Enhancing Harmonic Reduction in Multilevel Inverters using the Weevil Damage Optimization Algorithm

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Abstract—**In this study, we investigate the efficacy of the newly developed Weevil Damage Optimization Algorithm (WDOA) for addressing harmonic distortion in multilevel inverters. Specifically, harmonics of the fifth and seventh orders are targeted for elimination in a seven-level cascaded multilevel inverter, while harmonics of the fifth, seventh, eleventh, and thirteenth orders are addressed in an eleven-level cascaded multilevel inverter. Through simulation studies encompassing different modulation index values, we demonstrate the effectiveness of the WDOA optimization algorithm in selectively removing harmonics and reducing overall harmonic distortion. While the results showcase promising outcomes, further quantitative metrics and comparative analysis are warranted to fully evaluate the algorithm's performance and its potential implications for practical applications in multilevel inverter systems.**

Keywords—Multilevel Inverters; Harmonic Distortion; Weevil Damage Optimization Algorithm; Selective Harmonic Elimination; Simulation Studies; Modulation Index Values.

I. INTRODUCTION

In recent years, the development of smart grids has underscored the increasing significance of inverters, particularly with the rising adoption of renewable energy sources. Harmonic quality issues persist as notable challenges in electrical systems, manifesting in power losses, electromagnetic interference, and torsional vibrations in AC motor drives [1]-[9]. However, the deployment of multilevel inverters offers promising avenues for mitigating such challenges while enhancing system efficiency and stability [10]-[16].

Previous research has extensively explored techniques to optimize switching angles in multilevel inverters for high-order harmonic elimination. While approaches like the Resultant Theory [17]-[24] have shown efficacy in low-switch applications, challenges arise in solving high-degree polynomial equations for systems with more than two data layers. Similarly, the Newton-Raphson method [4], though effective, hasn't been extensively applied to high-level inverter calculations. In contrast, researchers have explored population-based optimization techniques including Genetic Algorithms (GA), Harmony Search (HS), Moth-Flame Optimization (MFO), and the Red Deer Algorithm (RDA) [6]-[11] when traditional methods fall short in high-level inverter scenarios.

Addressing these challenges, this paper introduces the Weevil Damage Optimization algorithm (WDOA), a swarm-based meta-heuristic inspired by insect behavior. WDOA leverages the flight power, long nose power, and damage power of insects associated with crop damage to optimize specific objective functions. In this study, we explore the application of WDOA to reduce harmonics and minimize total harmonic distortion (THD) in multi-level inverters.

The primary objective of this paper is to demonstrate the effectiveness of the WDOA method in addressing selective harmonic elimination and THD minimization in multi-level inverters. To achieve this goal, we conduct numerical simulations on seven-level and eleven-level cascade multi-level inverters, analyzing the performance of WDOA under different modulation indices.

The remainder of the paper is organized as follows: Section 2 provides a concise overview of multi-level cascaded inverters. Section 3 elucidates the working principles of the Weevil Damage Optimization Algorithm (WDOA). In Section 4, we present the optimization model leveraging WDOA for harmonic elimination and THD minimization. Section 5 presents the numerical simulation results and their analysis. Finally, Section 6 concludes the paper, summarizing key findings and outlining avenues for future research.

II. Multi-Level Inverters

The single-phase cascaded H-bridge multi-level inverter circuit topology is shown in Fig. 1(a). A separate DC source feeds each single-phase H-bridge (full bridge). The four main switches, S11, S12, S13, and S14, of each inverter can be combined in different configurations to transmit the DC source to the AC output as +VDC, 0, or - VDC shown in Fig. 1(a). Cascaded H-bridge multi-level inverters produce output voltage levels that are more than twice the number of separate DC sources. By applying the Fourier transformation, the step waveforms can be expressed in the following manner [25]-[32]: In Fig. 2(b), the Fourier analysis coefficients of the inverter output waveform are given in equation (1) for fundamental and the equation (2) for fundamental, 5th, 7th, 11th and 13th order harmonics.

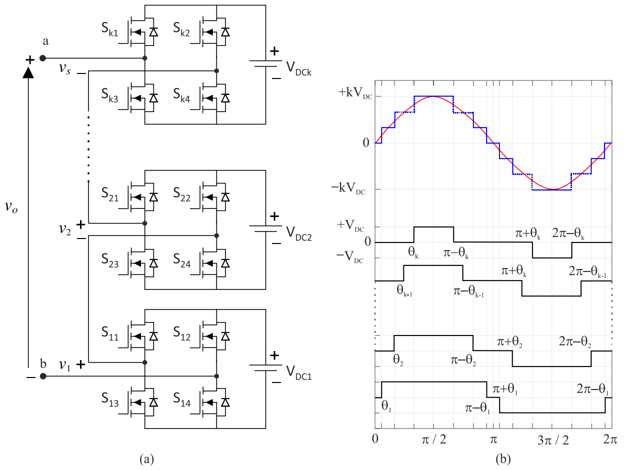

Fig. 1. Single-phase N-level CHB-MLI (a) circuit structure (b) output voltage waveform

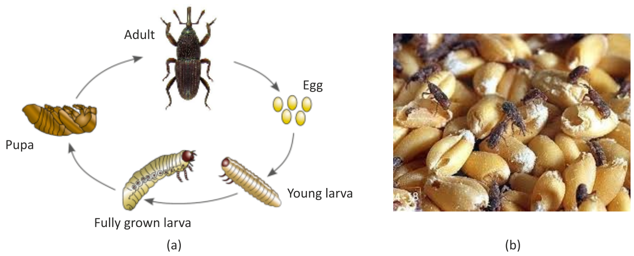

Fig. 2. Wheat weevil (a) of life cycle and (b) crop damages

$$V(\omega t)=\frac{4V_{dc}}{\pi}\sum_{n}[cos(n\theta_1)+cos(n\theta_2)+\cdots+cos(n\theta_s)] \\ sin\left(\frac{n\omega t}{n}\right),\quad n=1,3,5,7,\cdots \tag{1}$$

$$H(n)=\frac{4}{n\pi}\sum_{n}[cos(n\theta_1)+cos(n\theta_2)+\cdots+cos(n\theta_k)] \\ n=1,3,5,7,\cdots \tag{2}$$

Here, the switching angles $\theta_1, \theta_2, \ldots, \theta_k$ must satisfy the restriction given in equation (3).

$$0\le\theta_1\le\theta_2\le\ldots\le\theta_k\le\frac{\pi}{2} \tag{3}$$

Two different harmonic values were measured in the study. The first is THD%, and the other is THDe%. The equations of these harmonics are given in equations (4) and (5), respectively. The THD% limit value is normally infinite but will be considered up to the 50th harmonic. THDe represents the total value of the harmonics to be eliminated. When calculating the THDe% [33]-[40] value, the maximum harmonic value to be eliminated is taken into account [40]-[62].

$$\%THD=\frac{\sqrt{V_5^2+V_7^2+V_{11}^2+\cdots V_{49}^2}}{|V_1|} \tag{4}$$

$$\%THD_e=\frac{\sqrt{V_5^2+V_7^2+\ldots}}{|V_1|} \tag{5}$$

The purpose of the optimization model is to lessen the occurrence of odd-order, low-frequency harmonics. If there are k H-bridges, then $k-1$ harmonics may be eliminated. For seven levels, three equations are created. The first equation is used to control the fundamental harmonics, and the other equations are used to eliminate the selected harmonics in question (6).

$$\begin{aligned} h(1)&=cos(\theta_1)+cos(\theta_2)+cos(\theta_3)=3Mk\frac{\pi}{4} \\ h(5)&=cos(5\theta_1)+cos(5\theta_2)+cos(5\theta_3) \\ h(7)&=cos(7\theta_1)+cos(7\theta_2)+cos(7\theta_3) \end{aligned} \tag{6}$$

There are five h-bridges for the 11-level h-bridge cascade multi-level inverter. Therefore, four harmonics can be eliminated.

$$\begin{aligned} h(1)&=cos(\theta_1)+cos(\theta_2)+cos(\theta_3)+cos(\theta_4) \\ &\quad+cos(\theta_5)=5Mk\frac{\pi}{4} \\ h(5)&=cos(5\theta_1)+cos(5\theta_2)+cos(5\theta_3) \\ &\quad+cos(5\theta_4)+cos(5\theta_5) \\ h(7)&=cos(7\theta_1)+cos(7\theta_2)+cos(7\theta_3) \\ &\quad+cos(7\theta_4)+cos(7\theta_5) \\ h(11)&=cos(11\theta_1)+cos(11\theta_2)+cos(11\theta_3) \\ &\quad+cos(11\theta_4)+cos(11\theta_5) \\ h(13)&=cos(13\theta_1)+cos(13\theta_2)+cos(13\theta_3) \\ &\quad+cos(13\theta_4)+cos(13\theta_5) \end{aligned} \tag{7}$$

In equations (6) and (7), M represents the modulation index. M can be defined as the ratio of the peak value (h_{1p}) of the desired base voltage given in (8) to the total DC input voltage [42]-[55].

$$M=\frac{h_{1p}}{kV_{DC}} \tag{8}$$

$h(1)$ is the fundamental harmonic, and its voltage should be modified such that it corresponds to the fundamental voltage that is wanted. Equations $h(5)$, $h(7)$, $h(11)$, and $h(13)$ are considered to be chosen harmonics, and they have to have a value of zero. In this study, the fitness function given in equation (9) is used for a 7-level multi-level inverter.

$$f=\min_{\theta_i}\{|h_{ref}-h_{1p}|+(h_5)^2+(h_7)^2\}=0 \tag{9}$$

For an 11-level multi-level inverter, the conformity function given in equation (10) is used.

$$f=\min_{\theta_i}\{|h_{ref}-h_{1p}|+(h_5)^2+(h_7)^2+(h_{11})^2+(h_{13})^2\}=0 \tag{10}$$

The fitness function given in Equation (9) and (11) includes the selected harmonics. The WDOA algorithm will solve these equations.

$$WDOA = ESI \sum_{i=1}^{n} \sum_{DDV=1}^{n} (W_{i0}[\varphi, \psi]) * RIR\ of\ \mu \tag{11}$$

III. Weevil Damage Optimization Algorithm

Weevil Damage Optimization Algorithm (WDOA) is a metaheuristic optimization algorithm [13]. This algorithm mimics the damage power of weevils on agricultural products and utilizes this power to optimize it. WDOA operates as a swarm-based algorithm, meaning it enables interaction among a group of individuals or solution candidates. This algorithm attempts to solve optimization problems by modeling the natural behaviors of weevils. The working principle of the algorithm starts by creating a population where individuals (weevils) represent potential solutions. Each individual represents the parameters or variables of a solution. These solutions contain suitable parameter values to optimize the target function, which is desired to be maximized or minimized in agricultural products or other optimization problems. WDOA, different components that mimic the flight power, snout power, and damage power of weevils. Flight power represents the search ability in the solution space, while snout power symbolizes the changeability of solutions. Damage power enables the solutions to adapt in order to reach the optimal value of the target function.

WDOA works as an iterative process that allows individuals to come together and discover the best solutions. In each iteration, the new positions and fitness values of individuals are calculated. In this way, the population approaches better solutions over time. The advantages of WDOA include its ability to process parallel, its ability to provide diversity, convergence to the global optimum, and its suitability for different optimization problems. Therefore, WDOA is an effective algorithm used in agriculture, engineering and other optimization fields.

WDOA stands for Weevil Damage Optimization Algorithm. It is a metaheuristic optimization algorithm used to find an optimal solution for the environmental situation in weevil populations. The algorithm follows the following steps until the termination condition is met:

1. The best individual from the previous population is preserved.
2. The Snout Power Rate (φ) and Fly Power Rate (ψ) of each weevil are calculated and scattered based on the Environmental Situation Index (ESI).
3. The Damage Decision Variable (DDV) determines the damage of each weevil, where higher damage power increases the chances of survival.
4. The mutation rate (μ) known as the Reproduction Environment Rate (RIR) affects the diversity of the population. Higher values of μ lead to better exploration of the search space.
5. The ESI value is calculated for each weevil, and the population is sorted. The best individual from the previous generation and the new best individuals moves on to the next generation. The algorithm aims to optimize the ESI and find the best environment for weevil reproduction.

IV. Test and Results

Harmonic elimination in the multilevel inverter, Weevil Damage Optimization algorithm has been tested on 7 and 11 level inverters. The WDAO optimization source code given in [13] has been modified to be used in the multilevel harmonic elimination problem. It was implemented using MATLAB software. Test simulations were performed on a laptop with Intel(R) Core (TM) i7-10870H CPU @ 2.20GHz, 16.0GB, GeForce RTX 2060 NVIDIA graphics card. In the simulations, for the 7 and 11 level multilevel inverter, tests were performed for modulation indices 0.1 to 1 in increments of 0.02. The optimization simulations for each modulation index, and the best numerical results were reported and shown in the Fig. 3 to Fig. 6.

The optimal switching angles of a 7-level cascaded multilevel inverter for various modulation indices are shown in Fig. 3. On the other hand, Fig. 4 presents the graph of THD, THDe, 5th, and 7th harmonic values for modulation indices ranging from 0.1 to 1. The graph indicates that THDe values are zero for modulation indices of 0.5 and above.

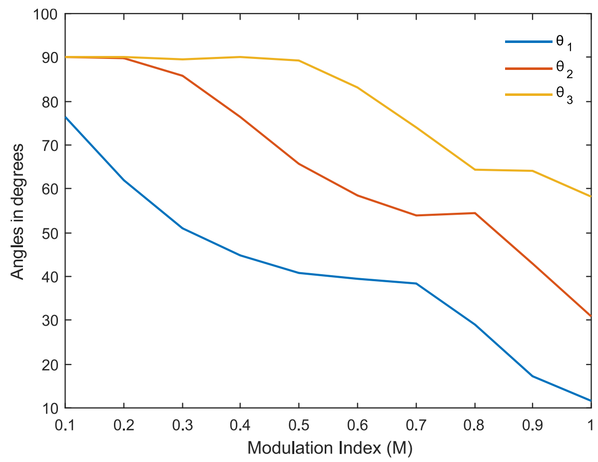

Fig. 3. Optimum switching angles for different modulation indexes (7 level multilevel inverter)

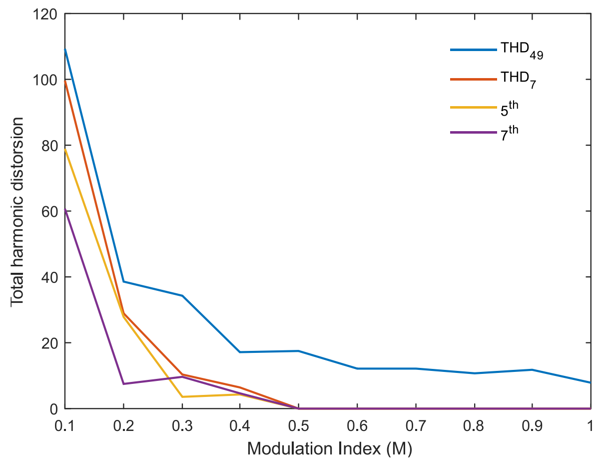

Fig. 4. THD for different modulation indexes (7 level multilevel inverter)

Similarly, Fig. 5 shows the optimal switching angles of an 11-level cascaded multilevel inverter for a variety of modulation indices. Fig. 6 displays the graph of THD, THDe, and selected harmonics (5th, 7th, 11th, and 13th) for modulation indices ranging from 0.1 to 1. Again, the graph shows that THDe values are zero for modulation indices of 0.5 and above.

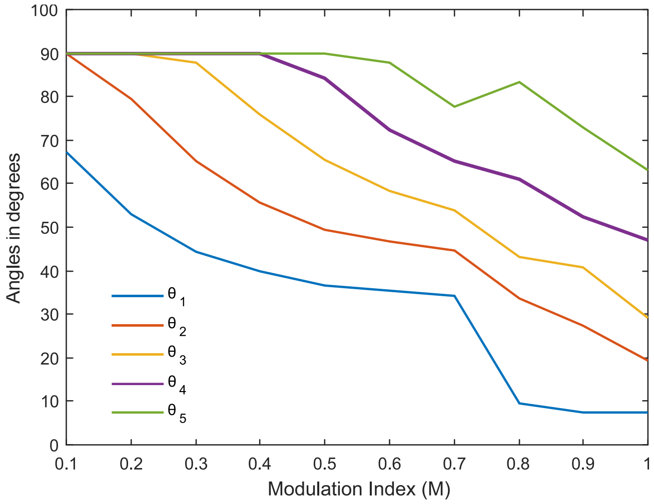

Fig. 5. Optimum switching angles for different modulation indexes (11 level multilevel inverter)

A more detailed description of the calculations is presented in Table I for the 7-level case and Table II for the 11-level case. As shown in Table I, WDOA was able to find solutions for the optimum THD within a wide range of modulation indices from 0.1 to 1.0 for the 7-level case. However, the algorithm identified the optimal modulation range for Selective Harmonic Elimination-Pulse-width modulation (SHE-PWM) to be between 0.5 and 1.0.

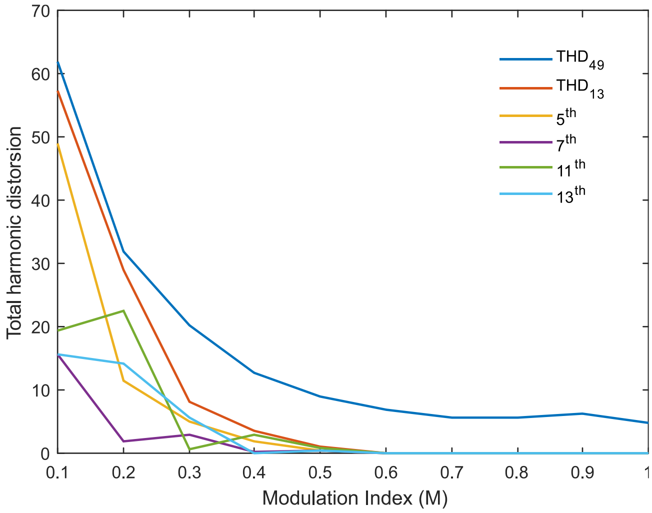

Fig. 6. THD for different modulation indexes (11 level multilevel inverter)

Similarly, in Table II, WDOA found solutions for the optimum THD within a wide range of modulation indices from 0.1 to 1.0 for the 11-level case, and the optimal modulation range for SHE-PWM was again between 0.5 and 1.0.

TABLE I. MODULATION INDEX & SWITCHING ANGLES AND HARMONIC ANALYSIS (FOR 7 LEVEL)

M	**Switching angles (degree)**			**Fundamental Voltage**			**Harmonics**			
	θ1	**θ2**	**θ3**	**Vref(rms)**	**V(rms)**	**error (%)**	**THD (%)**	**THDe (%)**	**h5**	**h7**
0.10	76.4076	90.0000	90.0000	22	21.99	0.05	109.15	99.52	78.91	60.65
0.20	62.0154	89.8860	89.9992	44	43.93	0.16	38.42	28.99	27.96	7.67
0.30	51.0544	85.8275	89.6839	66	65.86	0.21	34.41	10.28	3.73	9.58
0.40	44.7920	76.5375	90.0000	88	87.83	0.19	17.14	6.43	4.39	4.70
0.50	40.7858	65.8061	89.3632	110	109.7	0.27	17.45	0.08	0.03	0.02
0.60	39.4143	58.5396	83.0648	132	131.8	0.15	12.22	0.09	0.02	0.09
0.70	38.2985	53.9176	73.9122	154	153.7	0.19	12.25	0.04	0.02	0.03
0.80	29.1579	54.4048	64.4603	176	175.7	0.17	10.66	0.05	0.01	0.04
0.90	17.3485	42.8314	64.0712	198	198	0.00	11.80	0.04	0.02	0.02
1.00	11.6242	30.8025	58.3597	220	220	0.00	7.80	0.05	0.01	0.03

TABLE II. MODULATION INDEX & SWITCHING ANGLES AND HARMONIC ANALYSIS (FOR 11 LEVEL)

M	**Switching angles (degree)**					**Fundamental Voltage**			**Harmonics**					
	θ_1	**θ_2**	**θ_3**	**θ_4**	**θ_5**	**Vref(rms)**	**V(rms)**	**error (%)**	**THD (%)**	**THDe (%)**	**h5**	**h7**	**h11**	**h13**
0.10	67.404	89.756	89.762	89.998	90.000	22	21.96	0.18	61.86	57.24	49.07	15.66	19.37	15.74
0.20	52.943	79.394	90.000	90.000	90.000	44	43.92	0.18	31.97	29.04	11.49	1.89	22.49	14.21
0.30	44.295	65.107	87.694	89.787	90.000	66	65.91	0.14	20.22	8.09	5.09	2.88	0.64	5.55
0.40	39.790	55.714	75.870	90.000	90.000	88	87.9	0.11	12.64	3.47	1.89	0.24	2.90	0.07
0.50	36.710	49.560	65.448	84.178	90.000	110	109.8	0.18	9.06	1.08	0.50	0.36	0.79	0.42
0.60	35.334	46.879	58.475	72.399	87.682	132	132	0.00	6.89	0.06	0.02	0.02	0.03	0.01
0.70	34.234	44.684	54.013	65.326	77.736	154	153.7	0.19	5.56	0.06	0.04	0.01	0.02	0.02
0.80	9.660	33.542	43.178	61.079	83.425	176	175.6	0.23	5.57	0.03	0.01	0.02	0.01	0.01
0.90	7.527	27.318	40.654	52.372	72.973	198	197.6	0.20	6.22	0.04	0.01	0.00	0.02	0.03
1.00	7.570	19.246	29.107	47.108	63.020	220	219.9	0.05	4.84	0.04	0.02	0.01	0.01	0.02

V. CONCLUSION

This article uses a newly developed heuristic WDOA method to solve the problem of harmonic elimination and THD for multi-level inverters. The 7-level and 11-level multi-level inverters were employed to showcase the effectiveness of the optimization model in minimizing THD and eliminating harmonics. The optimal switching angles were computed for different modulation indices, and the corresponding THD values were presented as the simulation results. For the 7-level case, the fundamental voltage is controlled with less than 0.27% error, as can be seen, while the selected harmonics are effectively suppressed. Similarly, for the 11-level inverter case, the fundamental voltage is controlled with less than 0.23% error and the selected harmonics are effectively suppressed. Thus, with numerical simulations, it has been shown that the WDOA algorithm successfully solves the harmonic elimination problem.

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