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Evolutionary Metaheuristic Methods Applied to Minimize the THD in Inverters: A Systematic Review

Oscar Sánchez-Vargas[1*], Susana Estefany De León-Aldaco[1], Jesús Aguayo-Alquicira[1], Adolfo Rafael López-Núñez[2]

[1] Electronics Department, TecNM / Cenidet, Cuernavaca Morelos 62490, Mexico
[2] Electricity and Power Electronics Laboratory, TecNM/ITESI, Irapuato, Guanajuato 36821, Mexico

Corresponding Author Email: m20ce023@cenidet.tecnm.mx

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ABSTRACT

In recent research works, metaheuristic methods have been widely used to minimize THD in inverters, these methods provide better computation time and effective results compared to classical methods. This paper presents a systematic analysis with a comprehensive coverage of metaheuristic methods applied to multilevel inverters. The search focused on the characteristics of the inverters used in the articles (topologies, levels, loads and evolutionary method). The aim is to show which are the characteristics of the most used case studies for the application of evolutionary metaheuristic methods. The IEEEXplorer, ScienceDirect, IET Digital Library, Springer and WorldWideScience databases have been used for the review since 2010. The results of the review show that many researchers use evolutionary algorithms, with Cascaded H-bridge Multilevel Inverter topology, RL loading and 7 levels. This highlights which features of the case studies are the most used and analysed to explore the advantages of using evolutionary metaheuristic methods.

1. INTRODUCTION

In recent years, several research projects have been carried out on the use of metaheuristic methods to optimize various processes in different areas of science and engineering, to demonstrate that better results can be obtained using these methods and seeking to make the best use of available resources. In short, optimization is to find a better configuration, within a set of variables to achieve the objectives of a problem, with the resources available, without breaking any limits of the process [1]. While metaheuristics are advanced algorithms to solve optimization problems, especially with incomplete or imperfect data [2].

The name or term metaheuristic derives from the Greek suffix "meta" meaning "beyond" or "superior" and the word "heuristic" meaning "to find". Metaheuristic methods can be divided into two main classes: trajectory-based and population-based. Trajectory-based is the term that refers to a search process that is characterized by following a trajectory in the search space. They start with a single initial solution and at each iteration or step, the current solution is replaced by a better solution. The performance of which is usually quite unsatisfactory [3]. They incorporate techniques that allow the algorithm to escape local minima. This implies the need for different criteria to reach a local minimum. Commonly used are the criteria of maximum CPU time, a maximum number of iterations, a solution s of sufficient quality, or reaching the maximum number of iterations without improvement (e.g., SA and TS).

While the population-based one uses a set of solutions also called population of solutions. These try in each iteration to replace the population to obtain a better result, to provide a natural and intrinsic way to explore the search space. However, the final performance depends on how the population is manipulated [3, 4].

Population-based methods have better performance for global optimization [5]. The following Figure 1 gives a classification of the different metaheuristic methods.

This paper shows the results of a systematic review of metaheuristic algorithms used for THD minimization in inverters. The main focus of the review was on reproductive population-based methods, which are mainly subdivided into Evolutionary Algorithms and Swarm Intelligence Algorithms. The objective of the systematic review, covering publications from 2010-2019 (10 years), is to make visible the growing trend in the application of these algorithms for THD minimization in inverters.

It is important to effectively reduce the THD because the presence of harmonics in motors causes heating, causing losses in the core, as well as causing parasitic torques in the axis, causing pulsating torques, as a result of which the motor degrades rapidly [6, 7]. In electronic equipment, they cause distortion of the voltages at the power supply nodes, causing poor operation in sensitive devices. In conductors they generate an increase in current, causing heating of cables and thermal losses. In capacitors they create parallel resonances in the system and amplification of harmonics causing heating and premature ageing of the capacitors. To find a minimum THD effectively is considered as an optimization problem [8].

The rest of the article is organized as follows: Section 2 contains a brief description, important aspects, and the corresponding equations for THD. Section 3 presents an introduction and characteristics of the metaheuristic methods, as well as diagrams of the DE and GA process. Subsequently, section 4 presents the results of the systematic survey. Finally, the conclusions are presented in section 5.

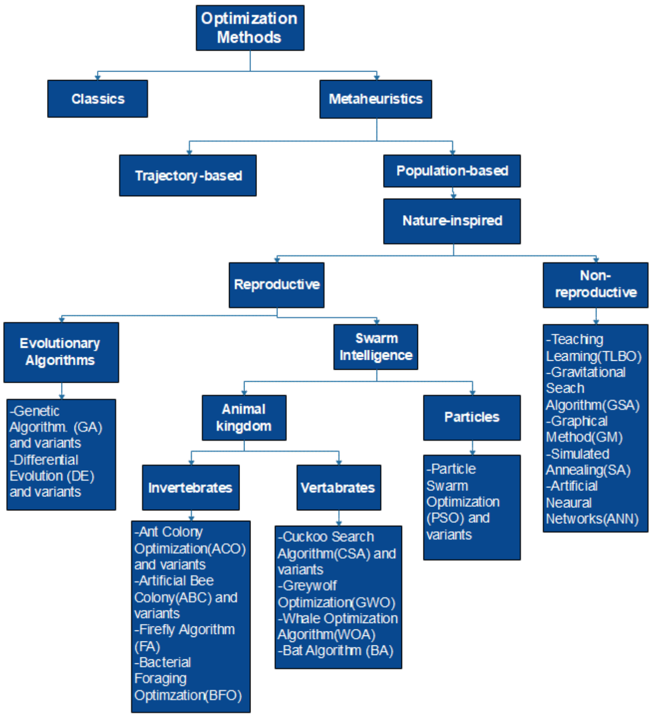

Figure 1. Classification of metaheuristic methods

2. OPTIMIZATION PROBLEM

An optimization problem consists of finding the best possible configuration of a set of variables. They fall into two categories: those where the solutions with real variables, and those with discrete variables [1]. In optimization, there are three important aspects, the objective function, decision variables, and constraints. The objective function is the criterion or property to be optimized, it can be expressed in a linear or nonlinear function of several variables; it can be based on weight, cost, volume, efficiency, or a combination of two or more attributes, in this case, it would be the reduction of THD in an inverter [9]. Decision variables or design variables are quantities that in the process are selected by the designer, they cannot be chosen arbitrarily since they must satisfy certain requirements that are specified. While the constraints as the name suggests, are restrictions that must be met in order to develop an acceptable design, they are expressed by linear inequalities [1, 5].

In the inverter the stepped waveform of the output voltage is analyzed using the Fourier series which is expressed in the following equation taking into account that it is of quarter-wave symmetry:

$$V_{out}(\theta) = \sum_{n=1,3,5}^{\infty} b_n \sin(n\theta) \tag{1}$$

where, n =1, 3, 5 are odd harmonics and b_n is given by:

$$b_n = \sum_{n=1,3,5}^{2N-1} \frac{4V_{dc}}{n\pi}(V_1\cos(n\alpha_1) + V_2\cos(n\alpha_2) + \cdots V_m\cos(n\alpha_N)) \tag{2}$$

where:
n = 1, 3, 5 .... 2N-1 (odd harmonics).
N = number of switching angles per quarter cycle.
m = number of dc sources.
a = switching angle.

The quality of the voltage waveform at the output is determined by how many harmonics it contains so equation 1 shows the THD formula following the IEEE 519 standard:

$$THD = \frac{\sqrt{\sum_{n=1,3,5,7...}^{50} V_n^2}}{V_1} * 100 \tag{3}$$

Recalling that the purpose is to minimize the objective function is to find optimal switching angles, having an optimal output voltage. Which can be expressed the objective function as:

$$\text{Minimize: } THD = \frac{\sqrt{\sum_{n=1,3,5,7...}^{50} V_n^2}}{V_1} * 100 \tag{4}$$

$$\text{Subject to: } 0 \leq \alpha_1 \leq \alpha_2 \ldots \leq \alpha_N \leq \frac{\pi}{2} \tag{5}$$

where, N = number of switching angles per quarter cycle and a= switching angle.

3. METAHEURISTIC METHODS

Metaheuristic methods are advanced search techniques, based on an intelligent procedure to perform an optimization. This process is not as rigorous as other mathematical processes [10]. Metaheuristics are strategies aimed at "guiding" the search process so that the search space is explored efficiently.

Metaheuristic algorithms are usually non-deterministic and therefore provide near-optimal solutions. They include several parameters that must be matched to the problem and may incorporate mechanisms to avoid being trapped in confined areas of the search space. More advanced techniques take advantage of the experience gained from previous searches. In order to guide the current search to a better solution [5].

Compared to classical methods, metaheuristic methods find a solution closer to the optimal one, but with a reduced time, which compensates for the accuracy of the solution with the computational time.

3.1 Differential evolution

The Differential Evolution algorithm, created by Rainer Storn and Kenneth Price in 1996, is a metaheuristic method, which conducts a random search in the population of solutions to locate global minima. It perturbs the population generated during the mutation process, while the diversity of the population is controlled by the crossover process [11]. During the selection process, it takes advantage of the survival of the fittest solution. Among the outstanding advantages of the differential evolution algorithm is that it is easy to implement, converges quickly, tends to reach the global optimal solution, and does not tend to remain local solutions [12].

The process of this algorithm consists of the following steps:

1. Initialization: A population of vectors or individuals is randomly generated.
2. Mutation: In this process, genetic characteristics are changed, or rather certain individuals in the population are perturbed. A parent vector is an individual of the current generation, which is called the target vector, the mutant vector obtained after the perturbation is called the donor vector.

3. Crossover: In this process, the aim is to generate a new generation of individuals or vectors, to have a "better" population. The offspring of the target vector and the donor vector is called the test vector.
4. Selection: In this process evaluates the individuals or test vectors with the target vectors, in other words, they compare parents with sons, in case the target vector turns out to be more effective than the test vector, it stays, otherwise the test vector replaces the target vector, in order to have a new and better generation [13, 14].

The processes of mutation, crossover, and selection will be repeated until the result or outcome is satisfactory. Figure 2 shows the ED process:

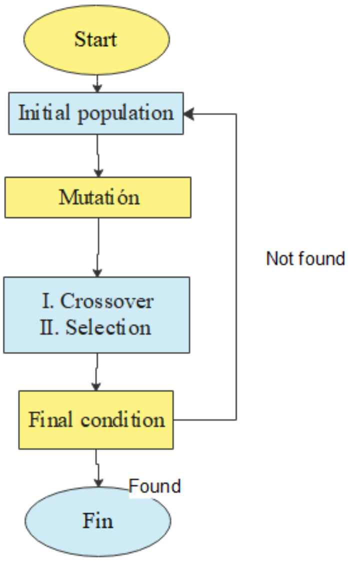

Figure 2. Differential evolution diagram [14]

3.2 Genetic algorithm

The Genetic Algorithm (GA) was created by J.H. Holland, in 1970, is a metaheuristic method that is based on the survival of the fittest from Darwin's theory of Natural Selection. The solutions are called "chromosomes" and are submitted to several processes.

It is one of the most widely used methods, it is flexible, it gives optimal solutions in a short time [12].

The GA encodes the parameters of the problem as genes, then randomly generates a set of solutions to the encoded parameters, these are called "initial population". Each individual that is feasible for the solution is considered a chromosome. The number of chromosomes indicates the size of the population. The chains of genes form a chromosome. In the case of large populations, there will be better genetic diversity, in the case of small populations, there will be a fast run time.

1. Initial population: randomly generates a population.
2. Assesses individual fitness: individual fitness is assessed and assigned to each member of the population. The function must be carefully determined, as it has a large effect on the quality of the outcome.
3. Selection: the best adapted "parents" are selected, according to the desired selection strategy. These are the ones that generate the next generation of individuals. For the next generation to be more fit and survive while the less fit ones are eliminated.
4. Crossover: The selected parents are combined to form the new generation of " sons ". The crossover process ensures that each son has the genes of each of his parents, these are exchanged to form a new and improved combination.
5. Mutation: Here some genes are randomly altered from the sons, to have a wide search space, not to remain stagnant, and prevent the solutions from falling into a local minimum.
6. Evaluation of the fitness function: Here the fitness of the children and parents are evaluated, in case an optimal solution is not reached, the process is repeated.
7. Reinsertion: the members of the older generation are replaced by their children if they have better fitness [15, 16].

The GA process is best illustrated in Figure 3:

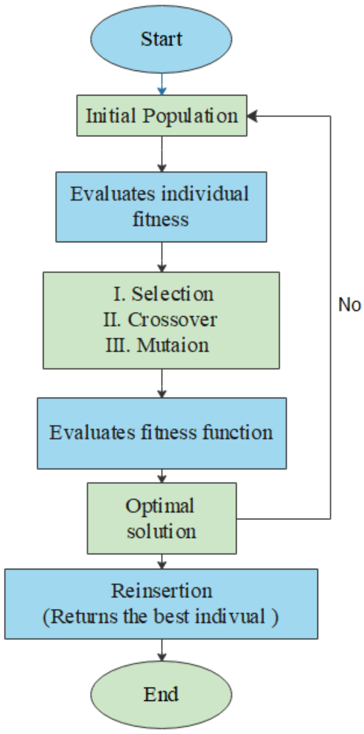

Figure 3. Genetic algorithm diagram [15]

4. SYSTEMATIC SURVEY RESULTS

For the literature review analyzed and classified in this article, the IEEExplorer, ScienceDirect, IET Digital Library, Springer, and WorldWideScience databases were consulted.

The search focused on metaheuristic optimization methods applied to basic multilevel inverter topologies (cascaded multilevel, clamped diodes, and flying capacitors), whose objective function was to minimize THD. The database was searched using keywords related to the proposed approach and looking for articles published over 10 years, from 2010 to 2019. A universe of publications of 71 articles was reviewed and classified. Table 1 lists the optimization methodologies used according to their classification.

Table 1. Classification and optimization methodologies are applied to multilevel inverters

Methodology						Objective function- Minimize THD
Metaheuristics	Reproductive	Evolutive Algorithms			DE and variants	[11, 16-55]
					GA and variants	[15, 16, 37, 46, 56-60]
		Swarm Intelligence	Particles		PSO and variants	[15, 32, 45-47, 50, 61-69]
			Animal Kingdom	Vertebrates	CSA and variants	[50, 59, 67, 70-76]
					GWO	[35, 59, 77]
					WOA	[68]
					BA	[76, 78]
				Invertebrates	ACO and variants	[18, 67, 72, 73, 79, 80]
					ABC and variants	[18, 70, 74, 75, 81]
					BFO	[82]
					FA	[71, 83]
	Non-reproductive				TLBO	[18, 50]
					GSA	[20]
					GM	[46]
					SA	[76]
					ANN	[60]
Classics					NR	[15, 61, 71]

Figure 4 shows a histogram of publications involving optimization procedures in multilevel inverters during the last 10 years and extrapolated for the following years. It can be seen the number of publications has increased significantly in recent years, showing an increasing trend.

In Figure 4, 71 publications were reviewed, 59.15% of the universe of publications were from conferences, while 40.85% of publications were from journals.

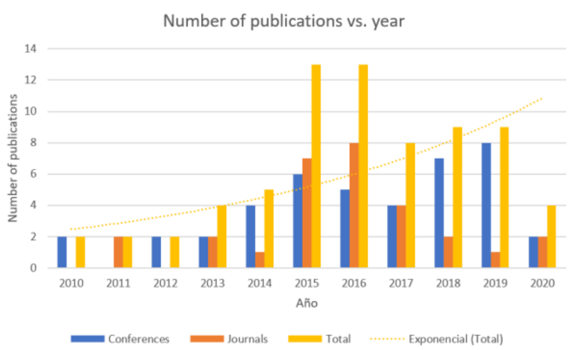

Figure 4. Number of articles using optimization algorithms in multilevel inverters

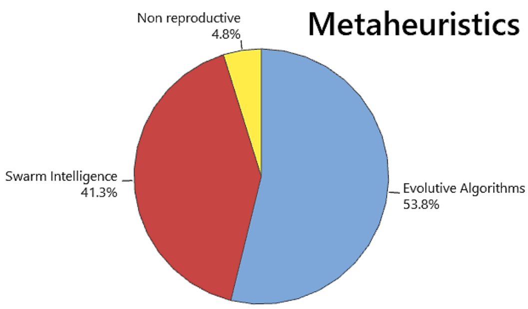

Figure 5. Distribution of metaheuristic methods applied to multilevel inverter optimization

Figure 5 shows the distribution of publications where metaheuristic methods were applied to reduce THD in multilevel inverters.

Figure 6 shows the distribution of publications using evolutive and swarm intelligence algorithms.

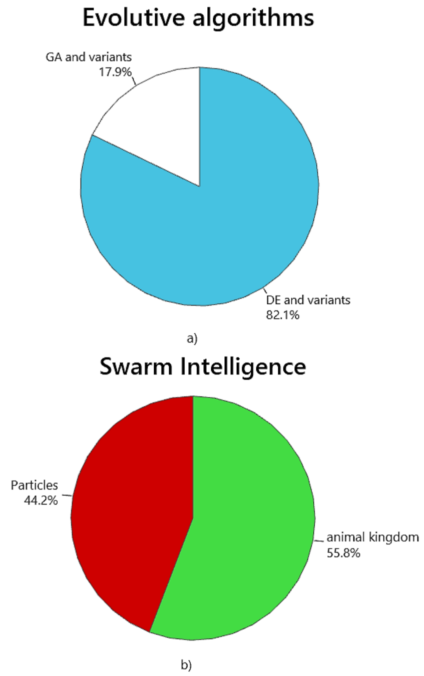

Figure 6. Distribution of publications a) Evolutive algorithms, b) Swarm intelligence

Figure 7 shows the distribution of the animal kingdom classification that invertebrates had 54.2% of mention in the animal kingdom, while vertebrates had 45.8%. In the case of particles, the majority were PSO and variants.

Figure 8 shows the distribution of levels used in the publications, with the highest frequency of seven levels, followed by five and 11.

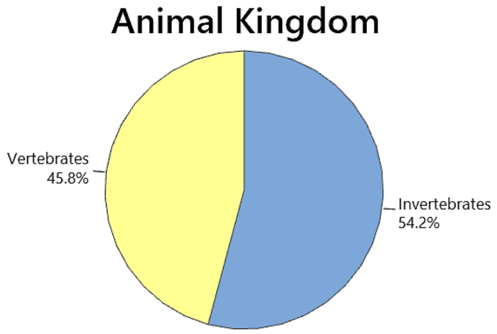

Figure 7. Distribution of publications in the animal kingdom section

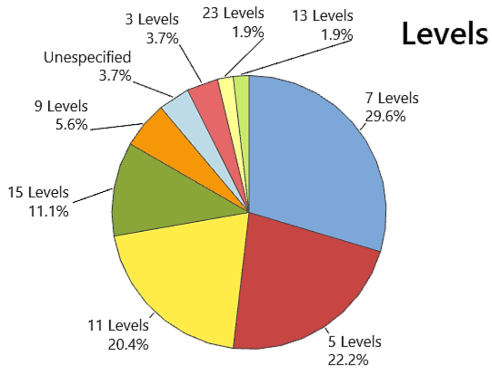

Figure 8. Distribution of publications of the number of levels of an inverter

It is observed that 29.6% of the publications opt for a multilevel inverter with seven levels.

Another important aspect of the design of a multilevel inverter is its topology. Figure 9 shows the distribution of publications with the different topologies used in these publications.

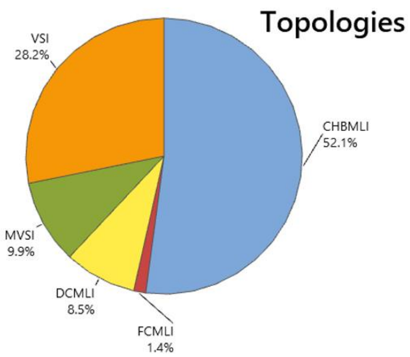

Figure 9. Distribution of publications of the topologies used

The acronyms in Figure 9 are listed:

- CHBMLI: *Cascaded H-Bridge Multilevel Inverter*.
- FCMLI: *Flying Capacitors Multilevel Inverter*.
- DCMLI: *Diode Clamped Multilevel Inverter*.
- MVSI: *Multilevel Voltage Source Inverter*.
- VSI: *Voltage Source Inverter*.

Figure 9 shows that in most of the articles analyzed in the review, 52.1% of the publications used the cascade multilevel topology, observing the clamped diodes in 8.5% of the universe of publications, while the flying capacitors were 1.4%.

The following figure shows the graph of the universe of publications with the phases of the topologies.

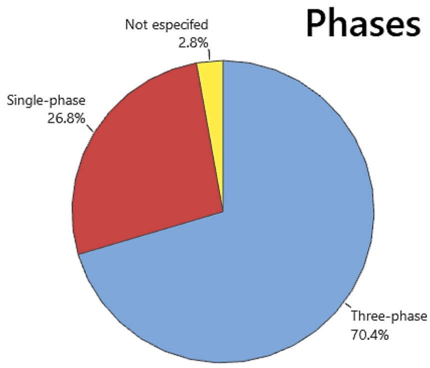

Figure 10. Distribution of publications of the number of phases employed

Figure 10 shows that the majority of the publications used a three-phase inverter with 70.4%, while single-phase inverters were only present in 26.8% of the publications. Figure 11 below shows the distribution and types of loads used in the publications.

It can be seen in the figure that the RL load has a percentage of 62%, the R load has a percentage of 26.8%, while the L load has only 4.2%.

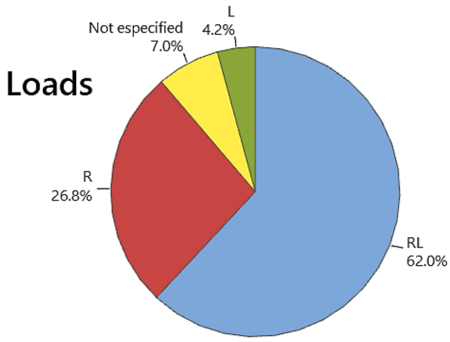

Figure 11. Distribution of publications by type of loads

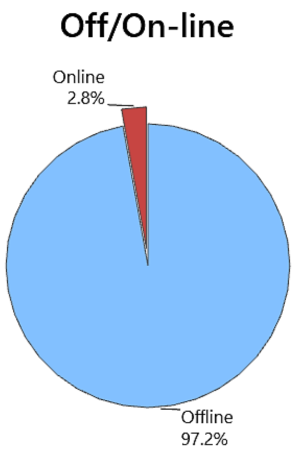

Figure 12. Distribution of Off/On-line configuration publications

A final aspect to consider when a multilevel inverter is whether it performs Off or online, an online optimization allows for restructuring and continuous adaptation while an application is running, using the information (maybe variables, or results) live [84]. While offline, data collection and programming are done before and implemented later in the system. The distribution of publications is shown in Figure 12.

The publications that performed Online, were those whose inverters used some hybridization, in addition to using some bio-inspired algorithm used fuzzy logic or some other additional aspect, although the THD reduction was quite effective, the control complexity was increased reasonably.

5. CONCLUSIONS

This paper presents a systematic review of the metaheuristic methods used to reduce the harmonic content in an inverter, focusing on multilevel topologies. The mathematical formulation of the objective function was presented.

The metaheuristic algorithms that are of interest for the optimization of the switching angle calculation were briefly introduced, highlighting the advantages over classical methods, and emphasizing the evolutionary methods.

An increasing trend can be observed in the number of scientific articles using metaheuristic methods for THD decrease, as well as new variants of some algorithms. The most used methods are evolutionary algorithms. Within the evolutionary algorithms, the differential evolution algorithm, or variants of this one is having a boom in recent years. Since they have shown quite reliable results and with fewer computer resources.

The articles mostly use seven-level multilevel inverters, although many also use five or eleven levels. Also, the most prominent topology in this article is the cascaded multilevel. Another important aspect is that the articles use more three-phase inverters with RL loads. Most of the publications use off-line optimization as it shows satisfactory results, while Online optimization is still rare, these use high computational effort, to ensure that the parameters are available when required.

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