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# Elimination of Harmonics in Modified 5-Level CHB Inverter Using DE Algorithm

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**ABSTRACT**

The main objective of this paper is to demonstrate the application of Selective Harmonic Elimination PWM (SHEPWM) based on Differential Evolution (DE) optimization algorithm to improve the AC output voltage quality of modified 5-level Cascaded H-Bridge (CHB) inverter. The DE optimization algorithm is used to solve non-linear transcendental equations necessary for the SHEPWM. 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.



## 1. Introduction

Several modulation strategies have been proposed and studied for the control of multilevel inverters such as Sinusoidal Pulse width modulation (SPWM) [1] and space vector pulse width modulation (SVPWM) [2]. A more efficient method called selective harmonic elimination pulse width modulation (SHE-PWM) 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 calculate the optimal switching angles such as Newton-Raphson (N-R) [3], 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). And if the chosen initial values are far from the global minimum, non-convergence can occur.

Selecting a good initial angle, especially for a large number of switching angles can

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be very difficult. Another approach is to use optimization algorithms such as Genetic Algorithm (GA) [4], FireFly algorithm (FFA) [5] and Particle Swarm Optimization (PSO) [6]. The main advantage of these methods is that they are free from the requirement of good initial guess.

The differential evolution (DE) is one of the most powerful optimization algorithms. Since its introduction in 1997 [7], the algorithm has drawn the attention of many scientists over the world, resulting in multiple variants derived from the original basic algorithm, with improved performance. The DE is a simple yet powerful algorithm ; it is composed of three main operations mutation, crossover and selection [8]. 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 five level inverter.

This paper presents a simple and fast optimal solution of harmonic elimination of a modified five level inverter with equal DC sources using the differential evolution algorithm. The algorithm is used to solve a system of non-linear equations that describes the waveform of the output voltage in order to obtain the optimal switching angles, to improve the output voltage quality.

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 switching 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 five level inverter based on STM32F407 Microcontroller unit, the section also presents and discusses the hardware implementation and the experimental results in details. The conclusion is presented in the last section.

## 2. Modified 5-level cascaded H-bridge inverter

The main objective of the proposed multilevel inverter is to reduce the number of semiconductor switches, without changing the staircase nature of the output voltage. The topology was originally proposed by Kh. El-Naggar in [9]. The proposed inverter should have the same number of input DC voltage sources as a traditional five level cascade H-bridge inverter. When compared to a conventional cascade topology, the proposed inverter provides a lot of advantages ; this configuration does not require a large number of components and does not need clamping diodes or balancing capacitors, the simplicity of its topology allows easier maintenance.

The proposed inverter presented in Fig.1 has a main H-Bbridge inverter formed by $S_1$, $S_2$, $S_3$ and $S_4$, two auxiliary switching devices $S_5$ and $S_6$ and two input DC voltage sources $V_{dc1}$ and $V_{dc2}$. The function of the auxiliary switching devices is to control the connection of the dc sources so as to construct the staircase output voltage. The valid switching states for all possible combination are given in Table.1.

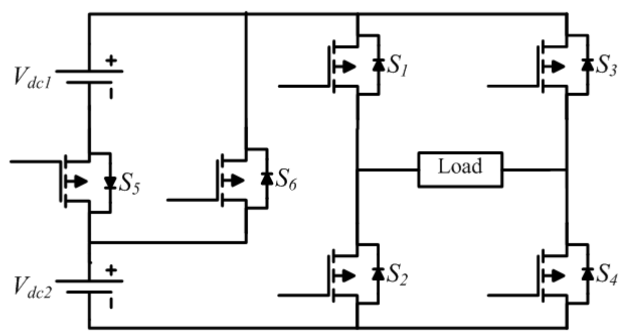


**Fig.** 1 – Structure of the proposed multilevel inverter.

**Table** 1 – Switching states of semiconductor devices for 5-level inverter.

| | Switches state | | | | | |
|---|---|---|---|---|---|---|
| Voltage levels (p.u.) | S1 | S2 | S3 | S4 | S5 | S6 |
| 2 | on | off | off | on | on | off |
| 1 | on | off | off | on | off | off |
| 0 | on | off | off | on | on | on |
| -1 | off | on | on | off | off | off |
| -2 | off | on | on | off | on | off |

## 3. Selective harmonic elimination using DE algorithm

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, and $P-1$ is the number of undesired harmonics that can be eliminated from the generated waveform. In a five level inverter, the number of voltage levels in quarter waveform is two which means the number of harmonics that can be eliminated is one ($3^{rd}$ harmonic).

In order to eliminate the undesired harmonics, the switching angles $\theta_1$ and $\theta_2$ represented in Fig. 2 must be computed.

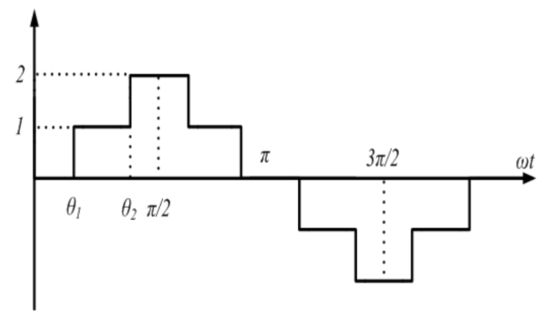


**Fig.** 2 – Quarter waveform of a five-level inverter.

For the staircase output voltage waveform of multilevel inverter as shown in Fig. 2 there are 2 voltage levels (in quarter waveform) and 1 undesired harmonic.

To control the peak value of the output voltage to be $V_1$ and eliminate the $3^{rd}$ harmonic the resulting equations and since the voltage waveform has quarter and half wave symmetry characteristics, the 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 $\theta_i$ is the ith switching angle, and $N$ is the number of voltage levels per half waveform. The optimal switching angles $\theta_1$ and $\theta_2$ can be determined by solving the following system of non-linear equations :

$$\begin{cases} H_1 = \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) = M \\ H_3 = \cos(3\theta_1) + \cos(3\theta_2) + \cos(3\theta_3) = 0 \end{cases} \tag{2}$$

where $M = (((N-1)/2)r/4)$, $r$ is the modulation index.

The obtained solutions must satisfy the following constraint :

$$0 < \theta_1 < \ldots < \theta_p < \pi/2 \tag{3}$$

An objective function is necessary to perform the optimization operation, the function must be chosen in such way that allows the elimination of low order harmonics while maintaining the amplitude of the fundamental component at a desired value Therefore the objective function is defined as :

$$F(\theta_1,\ \theta_2 \ldots \theta_p) = \left( \sum_{n=1}^{p} \cos(\theta_n\ ) - M \right)^2 + \left( \sum_{n=1}^{p} cos(3\theta_n) \right)^2 \tag{4}$$

The optimal switching angles are obtained by minimizing Eq. (4) subject to the constraint Eq. (3). The main problem is the non-linearity of the transcendental set of Eq. (2), the differential algorithm is used to overcome this problem.

The differential evolution algorithm (DE) is an optimization method is composed of three main steps initialization, mutation and crossover. The general structure of a DE program is shown in Fig. 3. The algorithm perturbs the population of vectors by employing the mutation, whereas its diversity is controlled by the cross-over process [10].

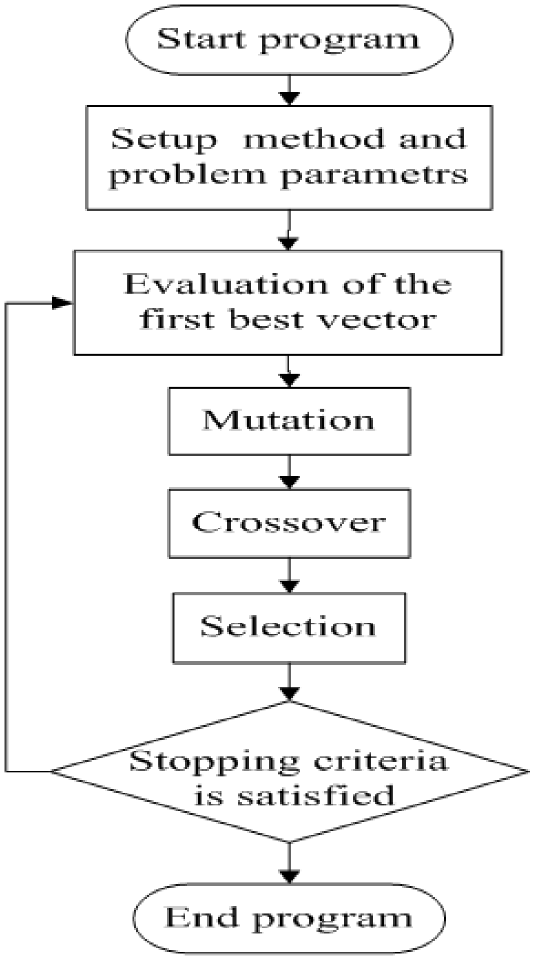


**Fig.** 3 – Flowchart of DE algorithm.

In the case of SHEPWM, differential evolution 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 allowable error value.

The optimization process starts by initializing the necessary parameters of the algorithm, such as the population size (NP), crossover probability (CP), upper and lower bounds ($\theta_{min}$ and $\theta_{max}$) and the maximum number of iterations. It should be noted that the boundaries must satisfy Eq. (3). The next step is to randomly generate an initial population of switching angles in this process the algorithm creates

$$\theta_{ij}^{(0)} = \theta_{\min ij} + rand_i\left(\theta_{maxj} - \theta_{minj}\right) \tag{5}$$

with $i = 1, 2, \ldots NP$ and $j = 1, 2, \ldots N$

where $\theta_{ij}^{(0)}$ is the initial population, $i$ presents the population size in this study $NP = 50$, $j$ is the number of decision variables which represents the number of switching angles, in case of a five level inverter $N = 2$. After the initialization process, the generated population is evaluated, the evaluation of the fitness of each individual is carried out by using (4).

The mutation process creates a mutant $v_{ij}$ vector based on the initial population ; this process is described by the following expression

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

$X_{r1}$, $X_{r2}$ and $X_{r3}$ are vectors randomly sampled from the generated population, $X_r = [\theta_{i1}, \theta_{i2}, \ldots, \theta_{iN}]$, the indices $r1$, $r2$ and $r3$ are integers randomly chosen from the range [1 NP], they are also chosen to be different from the index $i$, the parameter $F$ is the mutation constant which controls the amplification of the differential variation $(X_{r2} - X_{r3})$, the value of this parameter is randomly generated from the range [0 1], it should be noted that multiple mutation methods were reported in [11].

To improve the diversity of the population, the crossover operation comes into play, after generating the mutant vector $v_{ij}$ through mutation, this operation assures the production of fitter individuals, the result of this process is a vector $u$ obtained by mixing the components of $v_{ij}$ and $Xi$ the process can be expressed as :

$$u = \begin{cases} v_{ij} \; if \; rand \leq CP \; or \; j = j_{rand} \\ Xi \qquad\qquad\qquad otherwise \end{cases} \tag{7}$$

where $rand$ is a random number in the range of [0 1], $CP$ is the crossover probability constant, it controls the diversity of the population and it has a value between 0 and 1 [12], $j_{rand}$ is randomly chosen index. 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 :

$$X_i^{G+1} = \begin{cases} u_i^{G+1} \; if \; f\left(u_i^{G+1}\right) < f\left(X_i^{G}\right) \\ X_i^{G} \qquad\qquad\qquad otherwise \end{cases} \tag{8}$$

where $f(X)$ is the objective function to be minimized and $G$ is the generation count. Once the selection operation is completed, the algorithm loop is repeated until the stopping criteria is satisfied, in this study the DE algorithm is limited by maximum number of iterations $Nitr = 1000$.

## 4. Simulation results

In order to prove the theoretical predictions and to test the effectiveness of the proposed algorithm, the control method and the proposed inverter were developed and simulated using MATLAB/SIMULINK scientific programming environment ; the optimization program was executed on a computer with Intel(R) Core(TM) i3 CPU@ 2.13GHz Processor and 4GB of RAM, the optimization algorithm takes 974.463 seconds to complete the computation process.

To verify the effectiveness of the proposed method, total harmonic distortion (THD) is used as a performance indicator to evaluate the quality of output AC voltage waveform generated from the multilevel inverter, the THD is defined as the total amount of harmonics related to the fundamental, it can be calculated using the following formula :

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

The differential evolution algorithm is used to find the switching angles for each value of modulation index $r$ ; the total harmonic distortion is computed also for each $r$, Fig. 4 illustrates optimal switching angles (in degrees) versus modulation index $r$ with $r \in [0.2, 1.2]$, the angles are computed with a fine step-size of 0.01, and it can be seen that in some ranges of the modulation index, the obtained solutions exceeded the 90 degrees limit, those solutions are not going to be taken in consideration. Fig. 5 shows the variation of the total harmonic distortion (THD) versus the modulation index, these results are obtained by using equations (9) and (2).

To confirm the validity of the proposed algorithm, angles extracted from the obtained switching angles were applied to a mathematical model of a five-level inverter. The fundamental frequency used in this simulation is 50Hz, the input DC voltages are set to be ; $V_{dc1} = 15V$ and $V_{dc2} = 15V$ the switching angles to be applied (in degrees) are : $\theta 1 = 5.08°$ and $\theta 2 = 54.9°$ and which correspond to the modulation index $r = 1$.

Fig. 6 shows the output voltage obtained from the multilevel inverter for $r = 1$. Fig. 7 shows its spectra of the output voltage. As expected, the $3^{rd}$ harmonic is successfully eliminated, the total harmonic distortion $THD = 23.73\%$.

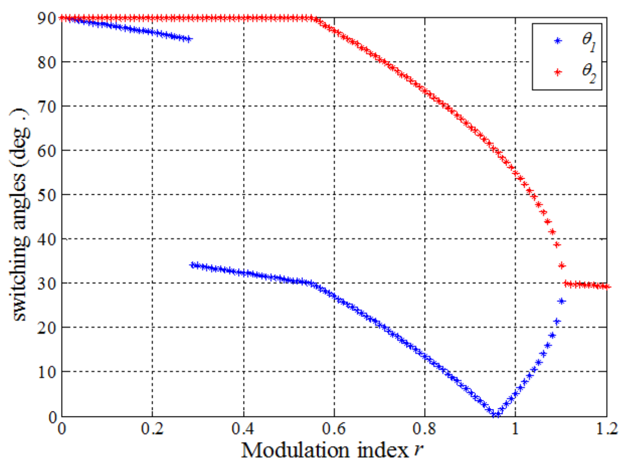


**Fig.** 4 – Switching angles versus modulation index.

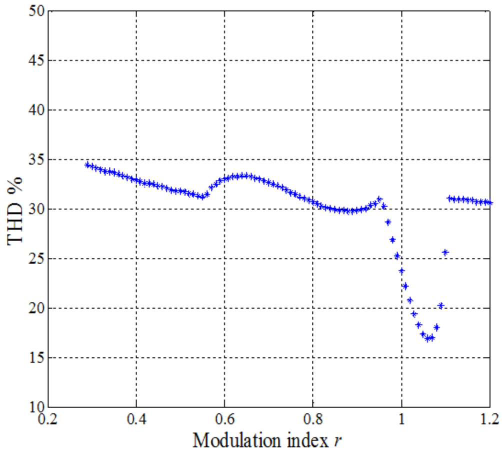


**Fig.** 5 – THD versus modulation index.

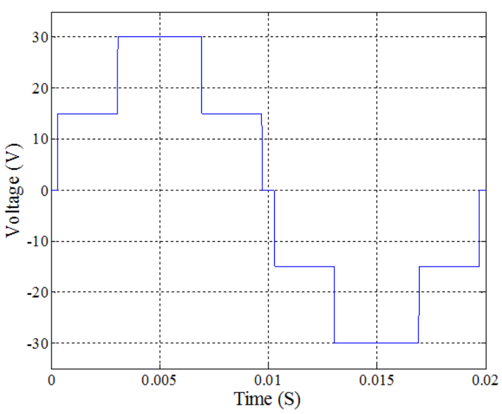


**Fig.** 6 – Output voltage generated by the inverter.

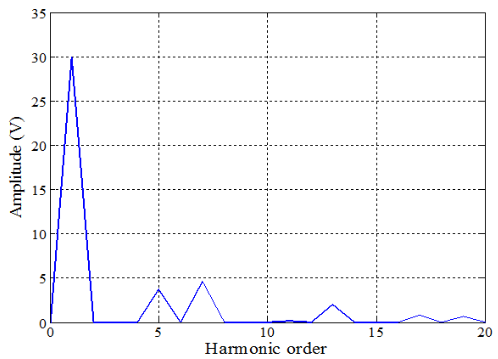


**Fig.** 7 – FFT of 5-level inverter voltage output.

## 5. Experimental results

The proposed method was validated by building a small scale laboratory prototype, IRF640(200V,18A) MOSFETs were used as switching devices SDS1000 oscilloscope100MHz 500Ms/s was used to capture the voltage waveforms, an STM32F407 microcontroller was used to generate control signals for the switching devices, the FFT analysis was performed by computer connected to the oscilloscope trough USB.

Fig. 8 presents the block diagram of the laboratory prototype of the five level inverter that is implemented as mentioned before with eight IRF 640 Metal Oxide Semiconductor Field Effect Transistors (MOSFET), it should be noted that those switching devices are also equipped with freewheeling diodes. TLP250 photocouplers are used to provide electrical isolation between the MCU and the power circuits, and also to provide proper and conditioned gate signals to the MOSFETs. The switching angles are calculated using differential evolution algorithm by a computer, once the switching angles are obtained, the switching patterns for each switching device will be stored inside the memory of the MCU as a look-up table.

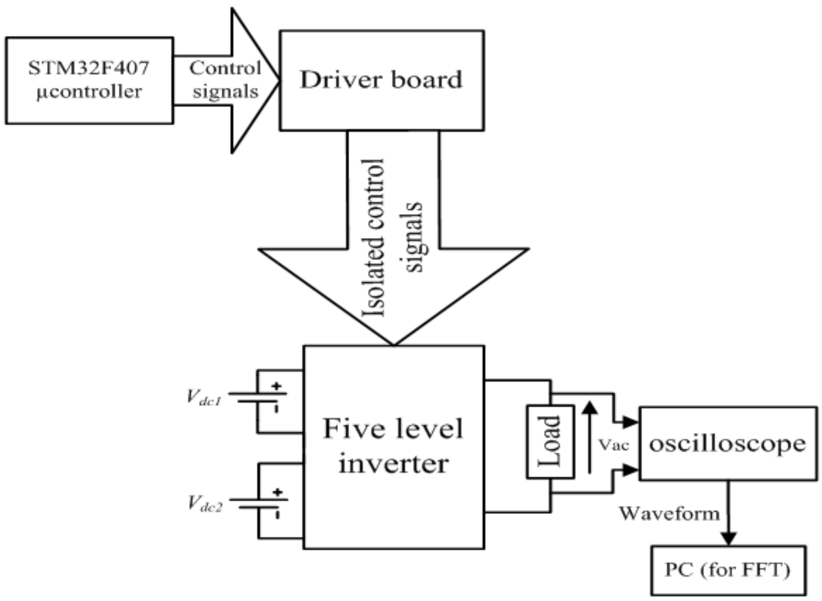


**Fig.** 8 – Block diagram of the hardware setup.

The single phase five level voltage pattern obtained in simulation shown in Fig. 6 is experimentally validated and the result is shown in Fig. 9. Fig. 10 illustrates the FFT analysis of the experimentally obtained voltage waveform; it can be clearly seen that the 3rd harmonic was successfully eliminated. This result matches perfectly the simulation result presented in Fig. 7. The total harmonic distortion of the experimental voltage waveform is 22.85% which is very close to the simulation result.

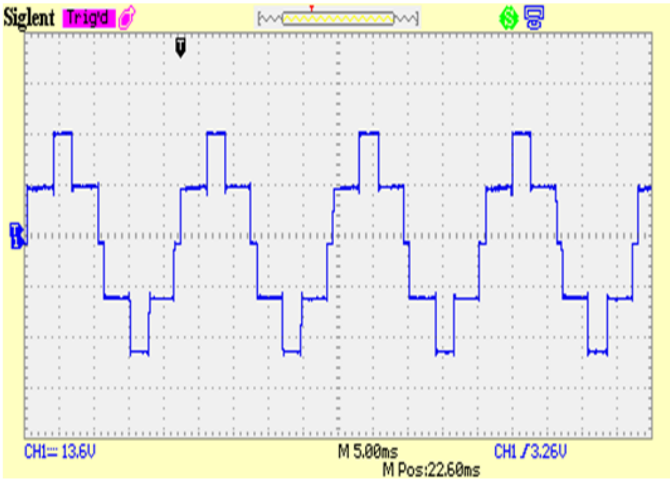


**Fig.** 9 – Output voltage waveform generated the proposed multilevel inverter.


**Fig.** 10 – FFT of 5-level inverter experimental voltage output.

## 6. Conclusion

This paper illustrates the use of differential evolution algorithm in selective harmonic elimination for a modified single phase five level CHB inverter to improve the harmonic quality of the generated output voltage. The proposed multi-level inverter with equal DC sources has the advantage of generating multiple voltage levels with less switching components. The differential evolution 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 total harmonic distortion (THD) was chosen as a performance indicator in order to examine the effectiveness of the proposed algorithm. The validity of the method has been proven by computer simulation using Matlab/Simulink scientific programming environment and verified by experimental hardware set-up based on STM32F407 microcontroller. The obtained results from the simulation and hardware show a good agreement with the theoretical prediction.

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