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Genetic Algorithm-Based Optimization of Switching Angles in Inverter for Selective Harmonic Elimination

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Seçici Harmonik Giderimi için İnverterdeki Anahtarlama Açılarının Genetik Algoritma Tabanlı Optimizasyonu

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Öz

Modern elektrik sistemlerinde güç elektroniği dönüştürücülerinin artan entegrasyonu, harmonik bozulma ve genel güç kalitesi konusundaki endişeleri artırmıştır. Bu endişeler özellikle hassas veya kritik yüklerin bulunduğu sistemlerde verimliliği, güvenilirliği ve dinamik kararlılığı olumsuz etkilemektedir. Bu sorunlara çözüm olarak, bu çalışmada gerilim kaynaklı eviriciler (VSI) için genetik algoritma (GA) tabanlı yeni bir kontrol yöntemi kullanan seçici harmonik elimine etme (SHE) tekniği önerilmektedir. Önerilen GA tabanlı kontrol yöntemi, temel bileşeni korurken belirli düşük mertebeli harmonikleri yok etmek amacıyla, temel genlik sabit tutulacak ve anahtarlama açıları çeyrek dalga simetrisi altında 0°–90° aralığında kalacak şekilde en uygun anahtarlama açılarını belirlemektedir. SHE yönteminde yer alan doğrusal olmayan transandantal denklemler önemli hesaplama zorlukları oluşturmaktadır. Newton–Raphson (NR) gibi geleneksel yöntemler doğru başlangıç değerlerine ihtiyaç duymakta ve yakınsama koşullarına duyarlıdır. Buna karşın, önerilen GA tabanlı kontrol yöntemi başlangıç değerine ihtiyaç duymadan daha güvenilir bir global optimizasyon süreci sunmaktadır. Önerilen kontrol tekniği MATLAB/Simulink ortamında modellenmiş ve simülasyonları gerçekleştirilmiştir. Elde edilen sonuçlar NR yöntemiyle karşılaştırılmıştır. Hem GA hem de NR yöntemleri başarıyla yakınsamış ve hedeflenen harmonikleri etkin biçimde yok etmiştir; ancak GA tabanlı kontrol yöntemi, başlangıç değerine ihtiyaç duymadan daha iyi bir yakınsama davranışı göstermiştir.

Anahtar Kelimeler: *Genetik Algoritma; Seçici Harmoniklerin Giderilmesi Darbe genişliği modülasyonu; İnverter;Toplam Harmonik Bozulma*

Abstract

The increasing integration of power electronic converters in modern electrical systems has raised growing concerns about harmonic distortion and overall power quality, which negatively impact efficiency, reliability, and dynamic stability, especially in systems with sensitive or critical loads. To address these issues, this study presents a selective harmonic elimination (SHE) technique for voltage source inverters (VSI) using a new control method based on a genetic algorithm (GA). The proposed GA-based control determines the optimal switching angles to retain the fundamental component while eliminating specific lower-order harmonics, under constraints such as maintaining a fixed fundamental amplitude and keeping switching angles within 0°–90° under quarter-wave symmetry. The nonlinear transcendental equations in SHE presents significant computational challenges. Traditional methods like Newton–Raphson (NR) require accurate initial guesses and are sensitive to convergence conditions. In contrast, the proposed GA-based control eliminates the need for an initial guess and provides a more reliable global optimization process. MATLAB/Simulink simulations were conducted to implement and evaluate the proposed control technique, and the results were compared with those obtained using NR. Both GA and NR successfully converged and effectively eliminated the targeted harmonics; however, the GA-based control demonstrated improved convergence behaviour without relying on an initial guess.

Keywords: *Genetic Algorithm; Selective Harmonics Elimination Pulse width modulation; Voltage Source Inverter; Total Harmonic Distortion*

1. Introduction

The power grid is experiencing a decline in power quality due to the increasing use of nonlinear loads.(Htita et al. 2024; Kalair et al. 2017), such as inverters (Taghvaie et al., 2023), rectifiers (Page 1958), motor drives (Jamil et al. 2007), electric arc ovens (Srivastava and Singh, 2019), and lighting ballasts (Mrabet et al. 2018), which has a detrimental effect (Khajeh et al. 2020) on the utility grid due to harmonic production (Chan et al. 2012; Rice 1986). This problem can cause (Desai et al. 2016) voltage flicker, excessive heating of transformers, and failure of protection devices in electric grids (Levačić et al. 2018) which causes negative impacts on power transmission, increases energy costs, and results in penalties for customers. Eliminating harmonics is crucial to avoid fines, higher energy costs, and damage to equipment. (Gadgil et al. 2022; Li et al. 2020) (Rai and Chakravorty 2020). SHE is a technique used in power electronics to produce pulse-width modulation patterns that eliminate specific harmonics. SHE can enhance the overall power quality of

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the power system by curtailing distortion and maintaining a high-power factor. Furthermore, SHE controls the amplitude of the fundamental frequency component while removing certain lower-order harmonics from the output voltage spectrum. This is accomplished by adjusting a set of firing angles for the power semiconductor components of the inverter within each fundamental cycle. SHE techniques use different modulation strategies (Ali et al. 2024; Subramanian and Albert Alexander 2024) like pulse width modulation, phase disposition (Zhou et al. 2023), and phase opposition disposition (Zhang et al. 2024) to eliminate lower-order harmonics in a multilevel inverter (Teja 2021).

Selective Harmonics Elimination Pulse Width Modulation (SHEPWM) is a control method used for eliminating low-order harmonics in output waveforms by calculating the firing angles of inverter switches. SHEPWM is based on the Fourier series, which provides the expansion of harmonic contents in the form of a set of nonlinear transcendental equations used to calculate these firing angles. However, due to the difficulty of solving a set of non-linear transcendental equations, several methods are introduced, such as Newton-Raphson (Antonenko and Maklakov 2023), and evolutionary algorithms (EA) (El-Naggar and Abdelhamid 2008; Salehi et al. 2011), EA algorithms include Imperialist Competitive Algorithm (ICA) (Reza Mohammadi et al. 2012), and genetic algorithm (GA), these EAs have been proven efficient in solving these non-linear equations. The EAs use fitness functions containing transcendental equations of fundamental and lower-order harmonics to minimise the fitness function for optimum firing angles and achieve a low total harmonic distortion. The ICA is an evolutionary algorithm that starts with an initial population and assigns each country to a colony. The best countries are chosen as imperialist states, and the rest form colonies. The colonies are divided among these imperialists based on their power, with each country's power inversely proportional to its cost. Moreover, GA mimics natural selection and evolutionary behaviour.

This paper introduced a new control technique for a three-level voltage source inverter using a genetic algorithm. The performance of the proposed method is verified using MATLAB/Simulink. The proposed method, based on the genetic algorithm, provides an alternative solution for the SHE problem without requiring initial conditions and ensures guaranteed convergence through the new control technique. The performance of proposed method is compared with Newton-Raphson method for solving the SHE problem. The paper structure is organised as follows. In Section 2, the methodology, including SHEPWM, Newton-Raphson, and genetic algorithm, is discussed. In Section 3, the simulation and results are presented. In Section 4, the conclusion is given.

2. Methodology

The primary objective is to suppress harmonic distortion and ensure that the THD remains within acceptable limits, by established power quality standards—most notably IEEE Standard 519 (519-2022 – *IEEE Standard for Harmonic Control in Electric Power Systems*). This standard prescribes stringent constraints on both the aggregate THD and the amplitudes of individual harmonic components that may be injected into the power grid or delivered to end-use loads. THD serves as a crucial metric, quantifying the overall deviation of a waveform from a pure sinusoid. Minimising THD and suppressing specific, often lower-order, harmonics (like the 3rd, 5th, 7th, 11th, 13th, etc.) is a primary objective in inverter design and control. Various modulation strategies are developed to shape the inverter output waveform and control its harmonic content. These broadly fall into two categories (Ghosh et al. 2017): high-switching-frequency techniques, such as Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Modulation (SVM), and low-switching-frequency control methods.

Among the low-switching-frequency control methods, SHE stands out as a powerful technique, particularly advantageous in medium-voltage and high-power applications where minimising switching losses is critical. Unlike high-frequency PWM, which shifts harmonics to higher frequencies that are easier to filter, SHE aims to directly eliminate specific lower-order harmonics from the output voltage spectrum while simultaneously controlling the amplitude of the fundamental frequency component. This is achieved by precisely determining a set of switching angles for the inverter's power semiconductor devices within each fundamental cycle. The output waveform, typically a staircase waveform in multilevel inverters or a stepped waveform in three-level inverters, is constructed based on these pre-calculated angles. The primary advantage of SHE lies in its ability to achieve excellent harmonic performance with a minimal number of switching events per cycle, thereby significantly reducing switching losses and improving overall inverter efficiency. (Hosseinzadeh et al. 2019; El Houda Gabour et al. 2021).

2.1 SHEPWM for Single-phase three-level inverter

The fundamental principle of SHEPWM relies on the Fourier series theory, which states that any periodic waveform can be represented as a sum of sinusoidal components, including the fundamental frequency and its

harmonics. By carefully choosing the instants at which the inverter switches turn on and off within a fundamental period, the harmonic content of the output waveform can be controlled. In SHEPWM, these switching instants, represented as angles (α_1, α_2, ..., α_N), are calculated such that the amplitudes of specific undesired harmonics become zero, and the amplitude of the fundamental component matches a desired reference value. The number of harmonics that can be eliminated (N-1) is directly related to the number of switching angles per quarter cycle (N) that can be independently controlled. In three-level single-phase voltage source inverters, there are three possible output waveform states: positive, negative, and zero. Figure 1 shows a generalised three-level inverter. SHEPWM waveform using a five-angle firing scheme in a quarter-wave symmetry waveform is demonstrated in Figure 2. Five cuts are made to the output waveform every quarter cycle. This allows elimination up to 4 harmonics while controlling the fundamental component according to the modulation index (m_i). SHEPWM offers fine control over the harmonic spectrum of voltage and current waveforms generated by DC to AC inverters.

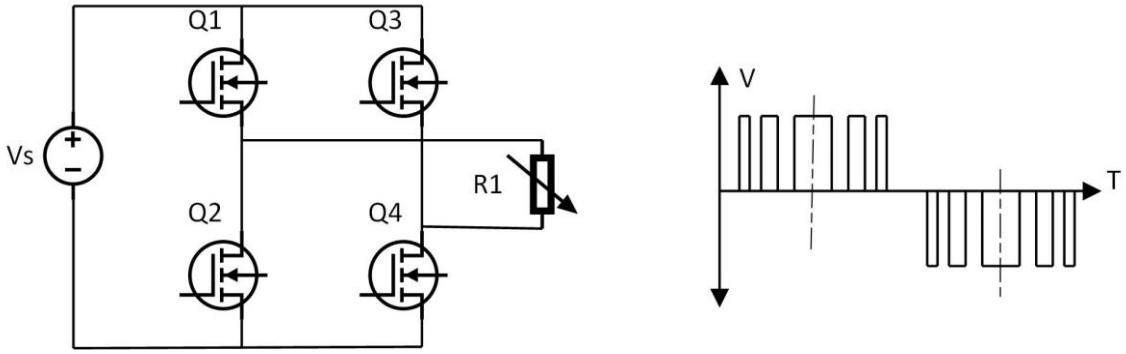


Figure 1. Single-phase three-level inverters with SHEPWM

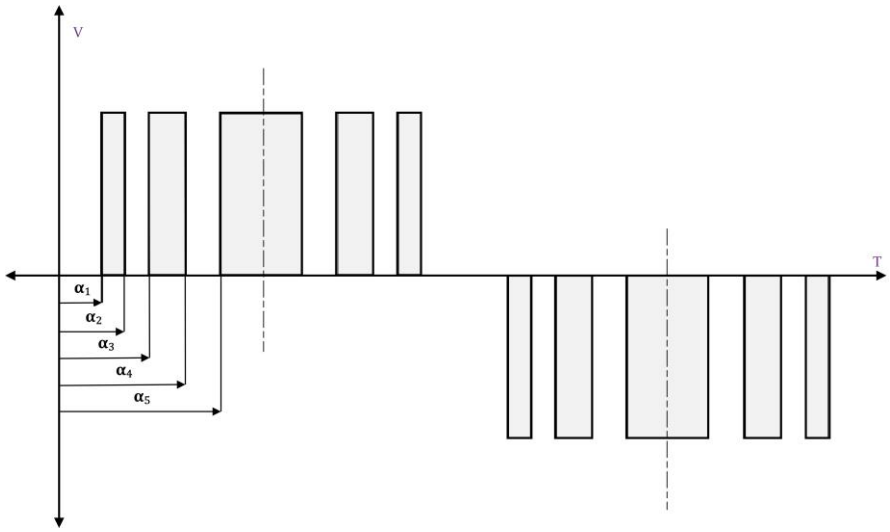


Figure 2. Quarter-wave symmetry SHEPWM 5-angle firing scheme

2.2 Newton-*Raphson Method*

In quarter-wave symmetrical waveforms, only the cosine terms of odd harmonics are present. In half-wave symmetrical waveforms, both sine and cosine terms of odd harmonics are present. In non-symmetrical waveform formulations, all odd and even harmonics, as well as a DC component, need to be controlled. In this study, quarter-wave symmetry is employed, allowing control over the output within a quarter cycle. Equations are set to eliminate lower-order harmonics while maintaining the fundamental component at a specific value. According to the quarter-wave symmetry 5-angle firing scheme shown in Figure 2. A general formula is derived to calculate the fundamental and harmonic components stated in Equation (1).

$$V_n = \frac{4V_{DC}}{n\pi}(cos(n\alpha_1) - cos(n\alpha_2) + cos(n\alpha_3) - cos(n\alpha_4) + cos(n\alpha_5)) \quad (1)$$

where V_n is the n^{th} harmonic voltage α_1, α_2, α_3, α_4, α_5 are the calculated switching angles.

In this study, the 3rd, 5th, 7th, and 9th order harmonics is eliminated. For the magnitude of the fundamental

voltage (n=1), Equation (2) is used for calculating the fundamental component. The Equations (3) to (6) are derived based on Equation (1) to calculate the magnitude of the 3rd, 5th, 7th, and 9th order harmonics, respectively.

$$V_1 = \frac{4V_{DC}}{\pi}(cos(\alpha_1) - cos(\alpha_2) + cos(\alpha_3) - cos(\alpha_4) + cos(\alpha_5)) = m_i V_{DC} \quad (2)$$

$$V_3 = \frac{4V_{DC}}{3\pi}(cos(3\alpha_1) - cos(3\alpha_2) + cos(3\alpha_3) - cos(3\alpha_4) + cos(3\alpha_5)) = 0 \quad (3)$$

$$V_5 = \frac{4V_{DC}}{5\pi}(cos(5\alpha_1) - cos(5\alpha_2) + cos(5\alpha_3) - cos(5\alpha_4) + cos(5\alpha_5)) = 0 \quad (4)$$

$$V_7 = \frac{4V_{DC}}{7\pi}(cos(7\alpha_1) - cos(7\alpha_2) + cos(7\alpha_3) - cos(7\alpha_4) + cos(7\alpha_5)) = 0 \quad (5)$$

$$V_9 = \frac{4V_{DC}}{9\pi}(cos(9\alpha_1) - cos(9\alpha_2) + cos(9\alpha_3) - cos(9\alpha_4) + cos(9\alpha_5)) = 0 \quad (6)$$

In the Newton-Raphson method, first an initial guess is assumed, second the Jacobian matrix is calculated using equation (8); finally, the angles are substituted in equation (7) to solve for the angles in each iteration.

$$\begin{bmatrix}\propto_1\\ \propto_2\\ \propto_3\\ \propto_4\\ \propto_5\end{bmatrix} = \begin{bmatrix}\propto_{1o}\\ \propto_{2o}\\ \propto_{3o}\\ \propto_{4o}\\ \propto_{5o}\end{bmatrix} - [J]^{-1} \times \begin{bmatrix}V_1\\ V_3\\ V_5\\ V_7\\ V_9\end{bmatrix} \quad (7)$$

$$J = \begin{bmatrix} \frac{\partial V_1}{\partial \alpha_1} & \frac{\partial V_1}{\partial \alpha_2} & \frac{\partial V_1}{\partial \alpha_3} & \frac{\partial V_1}{\partial \alpha_4} & \frac{\partial V_1}{\partial \alpha_5} \\ \frac{\partial V_3}{\partial \alpha_1} & \frac{\partial V_3}{\partial \alpha_2} & \frac{\partial V_3}{\partial \alpha_3} & \frac{\partial V_3}{\partial \alpha_4} & \frac{\partial V_3}{\partial \alpha_5} \\ \frac{\partial V_5}{\partial \alpha_1} & \frac{\partial V_5}{\partial \alpha_2} & \frac{\partial V_5}{\partial \alpha_3} & \frac{\partial V_5}{\partial \alpha_4} & \frac{\partial V_5}{\partial \alpha_5} \\ \frac{\partial V_7}{\partial \alpha_1} & \frac{\partial V_7}{\partial \alpha_2} & \frac{\partial V_7}{\partial \alpha_3} & \frac{\partial V_7}{\partial \alpha_4} & \frac{\partial V_7}{\partial \alpha_5} \\ \frac{\partial V_9}{\partial \alpha_1} & \frac{\partial V_9}{\partial \alpha_2} & \frac{\partial V_9}{\partial \alpha_3} & \frac{\partial V_9}{\partial \alpha_4} & \frac{\partial V_9}{\partial \alpha_5} \end{bmatrix} \quad (8)$$

where J is the Jacobian matrix

$\propto_1, \propto_2, \propto_3, \propto_4, \propto_5$ are the calculated firing angles. $\propto_{1o}, \propto_{2o}, \propto_{3o}, \propto_{4o}, \propto_{5o}$ are the previous values of the angles (or initial guess for the first iteration)

The Newton–Raphson method (He, 2000; Mehtre et al., 2019) can suffer from some convergence issues (He, 1999). It is only locally convergent, so it can fail or slow down if the initial guess is not very close to a true solution. In practice, this means the Newton–Raphson solution may converge very slowly or diverge entirely for the nonlinear SHE equations when the starting angles are not well chosen. In highly nonlinear SHE equations, this sensitivity means Newton-Raphson often converges only with great difficulty or many iterations, especially near critical operating points. Newton–Raphson's convergence is very fast when very close to the root, but Newton–Raphson can stall or fail if the Jacobian is singular, or the function is nearly flat. Hence, the conversion of the solution depends on the initial guess.

2.3 Genetic algorithm

The genetic algorithm is used with selective harmonic elimination to calculate the optimum firing angles for the inverter. These angles must satisfy the condition of eliminating lower-order harmonics while achieving the desired modulation index for the fundamental component of the output waveform. Many research was conducted on genetic algorithms (El-Naggar & Abdelhamid, 2008; Hosseinzadeh idr., 2019; Ramkumar idr., 2011; Salehi idr., 2011; W. Zhang idr., 2014) over the last thirty years. The process of natural evolution is modelled by a GA. It is common practice to apply this heuristic to produce practical answers to search and optimisation issues. In binary encoding, GA represents each candidate solution as a binary string, referred to as a chromosome, where each bit (or group of bits) corresponds to a gene. A collection of such chromosomes constitutes the population. Every set of parameters is converted into a fixed-length string symbol sequence, typically from the binary bits, and concatenated to form a whole string known as a chromosome. A full string known as a chromosome is created by concatenating each parameter set, which is encoded into a sequence of fixed-length string symbols, often from the binary bits. Following their sequential extraction from the concatenated text, substrings of a certain length are decoded and mapped into the value in the associated search space. GA are a subclass of EA, this is family of algorithms that use natural evolution-inspired methods, including inheritance, mutation, selection, and crossover, to solve optimisation issues. Figure 3 shows the flowchart for the genetic algorithm.

The genetic algorithm flowchart starts by generating an initial population of possible solutions (called chromosomes or individuals). Each chromosome represents a potential solution — for SHE, this means a set of switching angles. These are randomly generated within the defined constraints. The next stage is calculating the fitness value for each individual in the population. The fitness function measures how well the solution satisfies the objectives of eliminating specific harmonics and controlling the fundamental component. The selection process is used to select individuals (parents) for reproduction based on fitness values. Fitter individuals have a higher probability of being selected. Common selection methods: tournament selection, roulette wheel, and rank selection. Rank selection method is used in this paper. The selection is followed by

crossover (or Recombination), the combined parts of two parent chromosomes are used to create new offspring, which promotes the exchange of good features. Crossover occurs with a defined probability (e.g., 90%). Mutation is made by applying small random changes to individual genes (angle values) to maintain diversity in the population. Mutation occurs with a low probability (e.g., 1%–10%). After mutation termination condition is checked if one of the stopping conditions is met which they are maximum number of generations reached, or Fitness function converges (solution does not improve significantly), this is determined by the function tolerance parameter. if the condition is not met the algorithm recreate a new population by replace the old population with the new offspring. Elitism strategy is used by keeping the best individuals from the previous generation. Then go back to evaluate the new population. If the terminating condition is met, the algorithm ends and outputs the best solution found. Table 1 shows the genetic algorithm parameters that are used in this study.

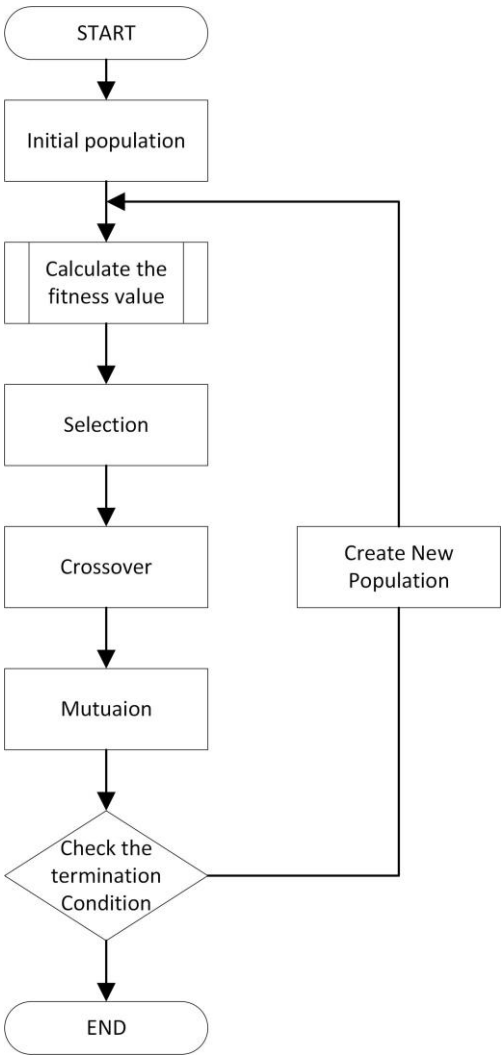


Figure 3. Genetic algorithm flowchart

Table 1. Genetic algorithm parameters

Parameter	Value
Population size	100
Max. Generations	500
Function Tolerance[a]	0.0001

[a]; The algorithm stops if the average relative change in the best fitness function value over Max Generations is less than or equal to function tolerance.

Equation 9 shows the general fitness function formula for the genetic algorithm to control the fundamental component and to eliminate the targeted harmonics V_3, V_5, V_7, V_9.

$$F = (V_1 - m_i V_{DC})^2 + {V_3}^2 + {V_5}^2 + {V_7}^2 + {V_9}^2 \quad (9)$$

where F is the fitness value m_i is the modulation index for the fundamental component

2.4 Optimisation for calculating the angles with the genetic algorithm

A modification in the control technique for calculating the firing angles is discussed to ensure fast convergence. As previously discussed in Section 2.2, the firing angles must satisfy the following condition, as illustrated in Figure 2.

$$\propto_1 < \propto_2 < \propto_3 < \propto_4 < \propto_5 < 90° \quad (10)$$

Using this constraint will lead to several problems, including infeasible solutions and delays to convergence. By modifying the controlling scheme, where each angle is calculated in terms of the previous angle, this helps in decreasing the range of the constraints for the genetic algorithm and eliminates infeasible solutions, which leads to fast convergence.

$$\alpha_1 = \beta_1 \quad (11)$$

$$\alpha_1 = \beta_1 + \beta_2 \quad (12)$$

$$\alpha_1 = \beta_1 + \beta_2 + \beta_3 \quad (13)$$

$$\alpha_1 = \beta_1 + \beta_2 + \beta_3 + \beta_4 \quad (14)$$

$$\alpha_1 = \beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 \quad (15)$$

Equations 11 to 15 express the classical control technique for firing angles α in terms of the modified firing angles β. The control technique using modified firing angles β is subject to the following constraints, as shown in equations 16 to 20, where the sum of all these firing angles is less than 90°.

$$20° < \beta_1 < 30° \quad (16)$$

$$0° < \beta_2 < 15° \quad (17)$$

$$10° < \beta_3 < 30° \quad (18)$$

$$0° < \beta_4 < 30° \quad (19)$$

$$0° < \beta_5 < 30° \quad (20)$$

Figure 4 shows the proposed control scheme for the firing angles. In the proposed firing scheme, the angles are referenced to the previous angle with limited constraints, which helps eliminate unwanted solutions and converge quickly to feasible solutions. Figures 5 and 6 demonstrate the control diagram using the new control technique.

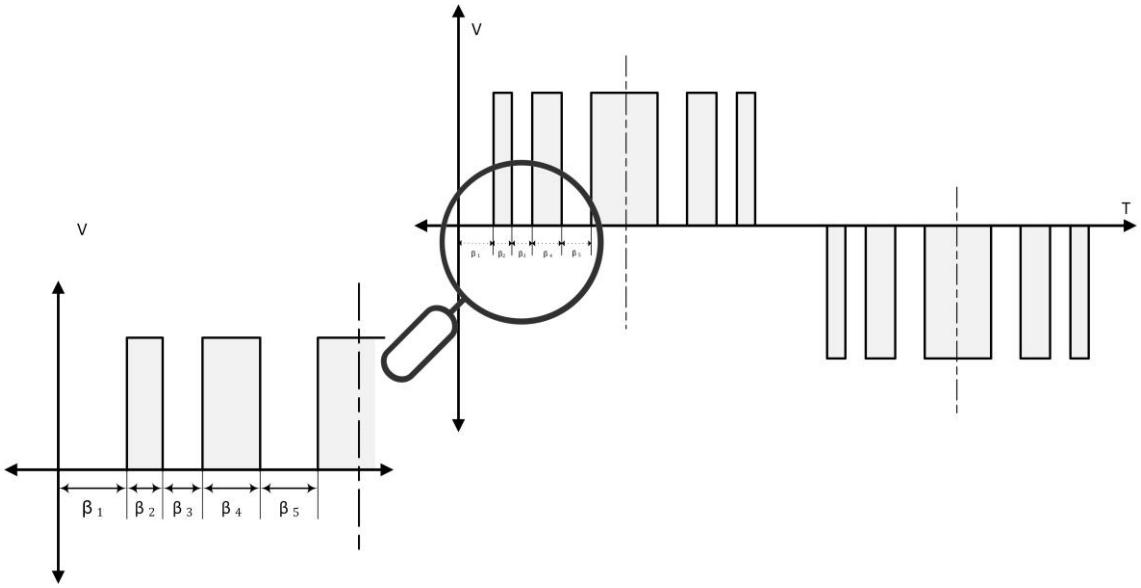


Figure 4. Proposed control technique with a new firing scheme for angles

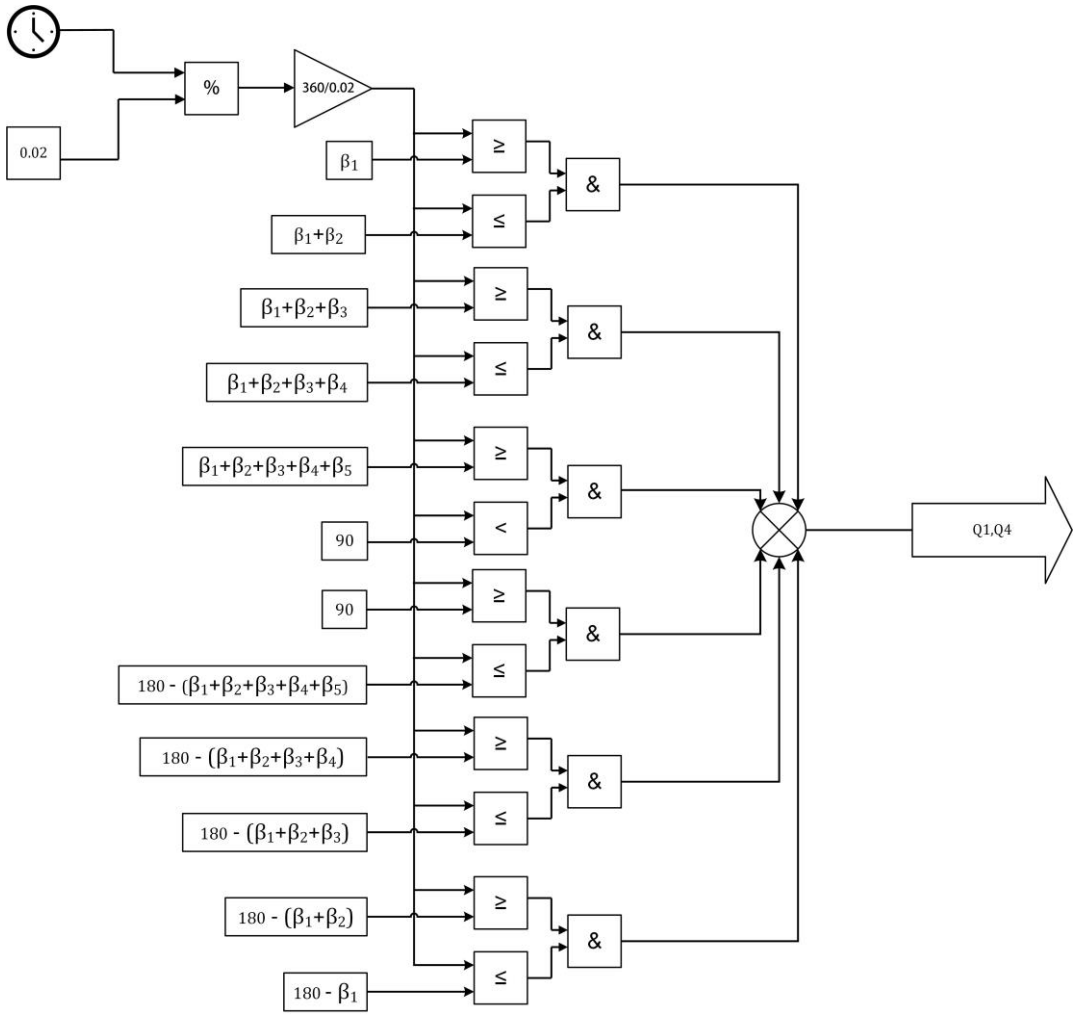


Figure 5. Control diagram of the transistors Q1, Q4

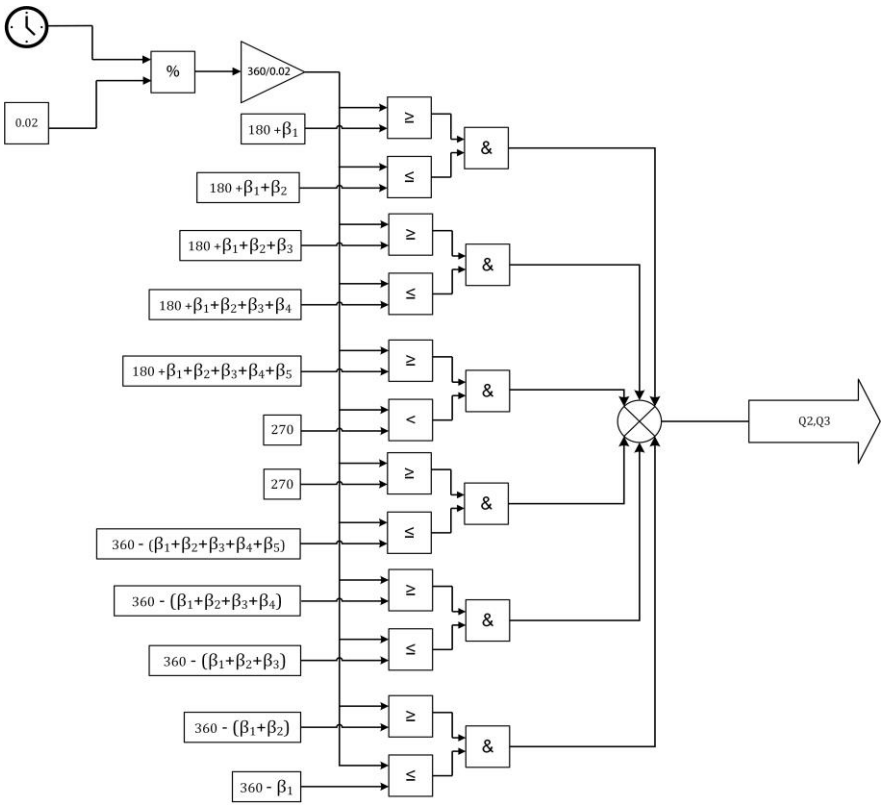


Figure 6. Control diagram of the transistors Q2, Q3

3. Simulation and Results

To evaluate the effectiveness of the GA for SHE with pulse width modulation, MATLAB Simulink is used for simulation; a single-phase inverter operating with five switching angles per quarter cycle is simulated to eliminate the 3rd, 5th, 7th, and 9th harmonics and control the fundamental component output. The performance of proposed GA based method is compared with Newton-Raphson method. The block diagram for the simulation model is shown in Figure 7.

The system includes a DC source that provides the required DC link voltage for the inverter. Power Inverter converts DC to AC using the gate signals. H-bridge is used with a single-phase three-level output.

An L-C filter is used to eliminate higher-order harmonics and improve the THD. The resistive load is used in this study. FFT & Harmonic Analyser (Feedback Loop) measures the harmonic content and THD in real-time. It provides feedback error to refine or optimise angles using a genetic algorithm. GA optimizes the switching angles that achieve the desired harmonic profile. The optimal set of switching angles (α_1, α_2, ..., α_n) is generated and sent to the PWM controller. The PWM generator converts switching angles into gate signals. Using the optimized angles, the PWM generator produces gating signals for the inverter switches to achieve the desired output voltage waveform.

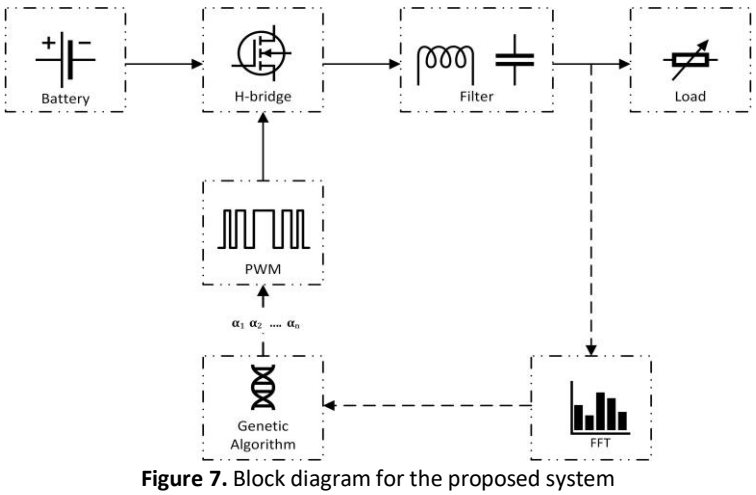


Figure 7. Block diagram for the proposed system

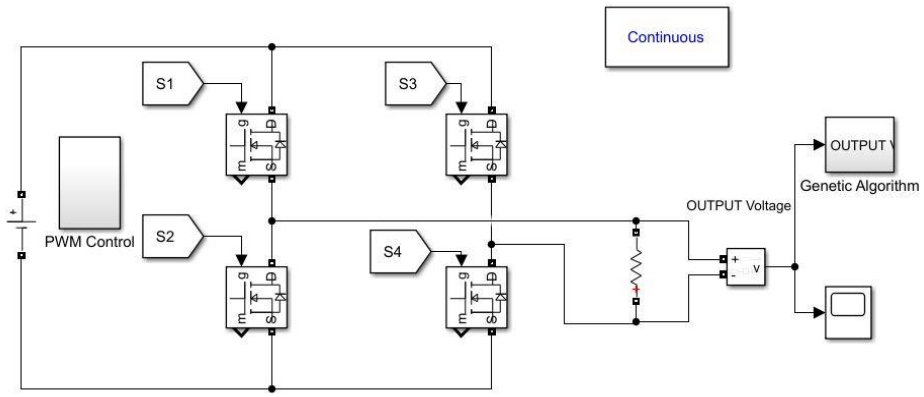


Figure 8. MATLAB Simulink simulation setup

3.1 Simulation Setup

Figure 8 illustrates the MATLAB/Simulink simulation of the proposed system using the genetic algorithm with the optimisation of firing angles.

Table 2. Simulation parameters

Parameter	Value
DC Bus Voltage (V_{dc})	325 V
Fundamental Frequency	50 Hz
Number of Angles	5 angles per quarter cycle
Selected harmonics for elimination	3^{rd} ,5^{th}, 7^{th}, 9^{th}
Population Size	100
Max no. of Generations	500
Function Tolerance	0.0001
Modulation index	0.1- 1
Resistance	100 Ω

The simulation was performed for each modulation index to ensure the elimination of 3^{rd}, 5th, 7th, and 9^{th} harmonics using the parameters shown in Table 2. The results for $m_i = 1$, $m_i = 0.5$ and $m_i = 0.1$ are provided. The output waveform with different modulation indices is shown in Figures 9,10, and 11. The output waveform maintains the quarter-wave symmetry, which is discussed previously in section 2.1. The fitness function depends on the magnitude of the fundamental component, with the desired modulation index and the magnitude of each selected harmonic for elimination, according to the fitness function was shown in Equation (9) in Section 2.3.

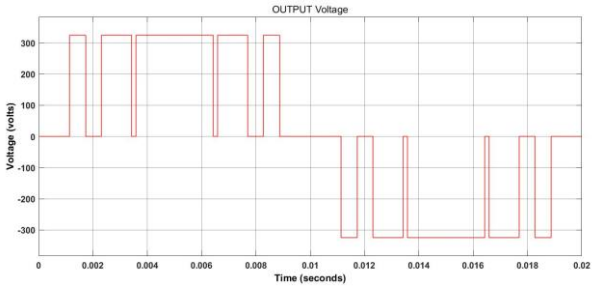


Figure 9. Output voltage waveform with mi=1

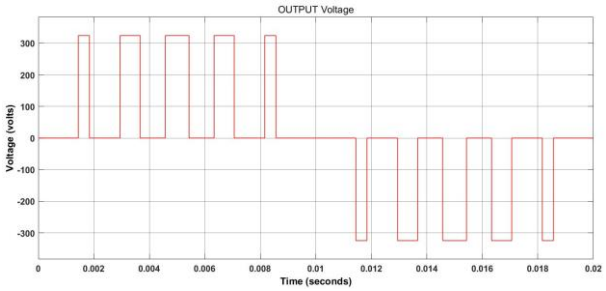


Figure 10. Output voltage waveform with mi=0.5

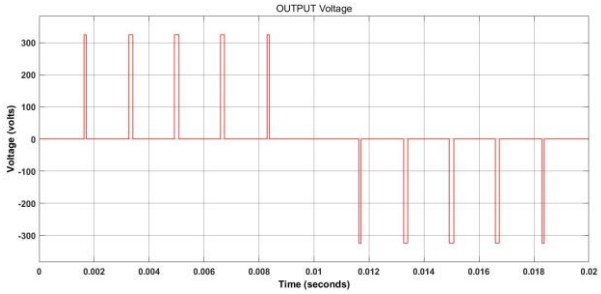


Figure 11. Output voltage waveform with mi=0.1

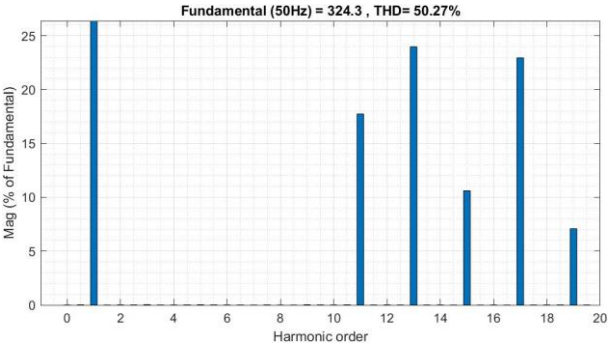


Figure 12. FFT using genetic algorithm with mi=1

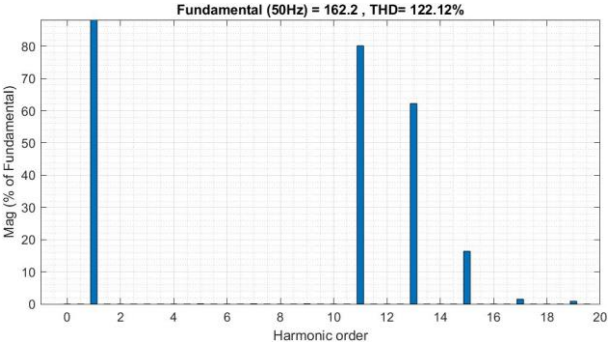


Figure 13. FFT using genetic algorithm with mi=0.5

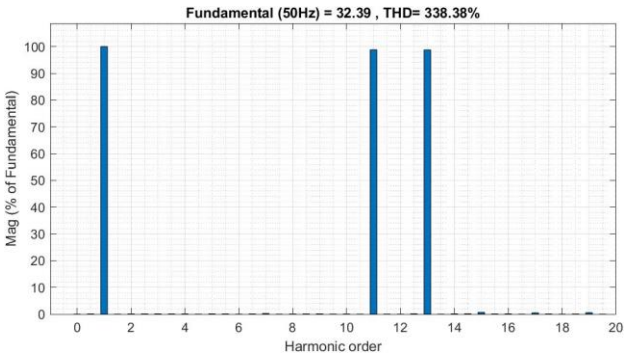


Figure 14. FFT using genetic algorithm with mi=0.1

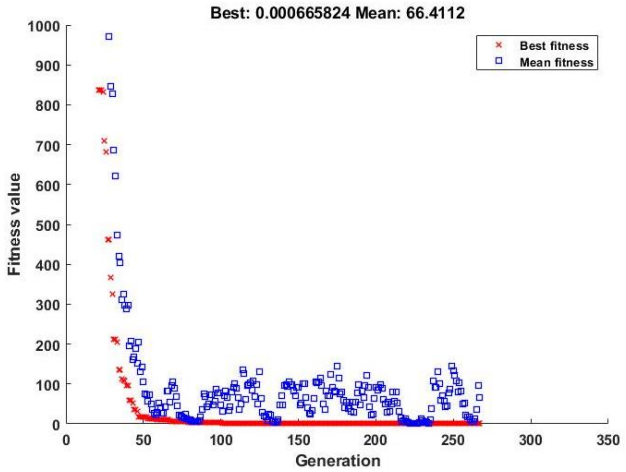


Figure 15. Genetic algorithm convergence with mi=0.1, best fitness value = 0.000665824

The genetic algorithm successfully converged to an optimal solution for the switching angles in less than 500 generations. The results of the FFT output, as shown in Figures 12, 13, and 14, confirm that the selected harmonic components (3^{rd},5^{th},7^{th}, and 9^{th}) are eliminated with each modulation index. The final cost function value is close to zero. The convergence behaviour of the genetic algorithm shown in Figures 15,16, and 17 demonstrates a rapid reduction in fitness values within the first 50 generations. This confirms the algorithm's efficiency in exploring the solution space and converging to the global optimum. Overall, the GA-based SHE approach demonstrated high accuracy, robustness, and adaptability across varying operating conditions.

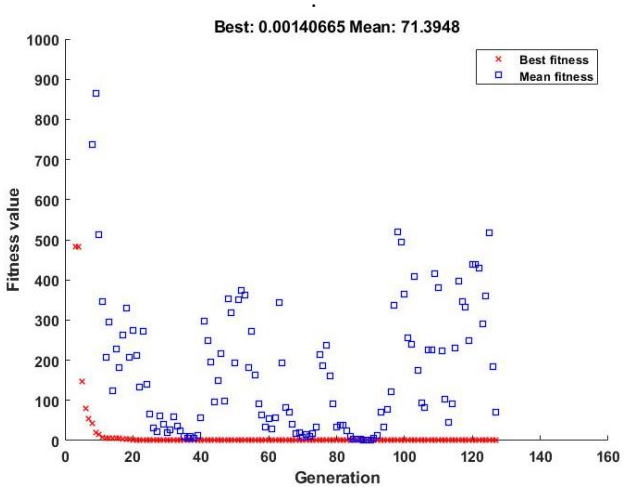


Figure 16. Genetic algorithm convergence with mi=0.5, best fitness value = 0.00140665

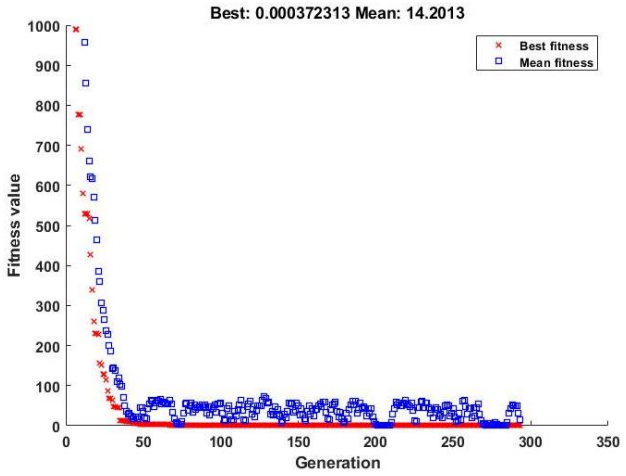


Figure 17. Genetic algorithm convergence with mi=1, best fitness value = 0.000372313

Table 3 presents the solutions of switching angles for different modulation indices, along with the number of generations required to obtain this solution using the GA. The obtained results are consistent with NR Method results reported in Table 4.

Table 3. The results using the genetic algorithm for various modulation indices.

Modulation Index (m_i)	β_1	β_2	β_3	β_4	β_5	No. of Generations	Fitness value
1	20.3425	10.7789	10.3802	19.9936	2.9007	247	4.15E-04
0.9	22.0278	11.2926	12.1315	22.6608	5.2249	151	4.08E-05
0.8	23.1028	10.6349	13.9747	20.7699	7.9848	126	3.94E-04
0.7	24.0792	9.6642	15.8864	18.2983	10.7481	114	1.54E-04
0.6	25.0066	8.5095	17.8418	15.6954	13.499	85	8.04E-05
0.5	25.9053	7.2307	19.8284	13.0626	16.2398	139	3.62E-04
0.4	26.7664	5.8686	21.846	10.4321	18.9758	229	6.14E-04
0.3	27.6071	4.4481	23.8745	7.812	21.7145	281	1.50E-03
0.2	28.427	2.9856	25.9104	5.2028	24.4619	270	1.40E-03
0.1	29.292	1.4985	27.8906	2.6005	27.2177	214	7.30E-03

Table 4. The results using the Newton-Raphson method for various modulation indices.

Modulation Index (m_i)	β_1	β_2	β_3	β_4	β_5
1	20.34551	10.7830982	10.37981	20.00837	2.899009
0.9	22.02746	11.2928547	12.13104	22.66091	5.224772
0.8	23.10194	10.6361717	13.9737	20.77155	7.983569
0.7	24.07853	9.66508744	15.88531	18.2992	10.74786
0.6	25.00672	8.50930731	17.84255	15.69445	13.49931
0.5	25.90236	7.23090441	19.83125	13.06211	16.24
0.4	26.77178	5.86781792	21.84219	10.43192	18.97543
0.3	27.61721	4.44593087	23.86895	7.811628	21.71194
0.2	28.43852	2.98431848	25.90671	5.20142	24.45635
0.1	29.23388	1.49806432	27.95157	2.598742	27.21619

Figure 18 shows the relation between the firing angle and the modulation index according to Table 4. In Tables 5, 6, and 7, the results obtained using the genetic algorithm and the Newton–Raphson method are compared for three different modulation indices, and the percentage error corresponding to each modulation index is discussed. The maximum percentage error is less than 1%, indicating that the solutions between the two methods are in consistent with each other.

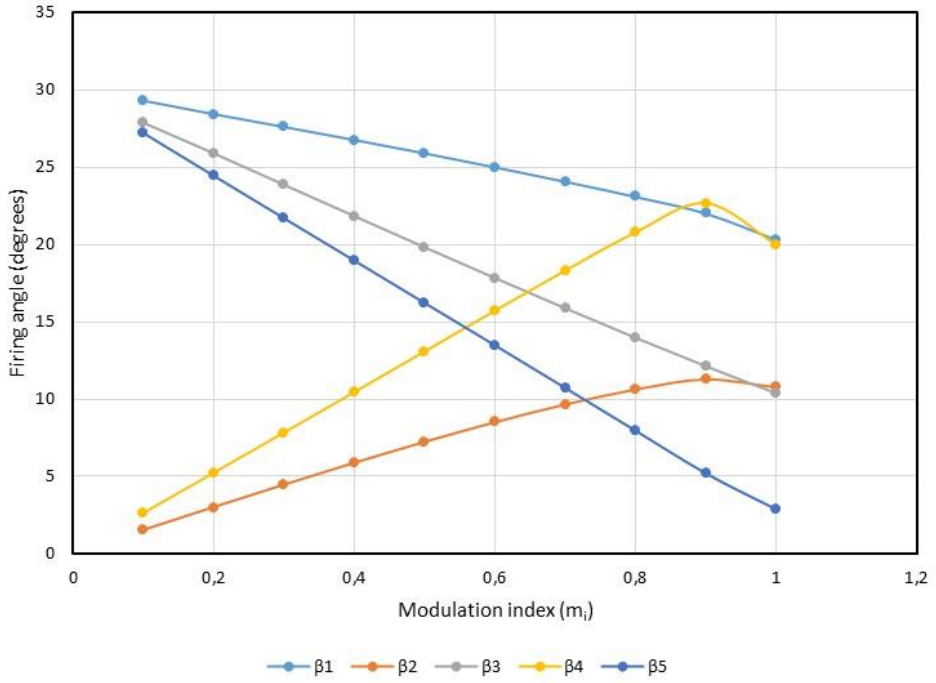


Figure 18. Genetic algorithm solution with different modulation indices

Table 5. Comparison between the Newton-Raphson method and the genetic algorithm with mi=1

Method	β_1	β_2	β_3	β_4	β_5
GA	20.3425	10.7789	10.3802	19.9936	2.9007
NR	20.34551	10.7830982	10.37981	20.00837	2.899009
Error	-0.00301	-0.0041982	0.00039	-0.01477	0.001691
Error %	-0.014794419	-0.038933152	0.003757294	-0.073819107	0.058330278

Table 6. Comparison between the Newton-Raphson method and the genetic algorithm with mi=0.5

Method	β_1	β_2	β_3	β_4	β_5
GA	25.9053	7.2307	19.8284	13.0626	16.2398
NR	25.90236	7.23090441	19.83125	13.06211	16.24
Error	0.00294	-0.00020441	-0.00285	0.00049	-0.0002
Error %	0.011350317	-0.002826894	-0.014371257	0.003751308	-0.001231527

Table 7. Comparison between the Newton-Raphson method and the genetic algorithm with mi=0.1

Method	β_1	β_2	β_3	β_4	β_5
GA	29.292	1.4985	27.8906	2.6005	27.2177
NR	29.23388	1.49806432	27.95157	2.598742	27.21619
Error	0.05812	0.00043568	-0.06097	0.001758	0.00151
Error %	0.198810421	0.029082863	-0.218127282	0.067648116	0.005548168

4. Conclusion

Harmonic distortion is a major concern in inverter systems, as it affects power quality and efficiency. The SHE technique is widely used to eliminate specific low-order harmonics such as the 3rd, 5th, 7th, and 9th components, thereby reducing the overall THD and precisely controlling the fundamental output voltage.

In this study, a new control strategy based on GA is proposed for determining the optimal switching angles in the SHE method. The proposed GA-based approach ensures reliable convergence without requiring an initial guess, addressing one of the major limitations of traditional numerical techniques. The SHE transcendental equations were solved using GA, and the results were validated and compared with the NR method using MATLAB/Simulink simulations.

Future work will focus on extending this approach to real-time optimization, performance evaluation under dynamic load conditions, and exploration of alternative inverter topologies to further enhance harmonic suppression and control performance.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, methodology and software, visualization and writing – original draft.

Author-2: Conceptualization, supervision and methodology– review and editing.

Declaration of Competing Interest

The authors have no conflicts of interest to declare regarding the content of this article.

Data Availability Statement

The authors declare that the main data supporting the findings of this work are available within the article.

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