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Comparative analysis of numerical, evolutionary and metaheuristic methods for experimental implementation of selective harmonic elimination in a five-level emerging inverter

Introduction. *Multilevel inverters (MLIs) are widely used in renewable energy conversion and high-performance power applications due to their ability to generate output voltages with low harmonic distortion and reduced switching stress. Selective harmonic elimination (SHE) remains one of the most effective modulation strategies for suppressing low-order harmonics; however, its practical implementation relies on solving nonlinear transcendental equations that often require robust and efficient computational methods.* ***Problem.*** *Determining optimal switching angles for SHE in MLIs remains a challenging optimization problem because of the nonlinear, non-convex nature of the governing equations and the need to simultaneously preserve the fundamental voltage component while eliminating selected harmonics. The choice of an appropriate numerical or optimization-based solution method directly affects computational efficiency, robustness, and practical implementability. The* ***goal*** *of the work is the reducing harmonic distortion of output voltage and determining optimal switching angles of a single-phase 5-level inverter using the Newton-Raphson (NR) method, particle swarm optimization (PSO) and genetic algorithm (GA).* ***Methodology.*** *The operating principle and harmonic model of the inverter are first established using Fourier series analysis. The SHE problem is formulated as a system of nonlinear equations subject to ordering constraints. The NR method is used as a fast numerical solver, while PSO and GA are employed as evolutionary and metaheuristic optimization techniques capable of handling non-convex search spaces. All algorithms are implemented in MATLAB/Simulink over a range of modulation indices. Experimental validation is carried out using an Arduino Mega 2560-based prototype, where the optimized switching patterns are executed in real time and the output voltage is analyzed using oscilloscope and harmonic measurement tools.* ***Results.*** *The three approaches converge to identical switching-angle solutions over the investigated modulation range, confirming the consistency of the formulation. Simulation results demonstrate effective elimination of the 3rd harmonic and its multiples, with the total harmonic distortion of the output voltage decreasing from 28.42 % at M = 0.55, f = 1 kHz to 14.88 % at M = 0.55, f = 10 kHz. In terms of computational efficiency, NR-SHE achieves the shortest execution time (0.516 s), while PSO-SHE (10.237 s) and GA-SHE (23.289 s) require longer computation. Experimental waveforms and harmonic spectra closely match the simulation results, validating the proposed approach.* ***Scientific novelty.*** *This work provides a unified comparative analysis of numerical, evolutionary and metaheuristic methods for SHE applied to a 5-level emerging inverter with a reduced switch count (6 switches instead of 8 in a conventional 5-level H-bridge). In addition, it demonstrates the feasibility of executing SHE-based modulation schemes on a low-cost Arduino microcontroller.* ***Practical value.*** *The presented results offer practical guidance for selecting suitable computational methods for SHE in MLIs and confirm that efficient harmonic control can be achieved using inexpensive embedded platforms. The findings are relevant for research, prototyping and educational applications in industrial electronics and power conversion systems.* References 21, tables 5, figures 12.

Key words: **emerging multilevel inverter, genetic algorithm, Newton-Raphson algorithm, particle swarm optimization, selective harmonic elimination.**

Вступ*. Багаторівневі інвертори (MLIs) широко використовуються в системах перетворення відновлюваної енергії та високопродуктивних енергетичних системах завдяки їхній здатності генерувати вихідну напругу з низьким рівнем гармонік та зменшеним напругою перемикання. Вибіркове усунення гармонік (SHE) залишається однією з найефективніших стратегій модуляції для зменшення гармонік нижчого порядку; однак її практична реалізація залежить від розв'язання нелінійних трансцендентних рівнянь, які часто вимагають надійних та ефективних обчислювальних методів.* ***Проблема****. Визначення оптимальних кутів перемикання для SHE в MLIs залишається складною задачею оптимізації через нелінійний, неопуклий характер керівних рівнянь та необхідність одночасного збереження основної складової напруги при усуненні вибраних гармонік. Вибір відповідного числового або оптимізаційного методу розв'язання безпосередньо впливає на обчислювальну ефективність, надійність та практичну реалізованість.* ***Метою*** *роботи є зменшення гармонійних спотворень вихідної напруги та визначення оптимальних кутів перемикання однофазного 5-рівневого інвертора за допомогою методу Ньютона-Рафсона (NR), оптимізації рою частинок (PSO) та генетичного алгоритму (GA).* ***Методика****. Принцип роботи та гармонічна модель інвертора спочатку встановлюються за допомогою аналізу рядів Фур'є. Задачу SHE сформульовано як систему нелінійних рівнянь з обмеженнями на впорядкування. Метод NR використовується як швидкий числовий розв'язувач, тоді як PSO та GA використовуються як еволюційні та метаевристичні методи оптимізації, здатні обробляти неопуклі простори пошуку. Всі алгоритми реалізовані в MATLAB/Simulink для діапазону індексів модуляції. Експериментальна перевірка проводиться з використанням прототипу на базі Arduino Mega 2560, де оптимізовані шаблони перемикання виконуються в режимі реального часу, а вихідна напруга аналізується за допомогою осцилографа та інструментів вимірювання гармонік.* ***Результати****. Три підходи сходяться до ідентичних рішень кута перемикання в досліджуваному діапазоні модуляції, що підтверджує узгодженість формулювання. Результати моделювання демонструють ефективне усунення 3-ї гармоніки та її кратних, при цьому загальне гармонічне спотворення вихідної напруги зменшується з 28,42 % при M = 0.55, f = 1 кГц до 14,88 % при M = 0.55, f = 10 кГц. З точки зору обчислювальної ефективності, NR-SHE досягає найкоротшого часу виконання (0,516 с), тоді як PSO-SHE (10,237 с) та GA-SHE (23,289 с) вимагають довших обчислень. Експериментальні форми хвиль та гармонічні спектри точно відповідають результатам моделювання, що підтверджує запропонований підхід.* ***Наукова новизна****. Ця робота надає уніфікований порівняльний аналіз числових, еволюційних та метаевристичних методів для SHE, застосованих до нового 5-рівневого інвертора зі зменшеною кількістю перемикачів (6 перемикачів замість 8-ми у звичайному 5-рівневому Н-мості). Крім того, вона демонструє можливість виконання схем модуляції на основі SHE на недорогому мікроконтролері Arduino.* ***Практична значимість****. Представлені результати пропонують практичні рекомендації щодо вибору відповідних обчислювальних методів для SHE в MLI та підтверджують, що ефективного гармонічного контролю можна досягти за допомогою недорогих вбудованих платформ. Результати є актуальними для досліджень, прототипування та освітніх застосувань у промисловій електроніці та системах перетворення енергії.* Бібл. 21, табл. 5, рис. 12.

Ключові слова: **новий багаторівневий інвертор, генетичний алгоритм, алгоритм Ньютона-Рафсона, оптимізація рою частинок, вибіркове усунення гармонік.**

Introduction. Since multilevel inverters (MLIs) can produce high-voltage outputs with improved power quality, they have become a hot topic in power electronics research [1]. Distributed generation systems, grid-connected renewable energies and multilevel resonant inverters make heavy use of these converters [2].

Review of recent publications demonstrates that, there are primarily 2 types of MLIs: traditional and new.

Topologies commonly used in inverters include the neutral-point-clamped, the flying-capacitor and the cascaded H-bridge [3]. Inverters with an uneven number of levels, inverters with fewer components, inverters with soft switches, and MLIs with a single source are all examples of recent advances [4]. The simplicity of control requirements, low total standing voltage, minimal switching losses, and cost-effectiveness of emerging topologies as compared to traditional designs are attracting attention [5]. There are 2 main types of modulation when it comes to generating gating signals for converter semiconductor devices. One type is high-switching frequency modulation, which includes techniques like sinusoidal pulse width modulation, and space vector pulse width modulation [6, 7]. On the other hand, fundamental-frequency modulation includes methods like selective harmonic elimination (SHE), optimal switching angle modulation, and nearest-level modulation [8]. The fundamental-frequency modulation is becoming more pragmatic because the advancements in digital control hardware as digital signal processors, field-programmable gate arrays and embedded controllers [9].

To put SHE into action, the best switching angles must be determined by solving nonlinear transcendental equations. Various methods, including algebraic approaches, numerical techniques, and metaheuristic and evolutionary algorithms, are employed to generate solutions [10]. Metaeuristic methods are great at finding good approximations when optimization problems are hard. Some algorithms that could be mentioned in this context are genetic algorithm (GA); flower pollination algorithm; gravitational search algorithm; grey wolf optimizer; artificial neural networks; particle swarm optimization (PSO); artificial bee colony; ant colony optimization; bald eagle search; salp swarm algorithm; wild horse optimization algorithm; and generalized pattern search [11–14].

The **goal** of this work is the reducing harmonic distortion of output voltage and determining optimal switching angles of a single-phase 5-level inverter using the Newton-Raphson (NR) method, particle swarm optimization and genetic algorithms. By providing a comparative perspective on numerical, metaheuristic and evolutionary techniques for solving the SHE problem, the findings offer practical guidance for selecting appropriate optimization methods and demonstrate that emerging multilevel topologies can be efficiently controlled using accessible, low-cost embedded platforms.

The key benefits of the proposed study are simplicity and low-cost implementation of the system. By covering the principles, applications and benefits of Arduino-based controlled inverters, this research seeks to be a reference for students and engineers interested in developing converter applications using this kind of open-source technology. Furthermore, the comparative analysis between a numerical method, metaheuristic algorithm and evolutionary algorithm presents valuable information to select the appropriate algorithm for harmonic elimination in MLIs.

Description of the MLI system. The basic architecture of the single-phase 5-level inverter is given in Fig. 1. The circuit comprises 2 DC sources, 6 electronic switches and resistor load. In a full switching period (T), the inverter has 12 switching transitions, where the switches operate periodically by complementary mode (S_1, S_2), (S_3, S_4) and (S_5, S_6), hence we can set (S_a, S_b, S_c) = = (S_1, S_3, S_5) to suggest the following switching system:

$$V_0 = \begin{cases} 0 & \xrightarrow{\text{if}} (S_a, S_b) = (0,0) \text{or} (1,1); \\ -V_{dc} & \xrightarrow{\text{if}} (S_a, S_b, S_c) = (0,1,0); \\ +V_{dc} & \xrightarrow{\text{if}} (S_a, S_b, S_c) = (1,0,0); \\ -2V_{dc} & \xrightarrow{\text{if}} (S_a, S_b, S_c) = (0,1,1); \\ +2V_{dc} & \xrightarrow{\text{if}} (S_a, S_b, S_c) = (1,0,1). \end{cases} \quad (1)$$

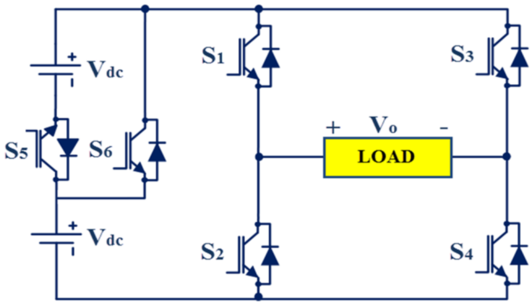

Fig. 1. Topology of the 5-level emerging inverter

By using equal power V_{dc} sources and appropriate switching modes, the inverter can generate 5-levels of output voltage (V_0): 0, $-V_{dc}$, $+V_{dc}$, $-2V_{dc}$ and $+2V_{dc}$ (Fig. 2).

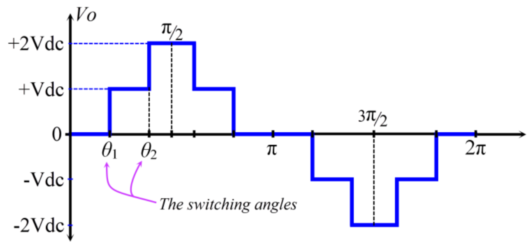

Fig. 2. The output voltage of the 5-level emerging inverter

Mathematical description of the harmonic problem. Harmonics refer to sine wave voltages or currents that occur at integer multiples of the fundamental frequency of the network. When harmonics combine with the fundamental sine wave voltage or current, they cause distortion in the energy waveform. These additional frequencies can lead to various issues in electrical systems, including overheating of equipment and distortion of power quality. To keep networks running smoothly and reliably, it's important to understand and deal with harmonics. If the total harmonic distortion (THD) is 0, it means that there are no harmonics in the electrical network. THD is the ratio of the RMS value of the harmonics in a signal (voltage or current) to the RMS value at the fundamental frequency.

The harmonics manifest as «lines» referred to as the spectrum. Harmonics beyond the 30th rank are often disregarded. The symmetry of output voltage waveforms leads to the near-elimination of even-order harmonics (e.g., the 2nd, 4th, 6th, and beyond). Consequently, these even harmonics are generally considered negligible. In contrast, odd-order harmonics (such as the 3rd, 5th, 7th, and beyond) frequently manifest in electrical grids and are therefore the primary focus of harmonic mitigation studies [5, 15]. The mathematical basis behind these signals was developed by J. Fourier. His seminal work proved that any complex signal which is periodic and piecewise-continuous can be resolved into a series of simple sinusoidal waves, called harmonics [10]. Via the Fourier series, this decomposition enables a powerful analytical method. It permits the engineer to analyze each harmonic component separately and then use the principle of superposition to determine the signal's behavior.

The standard trigonometric representation of the Fourier series for the output voltage $V_0(t)$ is:

$$V_0(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t)\right], \quad (2)$$

where $\omega_0 = 2\pi/T$ is the fundamental angular frequency; $a_0 = 0$ is the DC component; a_n, b_n are the Fourier coefficients: $a_n = 0$, while b_n is determined as:

$$b_n = \frac{2}{T}\int_0^T V_0(t)\sin(n\omega_0 t)\mathrm{d}t . \quad (3)$$

By integrating $V_0(t)$ over $[0, 2\pi]$ and performing standard algebraic simplifications, Eq. (3) is reformulated as:

$$b_n = \frac{4V}{n\pi}\left(\cos(n\theta_1) + \cos(n\theta_2)\right). \quad (4)$$

where θ_1, θ_2 are the switching angles.

Substituting (4) into (2) yields the expression for the inverter output voltage $V_0(t)$ as:

$$V_0(t) = \sum_{n=1}^{\infty}\left(\frac{4V}{n\pi}\left(\cos(n\theta_1) + \cos(n\theta_2)\right)\right)\sin(n\omega_0 t) . \quad (5)$$

For n=1, the output voltage of inverter $V_0(t)$ can be calculated by the fundamental harmonic h_1:

$$h_1 = \frac{4V}{\pi}\left(\cos(\theta_1) + \cos(\theta_2)\right). \quad (6)$$

The 3rd harmonic h_3 is defined as:

$$h_3 = \frac{4V}{3\pi}\left(\cos(3\theta_1) + \cos(3\theta_2)\right). \quad (7)$$

Following the analysis technique described in [16, 17], the optimal switching angles can be computed. This computation involves finding the solution of (8):

$$\begin{cases} 0 = \left(\cos(3\theta_1) + \cos(3\theta_2)\right); \\ M = \frac{1}{k}\left(\cos(\theta_1) + \cos(\theta_2)\right), \end{cases} \quad (8)$$

where k is the number of angles; M is the modulation index:

$$M = \frac{\pi h_1}{4 \cdot k \cdot V} . \quad (9)$$

It is also important that the best angles meet the conditions as:

$$0 < \theta_1 < \theta_2 < \pi/2 . \quad (10)$$

The next sections explain and analyze the suggested 3 optimization-based methods (NR, PSO, and GA) for solving the SHE problem. The objective is to find the best switching angles that meet the basic voltage requirements and eliminate the 3rd harmonic with its multiples.

Solving the SHE problem with Newton-Raphson (NR) algorithm. The NR approach, one of the beneficial numerical methods, can be used to compute and solve the set of transcendental nonlinear equations [18]. An initial estimate is made at the start of this iteration process, which eventually converges to the solution. The switching angles' initial approximation values are:

$$\theta^j = [\theta_1^j; \theta_2^j].$$

The nonlinear system is represented in matrix form:

$$F\left(\theta^j\right) = \begin{pmatrix} \cos\left(3\theta_1^j\right) & \cos\left(3\theta_2^j\right) \\ \cos\left(\theta_1^j\right) & \cos\left(\theta_2^j\right) \end{pmatrix}, \quad (11)$$

where:

$$F\left(\theta^j\right) = Z; \quad Z = \begin{pmatrix} 0 \\ \pi h_1/(4 \cdot V) \end{pmatrix}.$$

The derivative of the nonlinear system (11) is computed as:

$$\left[\frac{\partial F(\theta)}{\partial \theta}\right]^j = \begin{pmatrix} -3\sin\left(3\theta_1^j\right) & -3\sin\left(3\theta_2^j\right) \\ -\sin\left(\theta_1^j\right) & -\sin\left(\theta_2^j\right) \end{pmatrix}. \quad (12)$$

The steps for executing the NR algorithm for our study are as follows.

1) Set the initial values of θ^j when $j = 0$.

$$\theta^j = [\theta_1^j; \theta_2^j].$$

2) Compute the value of:

$$F(\theta^0) = F^0.$$

3) Linearizing the system around θ^0 :

$$F^0 + \left[\frac{\partial F(\theta)}{\partial \theta}\right]^0 \mathrm{d}\theta^0 = Z .$$

Such as:

$$\mathrm{d}\theta^0 = [\mathrm{d}\theta_1^0; \mathrm{d}\theta_2^0].$$

4) Compute $\mathrm{d}\theta^0$ utilizing the subsequent equation:

$$\mathrm{d}\theta^0 = \left(\mathrm{inv}\left[\frac{\partial F(\theta)}{\partial \theta}\right]^0\right)\left(Z - F^0\right).$$

5) Adjust the initial values

$$\theta^{j+1} = \theta^j + \mathrm{d}\theta^j.$$

6) The algorithm continues the prior steps for each equation until the required level of accuracy is achieved for $\mathrm{d}\theta^j$. The solutions of the equation must adhere to the constraint in (10).

Solving the SHE problem with PSO algorithm. An objective function in optimization is essential for eliminating undesirable harmonics while maintaining the fundamental component at its designated magnitude. Consequently, (13) establishes the objective function:

$$F(\theta_1, \theta_2) = \left(\sum_{n=1}^{2}\cos(\theta_n) - k \cdot M\right)^2 + \left(\sum_{n=1}^{2}\cos(3\theta_n)\right)^2 . \quad (13)$$

The optimal angles are established through the minimization of (13), subject to the constraints of (10). The primary issue is the nonlinearity of (8); thus, the PSO algorithm is utilized to address this challenge. Algorithm 1 below illustrates the pseudocode of PSO. The PSO algorithm consists of 3 components: 1) initial parameters; 2) assess the objective function; 3) particles' mobility involves updating their position and velocity.

Algorithm 1: PSO pseudocode

Input: objective function $F(\theta_1, \theta_2)$; swarm size N; iterations number N_{Iter}; acceleration constants c_1, c_2; minimum and maximum inertia weights w_{min}, w_{max}.

Output: optimal switching angles (θ_1, θ_2), a solution vector $G_{best} = (\theta_1, \theta_2)$ that minimizes $F(\theta_1, \theta_2)$.

Initialize:
$i_{ter} \leftarrow 0$
for each particle i = 1 **to** N **do**
Initialize position X_i randomly in search space [0, π/2].
Initialize velocity V_i to 0.
Evaluate fitness: $P^i_{best} \leftarrow F(X_i)$.
Set personal best: $P_i \leftarrow X_i$.
end for
Find global best: $G_{best} \leftarrow \mathrm{argmin}\, F(P_i)$
Optimization Loop:
while i_{ter} < max Iter **do**
for each particle i = 1 **to** N **do**
// update velocity and position

$V_{i+1} = ([V_i{\cdot}w] + [c_1{\cdot}r_1{\cdot}(P_{best} – X_i)]) + [c_2{\cdot}r_2{\cdot}(G_{best} – X_i)])$
$X_i \leftarrow X_i + V_i$
// apply position constraints: $0 < \theta_1 < \theta_2 < \pi/2$
if X_i violates constraints **then**
re-initialize X_i
end if
// Evaluate and update bests
if $F(X_i) < F(P_i)$ **then**
$P_i \leftarrow X_i$
if $F(P_i) < F(G_{best})$ **then**
$G_{best} \leftarrow P_i$
end if
end if
end for
$i_{ter} \leftarrow i_{ter} + 1$
end while
return G_{best}

In the PSO model, the search process is carried out by a population of interacting agents, referred to as particles. Each particle represents a candidate solution encoded as a parameter vector, and its motion within the search domain is governed by its velocity V_i and position X_i, both of which are initialized randomly. The initial position of a particle is considered its personal best P_{best}. After initialization, the quality of each particle is evaluated through the objective (fitness) function.

The global best solution G_{best} is identified by selecting the particle with the lowest fitness value among the swarm. Particle trajectories in the D-dimensional search space are updated based on 3 main components: the inertia weight, which regulates exploration; the cognitive term reflecting each particle's historical best performance P_{best}, and the social term guided by G_{best}. The velocity update for the (V_{i+1}) iteration follows the formulation given in (14), and the subsequent position update (X_{i+1}) is obtained using (15) [5]:

$$V_{i+1} = ([V_i{\cdot}w] + [c_1{\cdot}r_1{\cdot}(P_{best} – X_i)]) + [c_2{\cdot}r_2{\cdot}(G_{best} – X_i)]); \quad (14)$$

$$X_{i+1} = X_i + V_{i+1}. \quad (15)$$

The inertia weight is calculated as:

$$w = w_{\max} - j \cdot \left[\left(w_{\max} - w_{\min} \right) / N_{Iter} \right]. \quad (16)$$

Table 1 shows the setting of the PSO algorithm [5]. It is established in the literature that no definitive procedure or guideline exists for determining the parameters of metaheuristic algorithms. The parameter settings for metaheuristic optimization algorithms represent an optimization task in its own right. These parameters are typically tuned empirically or adapted dynamically to balance exploration and exploitation. The parameters typically recommended by researchers are $c_1 = c_2 = 2.05$, $w_{\min} = 0.4$, $w_{\max} = 0.9$. The literature review provides insight into the parameters that are nearly suitable. Additionally, the user may experiment with the parameters and analyze the outcomes, like we did in this study.

Table 1

The setting of PSO algorithm

Parameter	Symbol	Value
Swarm size	N	40
Iterations number	N_{Iter}	100
Number of variables	θ_1, θ_2, M	3
Limit intervals	θ_1	$\theta_1 \in [0, 90]$
	θ_2	$\theta_2 \in [0, 90]$
	M	$M \in [0.45, 0.85]$
The acceleration coefficients	c_1, c_2	2.05
Minimum inertia weight	$w_{\min}$	0.4
Maximum inertia weight	$w_{\max}$	0.9

Solving the SHE problem with GA algorithm. GA was first introduced as a model inspired by biological evolution. When set up adequately in a data space, GA is an effective method to solve optimization problems [19]. Optimization is the process of finding the best solution to a problem while keeping in mind a number of factors related to the system's properties and limitations. The genetic approach is employed to minimize (13) under the constraint of (10), allows for the determination of the optimal commutation angles. Algorithm 2 illustrates the GA pseudocode, delineating the method into 5 specific steps: 1) population initialization; 2) objective function evaluation; 3) selection; 4) crossover; 5) mutation.

Algorithm 2: GA pseudocode

Input: objective function $F(\theta_1, \theta_2)$. Population size. Maximum generations. Chromosome 3 (M, θ_1, θ_2) is the quantity of variables. Search spaces are the intervals limit. Encoding is binary with 10 bits per variable. Crossover type and its probability. Mutation type and its probability.
Output: optimal switching angles (θ_1, θ_2), the best individual that minimizes $F(\theta_1, \theta_2)$.
Initialize:
$g \leftarrow 0$ // Initialize generation counter.
Initialize $P(g)$ // Randomly generate initial population of N chromosomes.
for each chromosome i in $P(g)$ **do**
Decode chromosome to real values: $(\theta_1^i, \theta_2^i, M^i)$.
Evaluate fitness: $F_i \leftarrow F(\theta_1^i, \theta_2^i)$.
end for
Find best individual: ***Best*** $\leftarrow$ argmin$F(P(g))$.
Optimization Loop:
while $g < G_{\max}$ **do**
// Step 1: Selection (roulette wheel).
Create mating pool M_p by selecting N parents from $P(g)$ with probability proportional to fitness.
// Step 2: Crossover (random, $P_c = 1$).
for each pair of parents in M_p **do**
Perform random single-point crossover to produce two offspring.
Add offspring to offspring population $P_{offspring}$.
end for
// Step 3: Mutation (random, $P_m = 0.05$).
for each chromosome in $P_{offspring}$ **do**
for each bit in the chromosome **do**
if rand() $< P_m$ **then**
Flip the bit (0→1 or 1→0).
end if
end for
end for
// Form new generation & evaluate.
$P(g+1) \leftarrow P_{offspring}$ // new generation replaces the old.
for each chromosome i in $P(g+1)$ **do**
Decode chromosome to real values: $(\theta_1^i, \theta_2^i, M^i)$.
Evaluate fitness: $F_i \leftarrow F(\theta_1^i, \theta_2^i)$.
end for
// Update best solution
CurrentBest $\leftarrow$ argmin$F(P(g+1))$.
if F(*CurrentBest*) $<$ F(***Best***) **then**
Best $\leftarrow$ *CurrentBest*.
end if
$g \leftarrow g + 1$
end while
return ***Best***.

By using random processes to make new generations of solutions, the best one is chosen from a group of possible solutions. This method depends on 3 operators: selection, crossover and mutation, which are applied to the current population in order and repeated until a stopping point is reached [20].

The parameters of the GA are shown in Table 2. It is well-known in the literature that there is no method or rule for setting the parameters of metaheuristic algorithms. The found of these settings is, in fact, a problem on their own. It is possible to determine the range of optimum values by a literature review. Additionally, users can vary the parameters and compare the results, similar to the approach taken in this study.

Table 2

The parameters of the GA

Parameter	Value
Size of the population	50
Number of generations	100
Quantity of variables	3 (M, θ_1, θ_2)
Intervals limit	$\theta_1 \in [0, 90]$
	$\theta_2 \in [0, 90]$
	$M \in [0.1, 0.85]$
Number's length in binary	10
Selection	Roulette
Crossover	Random
Probability of crossover	100 %
Mutation	Random
Probability of mutation	5 %

Results discussion. The simulations were performed using the MATLAB/Simulink environment to execute the optimization algorithms. Figure 3 presents the switching angles θ_1 and θ_2 obtained using the NR, GA and PSO algorithms. As shown, all 3 methods converge to identical solutions for both switching angles over the modulation index M range 0.45–0.85. Therefore, we can primarily focus on the differences in implementation complexity and computational efficiency when evaluating these algorithms.

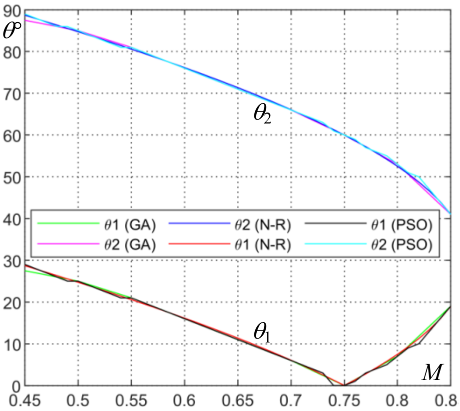

Fig. 3. The angles θ_1 and θ_2 versus M using the 3 algorithms

To demonstrate the effectiveness of the discussed SHE modulation technique and the proposed system, we performed 3 tests using different values of M for comparison purposes. In these tests 2 DC sources of 15 V are used. Table 3 displays the parameter settings in each of the 3 cases.

Table 3

Parameter settings to test the 5-level inverter

Test	Setting
Case 1	f = 1 kHz, M = 0.55, θ_1 = 21°, θ_2 = 81°
Case 2	f = 5 kHz, M = 0.65, θ_1 = 11°, θ_2 = 71°
Case 3	f = 10 kHz, M = 0.85, θ_1 = 19°, θ_2 = 41°

Simulation results. Figure 4 shows the simulation output voltage of the 5-level emerging inverter using SHE modulation in the 3 cases, and Fig. 5 – the simulation harmonic spectrum in this cases.

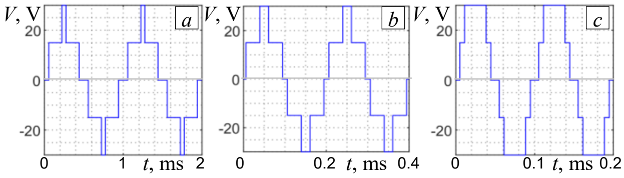

Fig. 4. The simulation output voltage of the 5-level inverter using SHE modulation: *a* – case 1; *b* – case 2; *c* – case 3

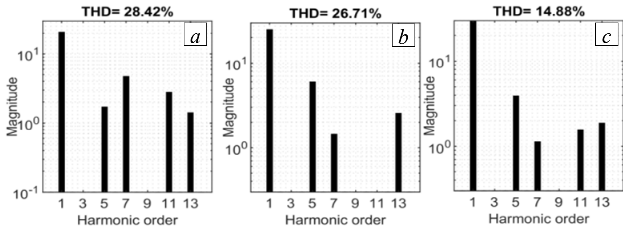

Fig. 5. The simulation harmonic spectrum of the inverter's output voltage: *a* – case 1; *b* – case 2; *c* – case 3

Across all 3 operating conditions, the 3[rd] harmonic and its multiples are effectively suppressed, confirming the success of the harmonic elimination strategy. In terms of overall distortion, the THD$_v$ of the output voltage is 28.42 % in case 1. This value decreases to 26.71 % in case 2 and is further reduced to 14.88 % in case 3, demonstrating a progressive improvement in waveform quality.

Experimental results. To validate the simulation results, experimental tests were conducted using an experimental prototype. Figure 6 shows photo of the experimental setup. An Arduino Mega 2560 chip is used to execute the SHE modulation code and generate the suitable gating signals. The harmonic spectrums are extracted using digital oscilloscope. The fluke power quality analyzer is used to measure the THD$_v$ values.

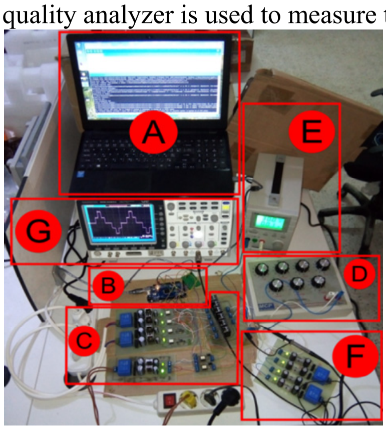

Fig. 6. Photo of the experimental setup:
A – PC with Arduino IDE software
B – Arduino Mega 2560 chip
C – 5-level inverter
D – resistive load
E, F – power supplies
G – oscilloscope

Figure 7 depicts the experimental output voltage of the 5-level emerging inverter using SHE modulation in case 1. Their associated harmonic spectrum is given in Fig. 8. The waveform results agree perfectly with the simulation results shown in Fig. 4,*a* and Fig. 5,*a*.

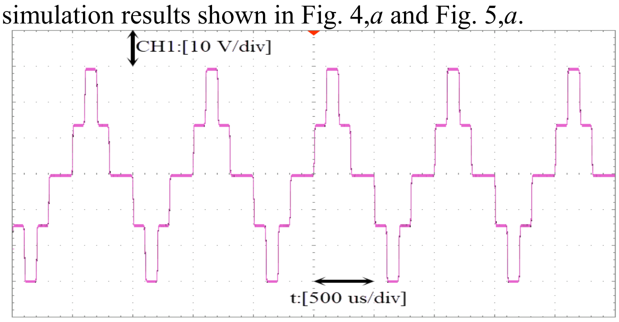

Fig. 7. The experimental output voltage of the 5-level inverter using SHE modulation in case 1

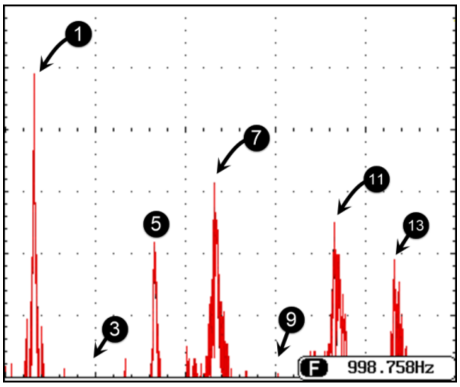

Fig. 8. The experimental harmonic spectrum
of the 5-level output voltage in case 1

Figure 9 depicts the experimental output voltage of the 5-level inverter using SHE modulation in case 2. Their associated harmonic spectrum is shown in Fig. 10. The waveform results agree perfectly with the simulation results shown in Fig. 4,*b* and Fig. 5,*b*.

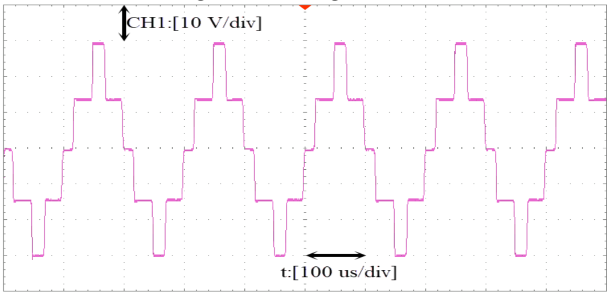

Fig. 9. The experimental output voltage
of the 5-level inverter using SHE modulation in case 2

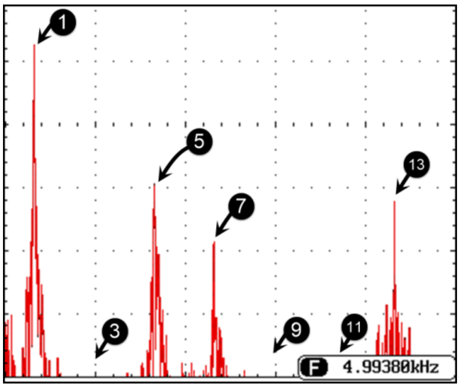

Fig. 10. The experimental harmonic spectrum
of the 5-level output voltage in case 2

Figure 11 displays the experimental output voltage of the 5-level inverter using SHE modulation in case 3. Their associated harmonic spectrum is given in Fig. 12. The waveform results agree perfectly with the simulation results shown in Fig. 4,*c* and Fig. 5,*c*.

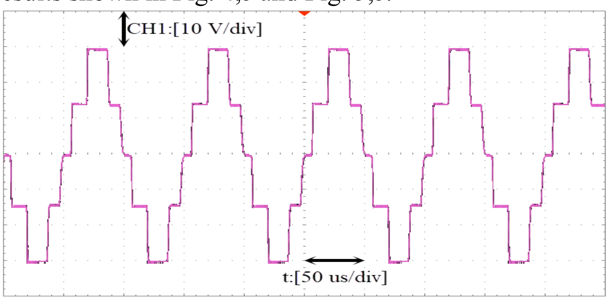

Fig. 11. The experimental output voltage
of the 5-level inverter using SHE modulation in case 3

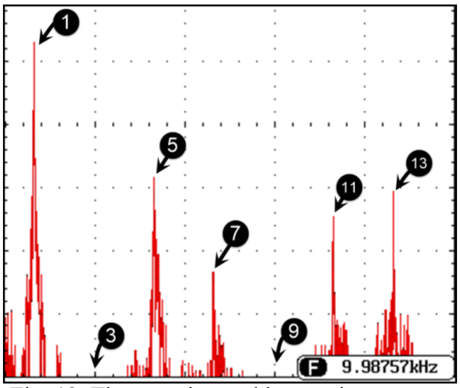

Fig. 12. The experimental harmonic spectrum
of the 5-level output voltage in case 3

Comparison of results. Figure 4 presents the simulated phase-voltage of the 5-level inverter for all 3 cases, while Fig. 7, 9, 11 show the corresponding measurements obtained from the experimental prototype. A comparison between both sets of results indicates a strong agreement, confirming the accuracy of the simulation model. Likewise, the harmonic analyses of the output voltage in all 3 cases exhibit close correspondence between the simulated and experimental spectra, as summarized in Table 4. In each operating condition, the 3rd harmonic and its multiples are effectively eliminated. These outcomes were achieved using a relatively simple implementation method, and the observed performance is consistent with results previously reported in [5, 21].

Table 4

THD_v comparison

Test	Simulation THD_v, %	Experimental THD_v, %
Case 1	28.42	29.7
Case 2	26.71	27.2
Case 3	14.88	15.1

Table 5 details the computation time necessary for finding the switching angles in each approach. The PSO-SHE necessitates 10.237 s, but the NR-SHE requires merely 0.516 s. The GA-SHE operates at a sluggish pace, necessitating 23.289 s.

Table 5

The execution time of the 3 algorithms

Method	The execution time, s
NR-SHE	0.516
PSO-SHE	10.237
GA-SHE	23.289

In fact, all 3 methods are able to produce valid switching angles for the SHE problem. However, their performances are significantly different regarding execution time, complexity, and interpretability. The NR method is the most rapid and computationally efficient approach due to the use of a deterministic numerical scheme. Indeed, its main advantage is that the associated solution process is fully interpretable: it naturally yields clear convergence behavior based on the Jacobian and nonlinear equations. However, NR requires a good initial guess and may fail to converge for some values of the modulation index, hence limiting its robustness.

On the other hand, PSO and GA are metaheuristic algorithms that search globally within the solution space. No starting values are needed which are close to the final solution. Therefore, they are more robust on problematic or multi-modal harmonic equations. However, metaheuristic methods behave like «black box» optimizers. Therefore, from an analytical point of view, they do not supply any insight in how the solution is reached, whereas their internal search dynamics are less interpretable than in NR methods. In general, the execution times are longer and parameters require careful tuning.

Overall, while the NR method is attractive because of its speed and interpretability, PSO and GA offer superior flexibility and robustness, especially when the harmonic elimination problem becomes highly nonlinear.

Conclusions.

1. This work focused on reducing output voltage harmonic distortion and determining optimal switching angles for a single-phase 5-level emerging inverter using 3 approaches: numerical (NR), evolutionary (GA) and metaheuristic (PSO). All approaches successfully achieved harmonic reduction and converged to the same switching angle solutions across the tested modulation indices, confirming the validity of the mathematical formulation and the reliability of the optimization process.

2. Simulation results showed that the 3rd harmonic and its multiples were effectively eliminated for all operating conditions. THD of the output voltage reduced progressively with frequency and modulation indices, decreasing from 28.42 % at (M = 0.55, f = 1 kHz) to 14.88 % at (M = 0.55, f = 10 kHz). These results demonstrate the effectiveness of SHE in reducing harmonic distortion and enhancing waveform quality in reduced-switch 5-level inverter topologies.

3. Numerical results show clear performance differences among the 3 methods. NR-SHE is the fastest (0.516 s) due to its deterministic structure, while PSO-SHE (10.237 s) and GA-SHE (23.289 s) require significantly longer times because of their search mechanisms. Thus, NR offers the best computational efficiency, whereas PSO and GA provide higher robustness for complex or highly nonlinear modulation indices. Methodologically, NR is interpretable and offers predictable convergence but depends on a good initial guess. In contrast, PSO and GA require no initial solution and explore the search space, improving robustness at the expense of longer execution times and less transparency in how the solution is obtained.

4. An Arduino Mega 2560 platform was employed to implement the optimized switching patterns, highlighting the feasibility of using low-cost open-source hardware for experimental validation and educational purposes. The measured waveforms and harmonic spectra closely matched the simulation results, thereby confirming the accuracy of the discussed numerical, evolutionary, and metaheuristic methods, as well as the practical reliability of the proposed inverter design.

5. The future works will focus on the integration of hybrid optimization schemes that combine the speed of deterministic methods with the global search capability of metaheuristics, enabling faster computation of switching angles while maintaining robustness against nonlinearities. Additionally, extending the inverter topology to higher-level or modular multilevel configurations may yield improved output waveform quality and reduced harmonic content. Implementing the optimization and control algorithms on high performance embedded platforms such as digital signal processors, field-programmable gate arrays processors can further accelerate computation time. Finally, this work opens pathways for applying the proposed approach to related energy conversion systems, including alternative converter structures and renewable energy based applications. Future studies may integrate photovoltaic, wind or hybrid solar-wind sources to develop sustainable, high performance power electronic systems optimized for modern energy infrastructures.

Conflict of interest. The authors declare that they have no conflicts of interest.

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