta_2)+\cos(3\theta_3)+\cos(3\theta_4)=0 \\ H_5=\cos(5\theta_1)+\cos(5\theta_2)+\cos(5\theta_3)+\cos(5\theta_4)=0 \\ H_7=\cos(7\theta_1)+\cos(7\theta_2)+\cos(7\theta_3)+\cos(7\theta_4)=0 \end{cases} \tag{2}$$

Where r is the modulation index.

We put $M = ((\frac{N-1}{2})(\frac{r}{4}))$.

The obtained solutions must satisfy the following constraint:

$$0 \prec \theta_1 \prec ... \prec \theta_P \prec \frac{\pi}{2} \tag{3}$$

When performing the optimization process it is fundamental to use an objective function. This function must be formulated in a way that allows the elimination of the chosen harmonics and also allows maintaining the amplitude of the fundamental component at the desired value consequently the objective function is defined as:

$$F(\theta_1\theta_2...\theta_p) = (\sum_{n=1}^{p}\cos(\theta_n) - M)^2 + (\sum_{n=1}^{p}\cos(3\theta_n))^2 + (\sum_{n=1}^{p}\cos(5\theta_n))^2 + (\sum_{n=1}^{p}\cos(7\theta_n))^2 \tag{4}$$

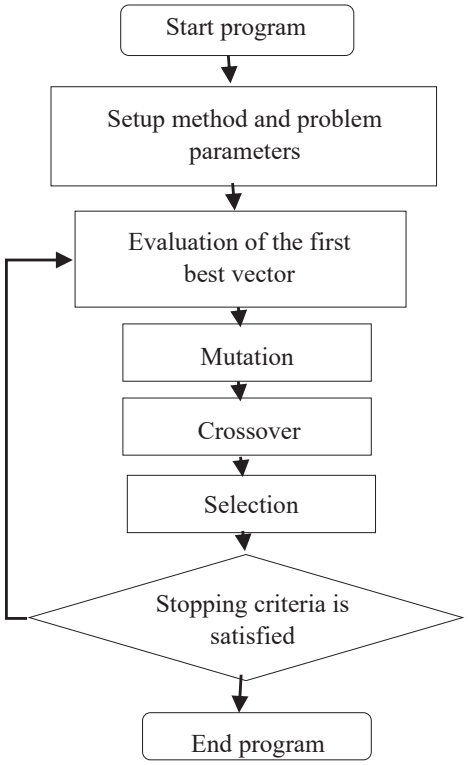

Fig. 3. Flowchart of DE algorithm

The optimal switching angles can be obtained by minimizing (4) subject to the constraint (3). The differential algorithm is used to overcome the main problem which is the non-linearity of the transcendental set of (2). The three main steps that include initialization, mutation and crossover are composing the algorithm. Fig. 3 illustrates the general structure of a DE program. When employing the mutation, the algorithm perturbs the population of vectors through its diversity is controlled by the cross-over process [16].

For the SHPWM strategy, the DE algorithm is used as an optimization tool to perform a random search for the global minima, which is forcing the objective function (4) towards an acceptable error value.

The optimization process begins by initializing the indispensable algorithm parameters like the crossover probability (CP), upper and lower bounds (θ_{min} and θ_{max}), population size (NP) and the maximum number of iterations. It is worth noting that the boundaries have to satisfy equation (3). The further stage is to arbitrary generating an initial population of switching angles in this process the algorithm produces.

$$\theta_{ij}^{(0)} = \theta_{\min ij} + rand_i(\theta_{mawj} - \theta_{\min j}) \tag{5}$$

with i = 1, 2,…,NP and j = 1, 2 ,…, N

Where $\theta_{ij}^{(0)}$ represents the initial population, i mean the population size in this study NP=75, j represents the number of decision variables that constitute the number of switching angles, in case of a nine-level inverter N=4. Following the initialization process, the evaluation of the generated population is done. Furthermore, the fitness of each individual evaluation is carried out by using (4).

Based on the initial population, a mutant v_{ij} vector is created by the mutation process. This process is outlined by the following expression:

$$v_{ij} = X_{r1} + F(X_{r2} - X_{r3}) \tag{6}$$

X_r1, X_{r2} and X_{r3} are vectors randomly sampled from the generated population, $X_r = [\theta_{i1}, \theta_{i2}, ..., \theta_{iN}]$, the indices *r1, r2* and *r3* are integers randomly chosen from the range [1 NP] and are as well chosen to be different from the index i, the F parameter is the mutation constant which controls the amplification of the differential variation $(X_{r2} - X_{r3})$, this parameter value is randomly generated from the range [0 1], it should be pointed out that multiple mutation methods were reported in [17].

The crossover operation comes into play in order to improve the diversity of the population after generating the mutant vector v_{ij} through mutation. This operation satisfies the production of fitter individuals with the result is a vector u that is obtained by mixing the components of v_{ij} and X_i. The process can be expressed as:

$$u = \begin{cases} v_{ij} \; if \quad rand \le CP \quad or \quad j = j_{rand} \\ X_i \quad otherwise \end{cases} \tag{7}$$

Where rand represents a random number in the range of [0 1], CP represents the crossover probability constant which controls the diversity of the population and a value between 0 and 1 [18], j_{rand} is an index that is randomly chosen. Once the crossover process is completed, the selection process comes into play to decide whether the u_i or X_i vector survives for the next generation, this process is carried out to choose the fittest individual. The selection process can be expressed mathematically as:

$$X_i^{G+1} = \begin{cases} u_i^{G+1} \quad if \quad f(u_i^{G+1}) \prec \quad f(X_i^G) \\ X_i^G \quad otherwise \end{cases} \tag{8}$$

where $f(X)$ represents the objective function to be minimized and G represents the generation count. After the selection operation is completed, the algorithm loop is repeated up to the stopping criteria is satisfied, in this work the DE algorithm is restricted by maximum number of iterations N_{itr} = 1000.

IV. Simulation Result

In order to demonstrate the theoretical predictions as well as to test the effectiveness of the proposed algorithm, the proposed inverter and the control method were developed then simulated using MATLAB/SIMULINK for scientific programming environment. A computer with Intel(R) Core(TM) i3 CPU@ 2.13GHz Processor and 4GB of RAM was used in order to execute the optimization program. It takes for the optimization algorithm 1549.37 seconds to complete the computation process.

For verifying the proposed method's effectiveness the Total Harmonic Distortion (THD) was used as a performance indicator in order to evaluate the quality of output AC voltage waveform generated from the multi-level inverter. Moreover, the THD is defined as the total amount of harmonics related to the fundamental which can be calculated using the subsequent formula:

$$THD = \frac{\sqrt{\sum_{n=3}^{19} H_n^2}}{H_1} \times 100 \tag{9}$$

The DE algorithm is used to observe the switching angles for every value of modulation index r; also, for each r the total harmonic distortion is also computed.

The optimal switching angles (in degrees) versus modulation index r with $r \in [0.2\ 1.1]$ are shown in Fig. 4 while the angles are computed with a fine step-size of 0.01.

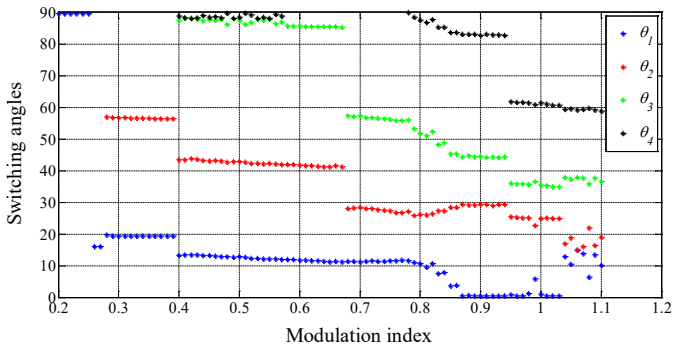

Fig. 4. Optimal switching angles obtain by DE algorithm versus modulation index

It can be seen that in some ranges of the modulation index such as $r \in [0.2\ 0.4]$ and also $\in [0.6\ 0.72]$, the obtained solutions exceeded the 90 degrees limit, these switching angles should not be taken into account. Fig. 5 shows the variation of the total harmonic distortion versus the modulation index, these results are obtained by using (8) and (2).

The validity of the proposed algorithm is to be confirmed. From the obtained switching angles we extracted angles that were applied to the mathematical model of the nine-level inverter. The output voltage obtained from the multilevel inverter for r=0.85 is illustrated in Fig. 6.

Fig. 7 shows the FFT analysis of the output voltage waveform. It can be clearly seen from the FFT analysis that the selected harmonics (3rd, 5th and 7th) are successfully eliminated, the total harmonic distortion of the generated waveform was found to be THD=14.12%.

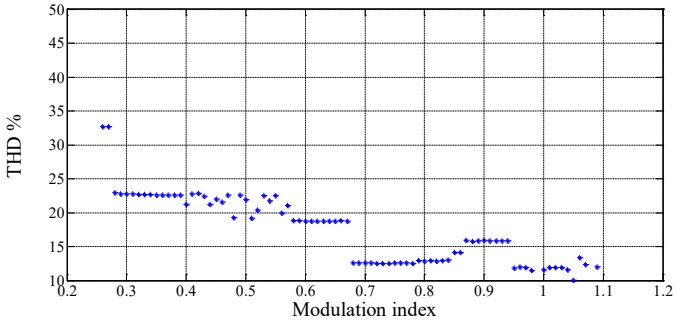

Fig. 5. Total harmonic distortion versus modulation index

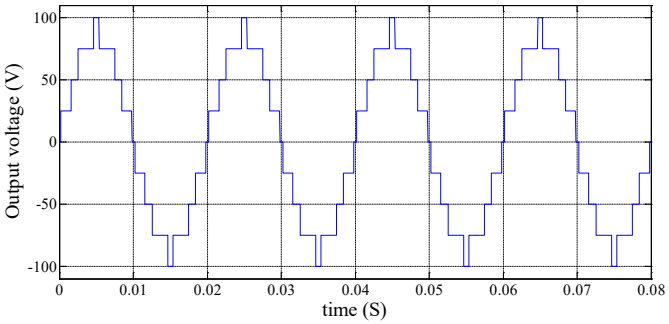

Fig. 6. Simulation results of output voltage waveform

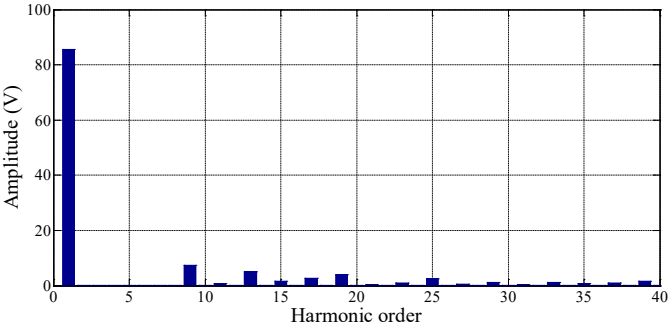

Fig. 7. FFT analysis for r =0.85

V. Experimental Results

The proposed method was validated by building a small scale laboratory prototype used as switching devices IRF640(200V,18A) MOSFETs, SDS1000 oscilloscope 100MHz 500Ms/s which was used to capture the voltage waveforms. In addition, in order to generate control signals for the switching devices a STMF407 microcontroller was used. A computer connected to the oscilloscope through USB was used for the FFT analysis. The experimental validation of the single phase nine-level voltage pattern obtained in simulation is shown in Fig. 6 and 7 illustrates and the results are illustrated in Fig. 9.

Fig. 9 illustrates the FFT analysis of the experimentally obtained voltage waveform; it can be clearly seen that the 3rd, 5th and the 7th harmonic were successfully eliminated. This result matches completely the simulation result seen in Fig. 7

The total harmonic distortion of the experimental voltage waveform is 14.20% which is very close to the simulation result. Fig. 10 and Fig. 11 demonstrates the experimental gating signals for the semiconductor switches from S1 to S8.

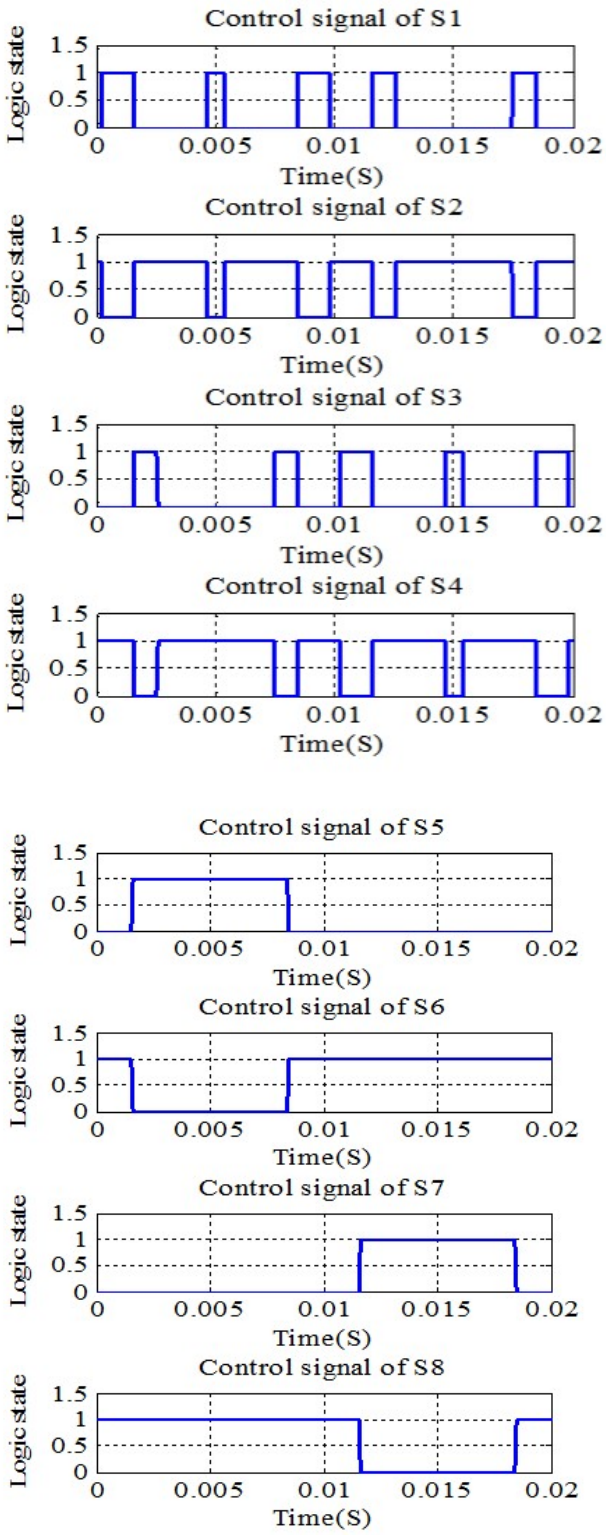

Fig. 8. Simulation results of gating signals

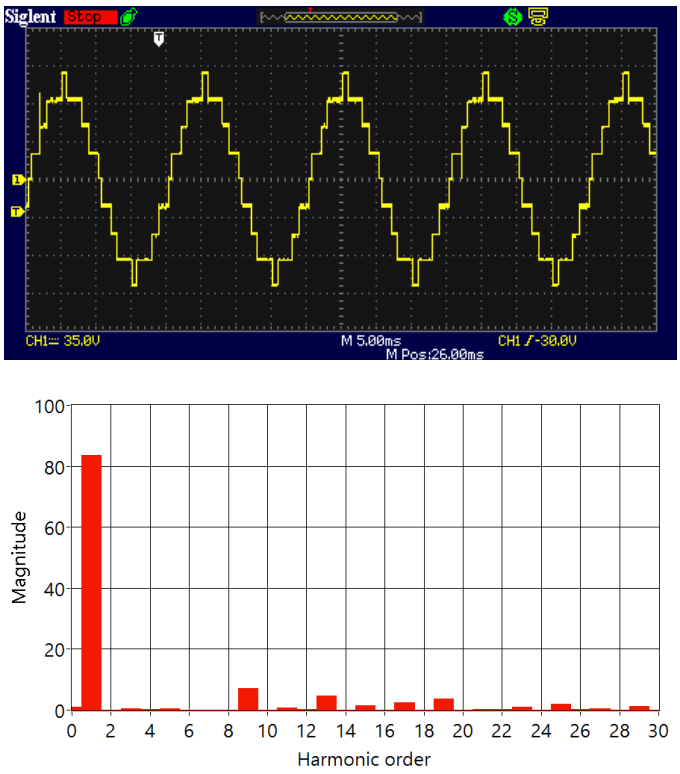

Fig. 9. Experimental result of the output voltage and the corresponding FFT analysis

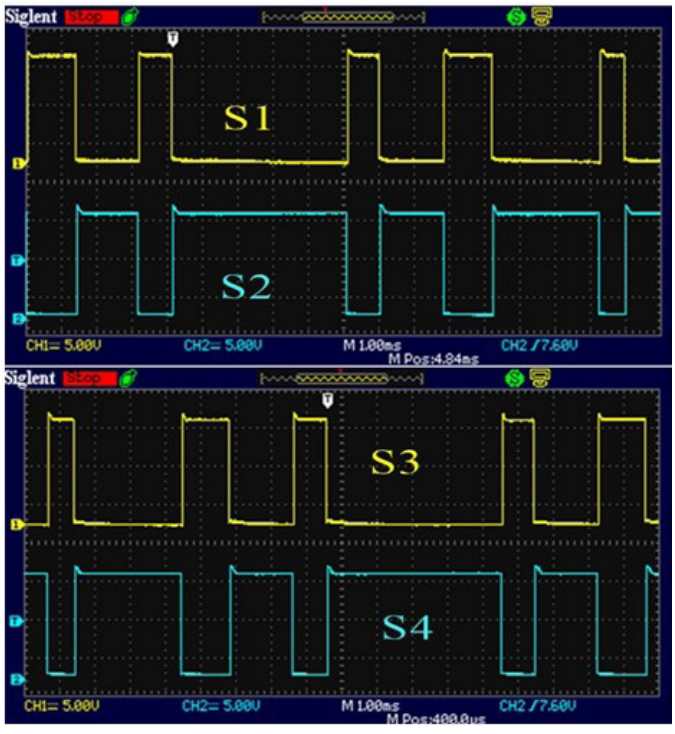

Fig. 10. Experimental gating signal waveforms for the semiconductor switches from S1 to S4.

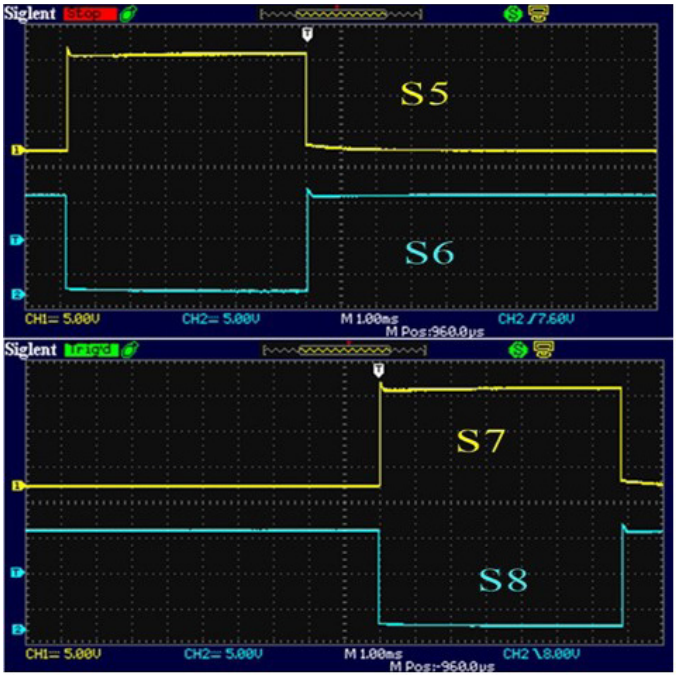

Fig. 11. Experimental gating signal waveforms for the semiconductor switches from S5 to S8.

VI. Conclusion

This study demonstrates the application of the DE algorithm in selective harmonic elimination for a nine-level voltage source cascade inverter which can improve the harmonic quality of the generated output voltage. The proposed inverter topology with non-equal DC sources has the advantage of generating nine voltage levels with less switching components.

The DE algorithm is used to solve a set of non-linear equations in order to obtain the optimal switching angles to perform the (SHE) modulation strategy.

The validity of the method has been confirmed by computer simulation using Matlab/Simulink scientific programming environment and verified by experimental hardware set-up based on STM32F407 microcontroller. The results from the hardware and simulation show a good agreement with the theoretical prediction.

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