Red deer algorithm-based selective harmonic elimination technique for multilevel inverters

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ABSTRACT

This paper proposed a red deer algorithm (RDA)-based selective harmonic elimination (SHE) method for multilevel inverters (MLIs). To eliminate the desired harmonic orders, the optimum switching angles of the MLI have been calculated using the proposed RDA. The calculated switching angles have been applied to the 3-phase cascaded H-bridged 11-level inverter. In addition, the performance of the proposed RDA method was compared with the results of methods such as the Newton-Raphson (NR) method, LSHADE/EpSin technique (LSHADE), whale optimization algorithm (WOA), and particle swarm optimization (PSO) used for the SHE problem in the literature. The results obtained prove that the proposed RDA optimization solves the SHE problems more effectively than other methods. It has also been observed that RDA produces good solutions in different modulation indexes.

1. INTRODUCTION

Multilevel inverters (MLIs) are a popular power electronics device used in mid-voltage and high-power applications instead of conventional two-level inverters. Basically, there are three conventional topologies for MLIs these are; cascaded H-bridge MLI (CHB-MLI), capacitor-clamped MLI (CC-MLI), and diode clamped MLI (DC-MLI) [1]–[3]. The robust and modular structure of CHB-MLI made it the most commonly used topology among the existing topologies [4]. Conventional inverters have high efficiency and a high-power ratio. However, the semiconductor switches experience higher stress as the desired power and voltage value are increased. Today, it is not possible to produce semiconductor power switches that can withstand medium voltage levels. Therefore, the use of MLI with lower voltage stress in switches in medium/high voltage applications has become popular [5]–[8].

However, this technology faces a harmonic problem that causes harmful effects on the load. Among harmonics, the most dangerous harmonics for the system are low-order harmonics because these harmonics cause torque fluctuations in electric motors, decrease efficiency, and reduce the lifetime of the system [9]–[12]. The control and modulation methods used by these inverters have become more challenging as MLI topologies have advanced [12]–[14]. An essential issue that needs to be resolved is the existence of low-order dominant harmonics in the cascading output voltage generated by MLI. These harmonics mostly cause malfunction, increased loss, and voltage ripple. These harmonics also have an impact on power quality [15]. Despite the fact
that there are other controls and modulation techniques, the selective harmonic elimination (SHE) technique is the primary modulation technique that solves the aforementioned issues.

Hence, the solution to the problem is extremely difficult. Three sorts of techniques can be utilized to address SHE issues; these are numerical techniques, algebraic techniques, and meta-heuristic algorithms. The gradient optimization and Newton-Raphson (NR) [16] methods can be given as examples of numerical methods; however, these iterative methods are mainly sensitive to the initial value and divergence problems are likely to occur, especially as the inverter level increases. If the initial value is not selected properly, the number of iterations may increase greatly or the solution may not be found. Algebraic methods are techniques such as resultant theory and Groebner bases theory for calculating optimized switching angles. These methods do not depend on the initial value but are very complex computationally; therefore, these methods can be applied only to low-level inverters. In meta-heuristic methods, SHE equations are solved using nature-inspired methods such as genetic algorithm (GA) [17] particle swarm optimization (PSO) [17], [18], LSHADE/EpSin technique (LSHADE) [19], whale optimization technique (WOA) [20], [21], and enhanced krill herd (EKH) [22]. There are certain common problems of algorithms such as PSO and GA; these include convergence to local optimum, early convergence, and either only global solution or only local solution.

This study proposes a novel red deer algorithm (RDA)-based optimization approach to the SHE problem that can overcome the above problems. The proposed RDA optimization has been applied for the first time for the SHE problem [23], [24]. According to the optimization methods used for the SHE problem in the literature, the most obvious superiority of RDA optimization is that it can adjust the diversification and intensification phases. Owing to this feature, RDA can trade off between the optimal minimization total harmonic distortion (OMTHD) and SHE (it can use the local and global search together). To validate the concept, switching angles for OMTHD and SHE-pulsewidth modulation (SHE-PWM) using RDA are found and applied to a 3-phase 11-level CHB-MLI. In addition, the harmonic results of the RDA-based SHE technique have been compared with the results of other techniques in the literature.

2. CASCADED H-BRIDGE MULTILEVEL INVERTER

Figure 1(a) displays the circuit diagram for the N-level three-phase CHB-MLI. Each phase is made up of a single-phase H-bridge inverter that is connected in series and is powered by a separate, discrete DC source. If the voltage value of DC sources is equal, it is called a symmetrical MLI, otherwise, it is called an asymmetric MLI. The proposed algorithm in this study is applied to the symmetrical structure. Figure 1(b) depicts the AC output voltage waveform (V) for an N-level MLI supplied by a symmetrical source. The output voltage for each phase can be expressed as (1):

\[ V = \pm V_{DC} \]  

Where k is the number of discrete DC sources. Also, k represents the number of H-bridge modules. The relationship between the number of DC sources (k) and the voltage level N can be given as (2):

\[ N = 2k + 1 \]  

Figure 1. Three-phase N-level CHB-MLI (a) circuit diagram and (b) output voltage waveform for single phase
3. SELECTIVE HARMONIC ELIMINATION PROBLEM IN MULTILEVEL INVERTERS

Low-order harmonics are eliminated by the SHE-PWM switching method via the creation of switching angles at the fundamental frequency. The number of discrete DC sources in this approach equals the number of switching angles (k). Switching each module just once will eliminate k-1 maximum number of harmonics from the output voltage of the inverter. The output voltage can be fourier expanded to reflect the required nonlinear harmonic equations to attain the optimal switching angles. The expression of the output voltage that contains all the harmonic components is given as (3) [5, 6]:

\[ V_0(\omega t) = \sum_{k=1}^{\infty} \frac{4kV_{dc}}{\pi} \cos(k\theta_1) + \cos(k\theta_2) + \cdots + \cos(k\theta_k) \sin(\omega t) \]  \hspace{1cm} (3)

For the output voltage, the harmonic components are mostly composed of the fundamental frequency and its multiple. The symmetrical output voltage represented in Figure 1(b) ensures the non-availability of even harmonic components. The output voltage consists of only odd harmonic components as expressed in (3), where \( \omega = 2\pi f \) and \( f \) is the fundamental frequency. The expression of the fundamental harmonic component \( V_1 \) of the output voltage is given thus:

\[ V_1(\omega t) = \frac{4kV_{dc}}{\pi} \cos(\theta_1) + \cos(\theta_2) + \cdots + \cos(\theta_k) \sin(\omega t) \]  \hspace{1cm} (4)

Where \( \theta_1, \theta_2, \ldots, \theta_k \) are switching angles and must meet the following condition:

\[ 0 \leq \theta_1 < \theta_2 < \cdots < \theta_k \leq \pi/2 \]  \hspace{1cm} (5)

In the SHE technique, the control of the fundamental voltage is carried out with the modulation index (M) which is the ratio of the peak value of the desired basic voltage \( V_{ip} \) to the total DC input voltage given in (6):

\[ M = \frac{V_{ip}}{kV_{dc}} \]  \hspace{1cm} (6)

The 3\( ^{rd} \) harmonic components and multiples of 3\( ^{rd} \) harmonics at phase-to-phase voltages can be disregarded in a balanced 3-phase system. As a result, the line voltage waveform's 5\( ^{th} \), 7\( ^{th} \), and 11\( ^{th} \) ... harmonic orders can be removed at the low switching frequency. In a 3-phase 11-level MLI, the following equations must be solved to eliminate undesired harmonics and generate fundamental harmonics of specified amplitude:

\[ V_5 = \cos(5\theta_1) + \cos(5\theta_2) + \cdots + \cos(5\theta_k) = 0 \]
\[ V_7 = \cos(7\theta_1) + \cos(7\theta_2) + \cdots + \cos(7\theta_k) = 0 \]
\[ V_{11} = \cos(11\theta_1) + \cos(11\theta_2) + \cdots + \cos(11\theta_k) = 0 \]
\[ V_{13} = \cos(13\theta_1) + \cos(13\theta_2) + \cdots + \cos(13\theta_k) = 0 \]  \hspace{1cm} (7)

The fundamental waveform's amplitude is managed by the first SHE equation, as shown in (7). To remove the selected harmonics, other equations are set to zero. After that, these equations are correctly solved. The goal is to remove or significantly reduce the low-order harmonics \( (V_5, V_7, V_{11}, \text{and } V_{13}) \) while ensuring the fundamental frequency maintains a steady voltage value at the desired value. To find the optimal SHE equation solutions, an RDA optimization strategy is suggested in this study.

4. IMPLEMENTATION OF RDA OPTIMIZATION TO SHE TECHNIQUE

The RDA [25] was first reported; this was followed by the introduction of a new RDA optimization strategy [26]. The main source of inspiration for this meta-heuristic was the unusual mating pattern of Scottish red deer (RDs) during the breeding season. Like other meta-intuitive methods, RDA is initiated with a set of randomly selected RDs, where the best RDs in the population are considered the "male RDs," while the others are called "hinds." The male RD should roar first; they are split into two categories—single male deer (stags) and commanders based on the strength of the roar phase. The commanders engage the stags in a battle to claim their harems. Here, only the commanders can create the harems. The number of hinds in the harems of the leaders is directly related to their roar and their prowess in the battle phase. The commanders consequently mate a number of hinds in their harems but each commander is allowed a limited number of mating with hinds from various harems. The other male deer (stags) can also mate with the closest hinds irrespective of the size of the harem. Both exploration and concentration phases are also focused on in this step. The mating procedure by which RDs offspring are created is a significant stage in RDA optimization. This stage also offers new solutions to the optimization problem. The next algorithmic stage is finally created by considering the solutions that are evolutionarily weak [26]. The following steps are performed to solve the SHE problem with RDA:
a. Determination of the cost function: the cost function for the SHE problem is defined as (8):

\[ f = \min \theta_i \left( V_{ip} - \left( \frac{4V_{dc}}{\pi} \cdot \sum_{i=1}^{k} \cos (\theta_i) \right) + \left( \frac{4V_{dc}}{\pi} \cdot \sum_{i=1}^{k} \cos (n \theta_i) \right) \right)^2 = 0 \]  

Where \( V_{ip} (H_i) \) is the desired fundamental harmonic, \( h_i \); are the harmonics that need to be eliminated. The first term controls the fundamental voltage and the second term represents low-order harmonics in the cost function.

b. Creation of the initial population: create the initial population according to (9):

\[ \text{Value} = f(\text{Red Deer}) = f(X_1, X_2, X_3, …, X_{N_{var}}) \]  

Where \( X_{N_{var}} \) specifies the size of the array, while the values \( X_1, X_2, \) and \( X_3 \) are the array’s components. Five variables are defined (\( \theta_1, \theta_2, \theta_3, \theta_4 \) and \( \theta_5 \)) since only one switching is made for each bridge in the eleven-level CHB-MLI. The number of variables will be the number of positions assigned to each deer. To start the algorithm, a random initial population of \( N_{pop} \) size is created, taking into account the fitness function.

c. Choosing the best solutions: randomly generated switching angles are evaluated according to the fitness function. Some of the best solutions (depending on the value selected in Table 1) are identified and stored as male RD.

d. Selection of commanders and stags: select the commander and stags according to (10):

\[ N_{\text{Com}} = \text{round} \{ \gamma \cdot N_{\text{male}} \} \]

\[ N_{\text{stag}} = N_{\text{male}} - N_{\text{Com}} \]

Where \( N_{\text{male}} \) is the number of all male deers, \( N_{\text{com}} \) represents the number of commanders, and finally, \( N_{\text{stag}} \) is the number of stags (single male deers).

e. Fight: each commander randomly fights the stags. The fighting process is performed using (12):

\[ \text{New}_1 = \frac{\text{Com} + \text{Stag}}{2} + b_1 \times \left( (\text{UB} - \text{LB}) \times b_2 \right) + \text{LB} \]

\[ \text{New}_2 = \frac{\text{Com} + \text{Stag}}{2} - b_1 \times \left( (\text{UB} - \text{LB}) \times b_2 \right) + \text{LB} \]

Where UB is the upper bound of the search space while LB is the lower bound. The fighting step is a random process and as such, the selection of \( b_1 \) and \( b_2 \) is done randomly between 0 and 1 in a uniformly distributed manner. A commander can approach a stag or vice versa in the resolution area. Any of the four solutions [single male RD (Stag), commander (Com), New1 (new status1), and New2 (new status2)] with better FF becomes the new commander.

f. Create harem: a harem is made up of a male commander and a group of captured female deer (hinds). The fighting capability of the commander determines the number of female deer in the harems.

g. Mating: mating can be done in three ways: i) mating each commander with females from his harem; ii) mating any commander with hinds from another harem; and iii) mating the stag with the nearest hind, irrespective of the harem restrictions.

h. Creation of offspring: during the mating phase, offspring are produced in all three cases according to (13). The Stag replaces Com during the third case in the mating phase:

\[ \text{off} = \frac{\text{Com} + \text{Hind}}{2} + (\text{UB} - \text{LB}) \times c \]

Where \( c \) is randomly generated in a uniformly distributed manner between 0 and 1.

i. Selection of the new generation: the next generation is chosen using two alternative methods. The first method involves keeping the best male RDs (Stag and Com) (a given proportion of the optimal solutions).
The second technique requires the selection of the hinds for the next generation utilizing a fitness competition or roulette wheel mechanism; the selection is done from among all the hinds and produced offspring during the mating stage. The selected male and female RDs produce the next generation.

j. Stop criterion: the number of iterations, the best-found solution, or a given time interval can all be considered as the stopping condition. The number of iterations is used as the stopping condition for RDA-based SHE-PWM. Repeat steps c through j until the stopping condition is satisfied.

Details of how RDA optimization can be used with SHE equations have been provided by [23], [24]; readers are referred to the relevant articles for more explicit information. RDA optimization parameters are adjusted to solve SHE equations in 11-level three-phase CHB-MLI. Figure 2(a) shows the optimum switching angles that the RDA optimization found in the range of modulation index of 0.1 to 1.0 to solve the SHE equation. Figure 2(b) shows the optimum switching angles that the proposed method finds to provide the OMTHD value. Figures 3(a) and (b) show total harmonic distortion (THD) and THD values within the modulation index range of 0.1 to 1.0 for SHE and OMTHD, respectively. Evidently, the proposed RDA-based method finds suitable solutions for SHE and OMTHD in the modulation index range of 0.4 to 1.0.

Two types of THD are computed in this work; the first is the overall THD; the second is the THD value that stands for the total of harmonics until the eliminated maximum harmonic orders. In the 11-level three-phase CHB-MLI, THD, and THD can be calculated as given in (14) and (15), respectively. The upper limit for THD is infinite, but THD is calculated up to the minimized harmonic orders.

\[
THD = \sqrt{\frac{\sum v_i^2 + v_5^2 + v_7^2 + \cdots + v_{5n}^2}{|V_1|}}, \quad \text{(for odd } k) \quad (14)
\]

\[
THD_e = \sqrt{\frac{\sum v_i^2 + v_5^2 + v_7^2 + \cdots + v_{3k-2}^2}{|V_1|}}, \quad \text{(for odd } k) \quad (15)
\]

5. RESULT

To prove the effectiveness of the proposed algorithm, the calculated switching angles were applied to the three-phase 11-level CHB-MLI. Each H-bridge module input voltage is selected as 50 V (Vdc=50 V).
These results show that the selected harmonics are minimized almost to zero and the fundamental harmonic is kept very close to the desired value. The switching angles in the unit modulation index to be minimized of selected harmonics are estimated as \( \theta_1=6.75^\circ \), \( \theta_2=18.98^\circ \), \( \theta_3=27.53^\circ \), \( \theta_4=45.49^\circ \), and \( \theta_5=62.40^\circ \). The switching angles in the unit modulation index for the best OMTHD value are obtained as \( \theta_1=8.02^\circ \), \( \theta_2=19.2^\circ \), \( \theta_3=27.82^\circ \), \( \theta_4=46.45^\circ \), and \( \theta_5=61.16^\circ \). For the best SHE solution, the inverter output phase voltage waveform is given in Figure 4(a). The frequency spectra of line voltage for THD and THD\(_e\) are depicted in Figures 4(b) and 4(c), respectively. Similarly, the output phase voltage and the frequency spectra of line voltage for THD and THD\(_e\) are given in Figures 5(a)-(c), respectively.

For SHE and OMTHD, the fundamental phase voltage is normally \( V_1=250 \text{ V} \) for \( M=1.0 \) from (6). The switching angles, THD, and THD\(_e\) values calculated for the NR, LSHADE, WOA, PSO, and the proposed RDA-based technique are given in Table 2. As can be seen, the proposed RDA-based SHE-PWM technique (RDA-SHE) eliminates selected harmonics better than another optimization techniques. The smallest THD\(_e\) value proves that the selected harmonics are efficiently minimized.

The table suggests that when the calculated switching angles for the RDA-SHE are applied, the THD\(_e\)% value is obtained as 0.04% and the THD% value as 4.50%. By using the suggested RDA method, the amount of intensification can be adjusted between the harmonics desired to be eliminated and the THD value. If prompted to obtain the best THD value, the intensification of the THD can be increased in the fitness function. In this case, the THD\(_e\)% and THD% values are obtained as 1.29 % and 3.96 %, respectively. From the perspective of minimum THD, the proposed RDA has given the best performance, but the harmonic value is higher than the calculated value for the SHE because optimization (RDA-OMTHD) is intensified to find a solution for the minimum THD value.

![Figure 4](image1.png)

**Figure 4.** For SHE solution (a) phase voltage waveform, (b) THD value of line voltage, and (c) THD\(_e\) value of line voltage

![Figure 5](image2.png)

**Figure 5.** For OMTHD solution (a) phase voltage waveform, (b) THD value of line voltage, and (c) THD\(_e\) value of line voltage

<table>
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<tr>
<th>Optimization techniques</th>
<th>Modulation index (M)</th>
<th>Switching angles (degree)</th>
<th>THD%</th>
<th>THD(_e)%</th>
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<td>NR method [16]</td>
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<td>1.29</td>
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</table>
6. CONCLUSION

In this paper, an RDA optimization is proposed for the elimination of selected harmonic orders in three-phase 11-level CHB-MLI fed by symmetric sources. Suitable switching angles for the modulation index values between 0.1 and 1 for the suggested RDA optimization were quickly calculated. The results show that the RDA method can successfully attenuate low-order harmonics while maintaining the fundamental output voltage. Furthermore, the proposed method can be used effectively to achieve the optimal THD value. Consequently, the proposed optimization method produces better solutions within the specified modulation index range compared to other existing optimization methods.

REFERENCES


BIOGRAPHIES OF AUTHORS

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