An Efficient Switching Scheme for Three Phase Multilevel Voltage Source Solar Inverter using a Novel Spatial Group Improvised Border Collie Optimization

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***Abstract*—** For three phase multilevel solar inverter, choosing an optimal switching scheme remains a significant challenge. Recently, various new pulse width modulation (PWM)-based switching methods have been efficiently used by the researchers for selecting a novel switching scheme. A novel spatial group improvised border collie optimization (*s*GIBCO)-based efficient switching scheme has been proposed in this paper to reduce the selective order harmonics. The proposed approach optimally determines the switching angles of the multilevel solar inverter, aiming to minimize the total harmonic distortion (THD). A key innovation of the method lies in its spatial group-based improvisation strategy, where sheep are grouped adaptively based on an calculated distance threshold. An eleven level three phase solar inverter serves as test system for validating the methodology. Comparative analysis with particle swarm optimization (PSO) and harmony search (HS) highlights the superior performance of the proposed *s*GIBCO technique in optimizing switching schemes. The results indicate that the proposed method can effectively guide the design of hardware multilevel inverters with optimal THD performance.

Keywords—selective harmonic elimination, spatial group improvised border collie optimization, particle swarm optimization, harmony search, total harmonic distortion, multi-level inverter.

I. INTRODUCTION (*HEADING 1*)

Multilevel inverters have become increasingly significant due to their ability to achieve higher voltage levels by combining multiple lower-voltage dc sources. Compared to traditional two-level inverters, multilevel inverters offers enhanced voltage handling capabilities and superior voltage quality. This devices are widely utilized for integrating distributed generation systems with the electrical grid. One of the primary challenges associated with multilevel inverters is the mitigation of harmonic distortion in the output voltage. To ensure compliance, the total harmonic distortion (THD) must remain within the limits specified by [1].

In recent years, researchers have explored various techniques for harmonic elimination, including fundamental frequency switching, pulse width modulation (PWM), and optimization-based PWM methods. Among this, the conventional PWM control method is commonly employed and effectively mitigated lower-order harmonics but struggles to completely eliminate higher-order harmonics. To overcome this limitation, the selective harmonic elimination pulse width modulation (SHE-PWM) technique has been developed. This method provides more precise control over the harmonic spectrum in the output voltage, as discussed in [2].

Significant achievements have been made in this field over the past three decades. Transcendental equations that define selective harmonic elimination problems can be transformed into polynomial equations, which are solvable using resultant theory, as highlighted in [3]. Research efforts have focused on solving these equations to determine the optimal PWM switching angles that minimize THD. For instance, one study employed a pure lexicographic monomial order to convert the complex high-order SHE equations into an equivalent triangular form, followed by a recursive algorithm to sequentially solve the triangular equations [4]. However, recent advancements have introduced swarm algorithms, which explore a population of solutions rather than a single point, for harmonic reduction in multilevel inverters. Metaheuristic approaches have gained popularity, such as the application of differential evolution (DE), for harmonic reduction using modified PWM techniques, as reported in [5]. Additionally, genetic algorithm optimization has been employed to design multilevel inverters for hybrid power applications [6]. Other widely used optimizations include ant colony optimization (ACO) [7], bat algorithm (BA) [8], artificial bee colony (ABC) [9], and cuckoo search algorithm (CSA) [10], all of which have shown effectiveness in reducing THD in output voltages. Recently, PSO has also been utilized for developing optimal switching schemes, offering reduced computation times and efficiently mitigating harmonic distortion in the output voltage waveforms of modified multilevel inverters, however BCO-based efficient switching scheme for multilevel solar inverter have not been explored much [11-22].

This paper presents a novel spatial group improvised border collie optimization technique for determining an efficient switching scheme. In this proposed approach, a specific group of ships is updated in each iteration. These groups are identified by evaluating the distance between ships, which are determined adaptively. The methodology has been applied to an 11-level multilevel inverter to compute the efficient switching scheme capable of producing lower THD. The proposed technique has been compared with PSO-based and HS-based switching schemes, and simulation results have been analyzed and discussed.

The remainder of the paper is organized as follows. Section II provides an overview of the general SHE scheme. Section III describes the proposed spatial group improvised border collie optimization technique for SHE. Section IV presents the simulation results and finally section V concludes the paper.

II. SELECTIVE HARMONIC ELIMINATION SCHEME

The output voltage waveform of a multilevel inverter includes harmonic components, as illustrated in Fig. 1. The output voltage $v(t)$ can be represented as Fourier Series as follows:

$$f(t) = \sum_{n=1}^{\infty}(a_n \sin n\theta_n + b_n \cos n\theta_n) \qquad (1)$$

The quarter wave symmetry of the waveform eliminates the presence of even harmonics. The amplitude of n-th harmonics is calculated using the first quadrant switching angles, represented as $\theta_1, \theta_2, \theta_3 \dots \theta_n$.

$$a_n = \left(\frac{4}{n\pi}\right)\left[1 + 2\sum_{k=1}^{m}(-1)^k \cos n\theta_k\right] \qquad (2)$$

and $0 < \theta_1 < \theta_2 < \cdots \theta_m < \left(\frac{\pi}{2}\right)$ (3)

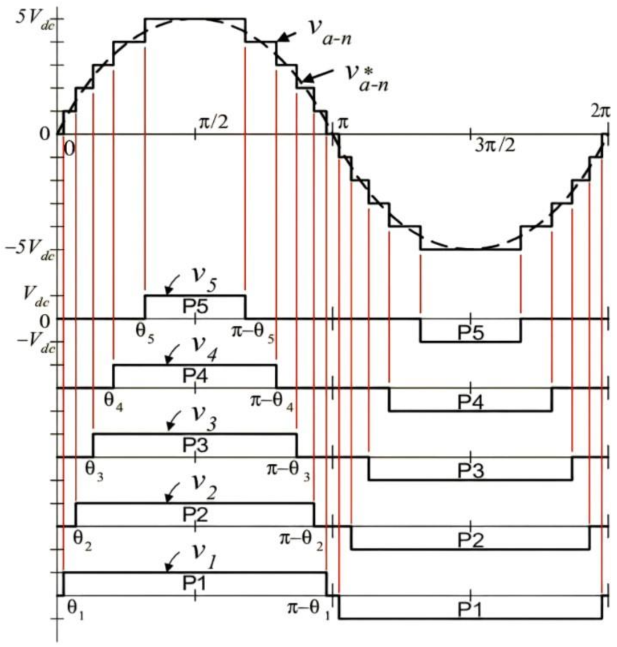

Fig. 1. Output voltage waveform of an 11-level multilevel inverter.

The (2) equation shows that θ has m no. of variables from switching angles θ_1 through θ_m of the first quadrant, where the equation has been expanded to the kth term for any odd harmonics.

For selected harmonic elimination, a_n is assigned to a value of which the harmonics to be eliminated.

$$a_1 = \left(\frac{4}{\pi}\right)\left[1 + 2\sum_{k=1}^{m}(-1)^k \cos n\theta_k\right] = M$$
$$a_5 = \left(\frac{4}{5\pi}\right)\left[1 + 2\sum_{k=1}^{m}(-1)^k \cos n5\theta_k\right] = 0 \qquad (4)$$
$$a_n = \left(\frac{4}{n\pi}\right)\left[1 + 2\sum_{k=1}^{m}(-1)^k \cos n\theta_k\right] = 0$$

Where M is the amplitude of the fundamental component. After solving the equations, θ_1 through θ_k are computed. Third order harmonics are eliminated in the three-phase balanced system and these are not taken into consideration in (4). It is proven that (m-1) harmonics can be eliminated through m number of switching angles. The main drawback of this equation is it shows discontinuity at some points where no solution is available.

In selective harmonic elimination (SHE) technique the main problem arises with certain indices when certain harmonics are set to zero. This issue has been addressed by setting the harmonics at minimum possible values. This method helps to generate pulses effectively.

Moreover, SHE generates multiple nonlinear transcendental equations which provides n number of solutions that can reduce THD at these points. However, out of these number of solutions only a particular set of solutions can reduce the total amount of THD at these points. Also always setting the equations at these points can help to achieve minimum THD but leads to abrupt change in the switching angle which may not be suitable for online application. Therefore, it has been attempted to attain optimum values rather than to achieve always minimum values of the proposed group improvised scheme as needed to find suitable solutions without abruptly changing the switching angle.

III. PROPOSED SPATIAL GROUP IMPROVISED BORDER COLLIE OPTIMIZATION

The non-linear transcendental equations are complex in nature because it has multiple solutions. So, the selective harmonic elimination problem has been converted into an optimization problem to limit the number of complexities in the non- linear equation. The %THD output can be obtained as:

$$\%\text{THD}=\left[\frac{1}{a_1^2}\sum_{n=5}^{\infty}(a_n)^2\right]^{\frac{1}{2}} \times 100 \qquad (5)$$

where n=$6i \pm 1$ $\quad (i = 1,2,3,4 \dots\dots)$

The objective function $F(\alpha) = F(\theta_1, \theta_2, \dots .\theta_m)$

subject to: $0 < \theta_1 < \theta_2 < \cdots \theta_m < \frac{\pi}{2}$;

$$a_1 = M;$$
$$a_2 \leq \varepsilon_1;$$
$$a_7 \leq \varepsilon_2; \qquad (6)$$
$$\vdots$$
$$a_n = \varepsilon_n;$$

where, $\varepsilon_1, \varepsilon_2, \dots \varepsilon_n$ are allowable limits of selective harmonics.

BCO algorithm is an iterative process inspired by the behavior of the herding dogs guiding a flock of sheep. Typically, three dogs are involved in directing, stalking and monitoring the sheep. After grazing, the dogs guide the sheep back to the farm. The positions of the sheep and the dogs are represented using random variables.

The three herding dogs are categorized based on their positions and fitness levels. The lead dogs possessing the highest fitness, guides the flock from the front and is responsible for gathering the sheep. The left and right dogs, with the second and third highest fitness levels (interchangeable), are tasked with stalking and monitoring the herd. The velocities of the lead, right and left dogs, denoted as V_f , , V_r and V_{le} respectively, for the next time step $(t+1)$, are computed using the following equations:

$$V_f(t+1) = \sqrt{V_f^2(t) + 2 \times P_f(t) \times A_f(t)} \quad (7)$$

$$V_r(t+1) = \sqrt{V_r^2(t) + 2 \times P_r(t) \times A_r(t)} \quad (8)$$

$$V_{le}(t+1) = \sqrt{V_{le}^2(t) + 2 \times P_{le}(t) \times A_{le}(t)} \quad (9)$$

In equation (7), (8) and (9), $P_f(t)$, P_r and $P_{le}(t)$ represent the position of lead, right and left dogs, respectively, while $A_f(t)$, $A_r(t)$ and $A_{le}(t)$ denote their accelerations in time t. These equations collectively updates the velocities of the three dogs in each iteration. The updated positions of the three dogs$P_f(t)$, P_r and $P_{le}(t)$ are given by:

$$P_f(t+1) = V_f(t+1) \times T_f(t+1) + \frac{1}{2} \times A_r(t+1) \times T_f(t+1)^2 \quad (10)$$

$$P_r(t+1) = V_r(t+1) \times T_r(t+1) + \frac{1}{2} \times A_r(t+1) \times T_r(t+1)^2 \quad (11)$$

$$P_{le}(t+1) = V_{le}(t+1) \times T_{le}(t+1) + \frac{1}{2} \times A_{le}(t+1) \times T_{le}(t+1)^2 \quad (12)$$

Here, $T_f(t+1)$, $T_r(t+1)$ and $T_{le}(t+1)$ denote the updated traversal times for lead, right and left dogs, respectively. Similarly, the position, velocity and acceleration of the gathered, stalked and monitored sheep can also be computed and updated accordingly.

To begin, the population size, population dimension, number of iterations, and the maximum and minimum limits of each dimensions are initialized, along with upper and lower boundaries. Subsequently, the position, velocity, acceleration and time are initialized. The fitness function, which in this case is based on the THD, is then evaluated and the lead dog, representing the best fitness value, is identified. Using the stalking and monitoring capabilities of the right and left dogs, the second and third best dogs are also selected. The positions of all sheep, including those that need gathering, stalking or monitoring, are updated accordingly.

The key contribution of this paper employs a spatial group improvise technique where the position of a specific group of sheep (S) requiring monitoring and stalking are updated based on their relative distances (d_{norm}). This group selection is guided by a distance-based threshold (d_{th}), ensuring efficient communication and interaction between closely positioned sheep.

To establish spatial neighborhood, the neighborhood of each sheep is defined as:

$$Ns = \{S\} | d_{norm} \le d_{th} \quad (13)$$

where, $d_{norm} = \frac{\|s - s^m\|}{max\{\|s - s^m\|\}}$; $m = 1,2, \ldots, S$ and $d_{th} = \frac{x_1 \times t + x_2 \times iter_{max}}{iter_{max}}$. The spatial group improvisation begins with a small d_{th} value, indicating that each sheep considered as a neighborhood with small radii. As a result, the proposed spatial group improvisation is initially influenced by a larger number of neighborhoods. Over successive iterations, the radius of each permissible neighborhood progressively expands.

When $d_{th} > 1$, all sheep combined to form a single neighborhood, as $d_{norm} \in [0,1]$, causing the algorithm to follow the classical BCO model. During each iteration, after forming the neighborhood, Ns, equation (7) to (12) are used to update velocity and position in the proposed algorithm.

The proposed methodology has been applied to an 11-level three phase inverter, where the optimized switching angles are calculated by varying the modulation index from 0 to 1. The proposed approach is then compared with two classical approaches such as PSO and HS-based switching schemes. Experimental results validate the effectiveness of the proposed method, demonstrating its superior performance in reducing harmonic distortion.

IV. Experimental Results

The proposed scheme has been implemented and tested in the MATLAB/Simulink environment. For multiple dc sources, several sets of switching angles within a modulation index range of 0 to 1 were computed to eliminate harmonics from 5th to the 25th order. The variation of these harmonics with respect to the modulation index is depicted in Fig. 2. The optimal switching angles, θ_1 to θ_5 , for 11-level inverter targeting the elimination of harmonics from 5th to 25th order are shown in Fig. 3. Correspondingly, the THD variation against the modulation index is also illustrated in Fig. 2.

The voltage spectrum of all targeted harmonics is represented in Fig. 4, highlighting the significant suppression of harmonic components within the range of 5th to 25th order achieved through the proposed technique. Furthermore, Fig. 5 compares the effectiveness of the proposed method with other optimization approaches, such as PSO and HS-based selective harmonic elimination techniques, demonstrating its superiority. The experimental results confirm that the proposed switching scheme effectively determines the optimal firing angles, thereby minimizing THD in the line voltage with high efficiency.

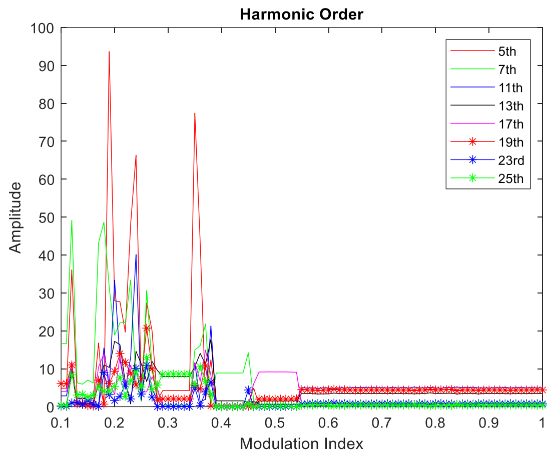

Fig. 2. Variation of selective harmonics with modulation index

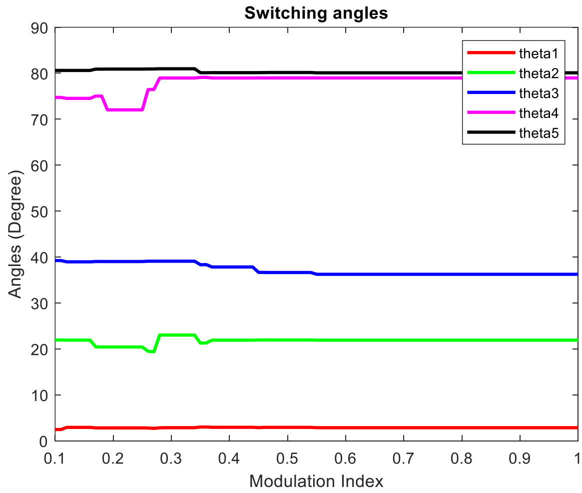

Fig. 3. Variation of switching angles with modulation index

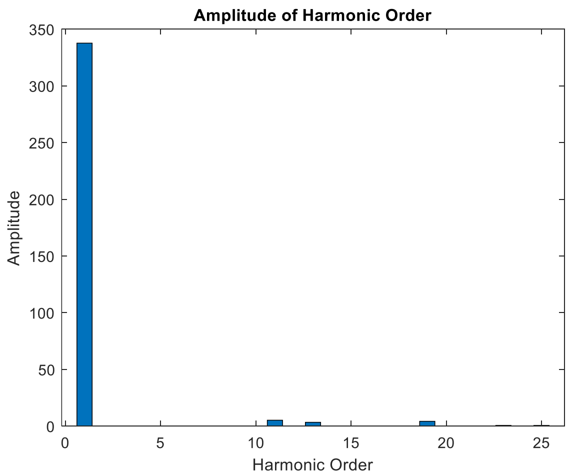

Fig. 4. Harmonic Spectrum

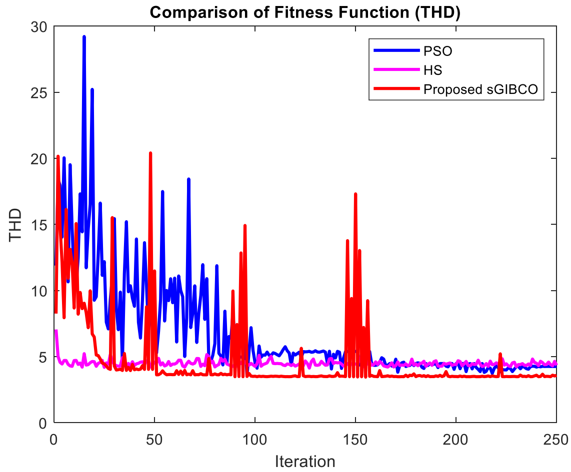

Fig. 5. Comparison of optimum THD values with PSO, HS and proposed *s*GIBCO

V. CONCLUSION

The proposed *s*GIBCO-based optimized switching scheme has been successfully applied to reduce the overall THD in the output voltage of a three phase multilevel solar inverter. The condition for achieving minimal voltage THD was determined by evaluating all possible sets of switching solutions. An optimal switching solution was then identified to minimize harmonic distortion effectively. This method was specifically designed for an eleven-level three phase voltage source solar inverter, demonstrating its effectiveness.

The *s*GIBCO methodology introduced in this paper shows promise for application to various configurations of multilevel inverters. Additionally, the proposed approach has been compared with PSO-based and HS-based optimized switching schemes, yielding comparable results. Future research should aim to validate the proposed methodology through hardware implementation for practical applications.

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