Optimization of the THD in a Multi-Level Single-Phase Converter using Genetic Algorithms.

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Abstract: - This paper presents the optimization of THD (Total harmonic distortion) in a DC-AC converter employing genetic algorithms. The selected topology for inverter circuit is the cascade multilevel converter with asymmetric DC supplies (4 stages). The aim is to reach a THD less than 5% and obtain an output waveform with a frequency of 60 Hz and an output voltage of 120 Vrms. The results were simulated in MATLAB and validated by implementing a prototype converter.


1. Introduction.
The multi-level inverters are an emerging technology that has arisen as an alternative to traditional dual level converters. These systems allow the conversion of electric energy provided by sources of direct current, such as batteries or solar panels, in an ideal sinusoidal alternating current, whose parameters (amplitude, frequency) can be fixed or variable.

The general concept [1] involves a high number of switches based on power semiconductors that develop the conversion in small steps, achieving an output waveform with low harmonic content.

The first work related to conversion in multiple steps or tension levels was patented in the year 1975 [2]. Previously, in the year 1980 a variant of multi-level converter was patented [3] to which anchoring diodes were added. The topology of the multi-level converter anchored by a capacitor (clamped capacitor) was introduced in the mid-1990s [4], [5]. This topology offers various advantages over the NPC (Neutral Point Clamped diode), as is clearly exhibited in [6]. The multi-level converter in succession with separate DC sources was patented in the year 1997 [7].

From the first works on multi-level converters, important advances that have allowed the development of this technology have been accomplished. Amongst the most relevant advances that, [6] and [7] can be cited, where there is a review of the state of art multi-level converters. What’s more, [9] presents a very interesting work that addresses the issue of the simulation of multi-level converters.

Another significant contribution has been made by Masters and PhD works focused on the multi-level converters, within those [10-13] are cited.

In order to evaluate the quality of the electric energy generated by an inverter circuit the THD or total harmonic distortion, which is a measure of the harmonic content of the output waveform, are usually used. The lower the THD, the better the quality of the signal. Due to the fact that in the inverter circuits the output waveform is generated by means of switching semiconductor devices, it is necessary to find the appropriate trip times that allow the reduction of the THD. Therefore, this need can be seen as an optimization problem.

On the other hand, heuristic optimization techniques have emerged as an alternative to the classic methods based on the statistics. The main reason is that it is inspired by natural processes resulting in them being less affected by the local maximum than the traditional techniques. Such is the case of genetic algorithms based on natural selection to find optimal solutions in a research space imitating biological processes such as crossing and mutation.

The work is organized as follows: section 2 presents the basic concepts of the multi-level converters. In section 3, the types of modulation employed in these types of convertors are studied.
Section 4 presents the concepts related to genetic algorithms. In section 5 the optimization problem is outlined, meanwhile in section 6 the results of the simulation obtained are presented. Finally, section 7 shows the validation of the simulation results through the physical implementation of the inverter.

2. Multi-Level Inverters

2.1 Multi-Level Conversion

Power multi-level conversion was introduced at the beginning of the 1980s. The general concept involves the use of a high number of switching semiconductor devices to develop the conversion in small voltage steps.

A schematic diagram of a single-phase inverter with different numbers of levels is shown in figure No 1:

![Fig.1. Single-Phase inverter of (a) Two levels, (b) Three levels, (c) m levels.](image)

As can be seen in figure No 2, in a multi-level converter seeks to synthesize a waveform much more similar to a sinusoidal signal, in which, depending on the number of available DC sources, the distortion will be much lower. Its main advantages include [6]:

- The disposition of the input voltage in multiple levels allows the working voltage of the converter to be increased several times using the same switches as a conventional converter.
- The power of the converters increases with the use of higher voltages, without the need to increase the current, therefore avoiding losses during conducting, and consequently improving the performance of the converter.

![Fig.2. Output voltage of the converter (a) 2 levels, (b) 3 levels, (c) 5 levels.](image)

2.2 Multi-Level Inverter in Cascade

This topology is based on the serial connection of single-phase inverters with independent power sources. Figure No 3, shows the power circuit for a single-phase inverter of three stages:

![Fig.3. Multi-level inverter in cascade.](image)

In the event that the power sources of all of the stages are the same, this converter is called the multi-level converter in symmetric succession. In the event that the power sources of the stages are distinct, this converter is called the multi-level converter in asymmetric succession. Generally in this type of converter, that DC sources between stages are related by a whole factor. The generation of the output waveform is obtained from the appropriate switching of each stage which allows you to add different levels of tension generated by the circuit, as seen in figure No 4:

![Fig.4. Synthesis of the output waveform of a multi-level inverter in symmetric cascade.](image)

3. Modulation Strategies

The main objectives of the of the strategy of switching DC/AC converters are, apart from regulation of amplitude and output frequency, the minimization of the harmonic content of the output voltage of the inverter and the balance of the instantaneous tensions of the converter’s capacities. A classification scheme of multi-level converter switching techniques is presented in Figure No. 5.
The most used technique in multi-level converters is staircase switching, which seeks to synthesize a staggered waveform very similar to a sinusoid with low harmonic content. This time of output can be seen in figure No 6 for 9 and 31 levels in the output of the converter.

With the purpose of improving the harmonic content of the output signal of the converter, it is possible to implement a sinusoidal modulation of multiple carrier pulse width (SPWM). In this case, the sinusoidal reference signal is compared to several triangular carriers depending on the number of levels on the converter. The signals obtained are used to adequately shoot the switching devices. In figure No 7 you can see an example of this type of modulation.

In addition, there are other variations of the techniques mentioned such as the RPWM or random PWM, delta modulation and trapezoidal modulation, which seek, in every case, to improve the harmonic content of the output signal to minimize the THD.

4. Genetic Algorithms
The genetic algorithm (GA) is a technique of search and optimization based on the principles of genetics and natural selection. An GA allows a population composed of many individuals to evolve under specific selection rules to a state that maximizes fitness or aptitude, i.e. minimizes the cost function [14]. Among the advantages of the GA the following stand out:
- It optimizes both with continuous and discreet variables.
- It allows a wide search in the solutions space to be carried out.
- It can handle a large number of variables.
- It is ideal for parallel computers.
- It optimizes variables with highly complex cost functions.
- It offers a list of ideal variables, not only a simple solution.

Figure No. 8 shows the general execution scheme of the genetic algorithm. The process starts with the random generation of an initial sample, continued by the selection of the individuals who are going to be crossed. Then the descendants which are subjected to gene-altering mutation are generated. The new individuals are evaluated and inserted into the sample to finally assess the optimization criteria and verify if this is fulfilled or if it is necessary to iterate again.

5. Approach to the Optimization Problem
As discussed in section 2.2, the multi-level converter output voltage consists of the sum of the individual levels of each converter stage, as shown in figure Nº 9.
The output voltage of this staggered waveform can therefore be expressed as [15]:
\[
v_{out} = \sum_{n=1}^{\infty} \frac{4V_{dc}}{n \pi} \left[ \sum_{k=1}^{s} \cos(n \theta_k) \right] \sin(n \omega t)
\] (1)

Where:
- \( n \) is the odd harmonic order (1, 3, 5, 7, 9…)
- \( s \) is the number of stages of the converter.
- \( k \) is an integer \( >0 \) (1, 2, 3, 4, 5…)
- \( \theta_k \) is the \( k \)-th shot angle, which must satisfy:
\[
\theta_1 < \theta_2 < \cdots < \theta_s < \pi/2
\] (2)

From (1), the amplitude of the odd harmonics, including the fundamental component can be expressed as:
\[
h_n = \frac{4V_{dc}}{n \pi} \sum_{k=1}^{s} \cos(n \theta_k)
\] (3)

Expanding the previous equation you have:
\[
h_n = \frac{4V_{dc}}{n \pi} \left[ \cos(n \theta_1) + \cos(n \theta_2) + \cdots + \cos(n \theta_s) \right]
\] (4)

Conduction angles \( \{\theta_1, \theta_2, \theta_3, \ldots, \theta_s\} \) can be selected in such a way that the entire harmonic voltage distortion is minimal. According to what is described, the problem of optimization can appear like this:

Minimize:
\[
THD\% = \left[ \frac{n}{h_1^2} \cdot \sum_{n=3}^{\infty} h_n^2 \right]^{1/2} \cdot 100
\] (5)

Where:
- \( h_1 \) is the amplitude of the fundamental harmonic.
- \( h_n \) is the amplitude of the \( n \)-th harmony, with odd \( n \).

Satisfying the equation (4), subject to the restrictions:
\[
h_1 = 169.7V
\] (6)
\[
h_n = 0 \quad \text{for } n > 1 \text{ odd } n
\] (7)
\[
0 < \theta_1 < \theta_2 < \cdots < \theta_k < \frac{\pi}{2}
\] (8)

Therefore the genetic algorithm, takes as sample the angles \( \theta_k \). Then, in each interaction of the algorithm the operators of selection, crossover and mutation are applied to find the solution to the equation described by (4), finally the cost function is evaluated, which in this case is the THD.

The algorithm stops when the stop conditions given by the number of iterations and/or the tolerance of the solution are satisfied.

6. Simulation Results

The proposed optimization scheme was simulated in MATLAB for a 4 stage multi-level single-phase asymmetric converter (31 levels) to a desired amplitude of the fundamental component of 169.7 V (120 Vrms), an output frequency of 60 Hz and a THD <5%. For the calculation of THD the top 40 harmonics of output signal were considered. The initial sample was 20 individuals for the GA and the maximum number of iterations was 200.

In figure No. 10 you can see the waveform of the output voltage of the converter as well as the harmonic spectrum in which the quality of the output signal can be seen.

The optimization of the THD as the GA is running is shown in Figure No 11, where you can see that it reaches a value of 2.084%. In Figure No 12 you can observe the optimization of the shot angles represented by \( x_k \). Figure No 13 shows the evolution of the harmonics of the output signal, there you can see that as the GA runs, the fundamental harmonic is inclined to the desired value (169.7 V) while the other harmonics are inclined to zero, as it is to be expected.

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Fig.10. Output waveform and specter of converter harmonics

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Fig.9. Construction of a phased signal from individual levels.
7. Implementation of the Prototype
To validate the simulation results a prototype of the multi-level converter was implemented and the shot angles obtained in the control card based on a PIC18F4550 were programmed. Figure No 14 shows a diagram in blocks of the experiment. A system of data acquisition based on digital oscilloscope Agilent DSO3202-A has been used to make the visualization and analysis of the waveform obtained.

Figure Nº 15 shows the current output waveform, while in figure Nº 16 you can see the profile of harmonics. The similarity of the actual waveform and the simulated waveform should be noted. A comparison of the results obtained is shown in table Nº 1.

<table>
<thead>
<tr>
<th>Table 1: Comparison of results</th>
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<tbody>
<tr>
<td>Simulation</td>
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</tr>
<tr>
<td>THD%</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>(Hz)</td>
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<tr>
<td>Vrms (V)</td>
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8. Conclusions

The results observed in figures Nº 9, 10, 11 and 12 show that the selected method to find the appropriate shot angles works in a satisfactory manner, allowing us to obtain a THD of just 2.084%.

The physical implementation of the converter demonstrates that the shot angles found in the simulations are appropriate, allowing us to obtain a waveform and a profile of harmonics very similar to the simulations.

The small difference that can be seen between the results of the simulation and the physical implementation are mainly due to shot delays that must be secured between switching devices from the same branch and small variations of DC sources.

The use of genetic algorithms means that it is unnecessary to address the solution of a system of transcendental equations formally, since the GA explores within the search space from several solution points and it is not focused on finding “exact” solutions but the best solution to the problem.

Since the GA is a meta-heuristic optimization method, each time that the GA is carried out it can reach a slightly different solution, but they satisfy the problem of minimization.

References