

A Novel NR-DA-Based ANN for SHEPWM in Cascaded Multilevel Inverters for Renewable Energy Applications

D. Vasavi Krishna¹, M. Surya Kalavathi¹, B. Ganesh Babu^{1,2}

Abstract: Harmonics is the major power quality problem caused by nonlinear devices, leading to malfunction or operational halt of the system. Low-order harmonics increase vibration and heat generation in motors. Therefore, controlling harmonics in the output waveform is the prime target for industrial applications to avoid economic loss. Selective harmonic elimination pulse width modulation (SHEPWM) is one of the techniques used for eliminating or minimizing selected harmonics in the output voltage waveform. This paper utilizes the Newton-Raphson method and Dragonfly Algorithms to calculate optimum switching angles for a Cascaded H-bridge Multilevel inverter (CHBMLI). The algorithms use non-linear equations to calculate the Switching Angles of MLI. The Dragonfly algorithm requires several iterations to reach an optimum solution. For complex problems, this algorithm becomes computationally expensive and time-consuming. A lookup table addresses the limitation by offline training an Artificial Neural Network (ANN) to generate the optimum switching angle for a given modulation index. Neural Fitting Tool in MATLAB software is used to train the ANN model. The simulation is performed using MATLAB SIMULINK software for both 5-level and 7-level CHBMLI configuration. The Dragonfly algorithm-based ANN achieves THD 8.84% when the modulation index (M) equals 0.8 for a 7-level inverter and THD 14.91% for a 5-level inverter and effectively minimizes third and fifth-order harmonics.

Keywords: SHEPWM, Newton-Raphson algorithm, Dragonfly Algorithm, Artificial Neural Network, Neural Fitting Tool.

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1. Introduction

Harmonic distortion is a serious concern due to the rapid growth of nonlinear loads, which include power electronics, variable frequency drives, and inverters. Switching devices such as metal-oxide-semiconductor field-effect transistors (MOSFET) and insulated-gate bipolar transistors (IGBT) within inverters turn on and off quickly using methods like pulse width modulation (PWM) to create pulses, which approximate a sine wave. When these devices turn on, there is a sudden increase in the waveform. When they turn off, it causes an abrupt stoppage of the current flow, which means the waveform suddenly drops. High-frequency components are created by the rapid transitions from on to off in all the switches. These harmonics harm the power quality and system performance [1]. Hence, mitigation of the harmonics is necessary. Several methodologies in PWM have been developed to reduce undesirable harmonics they are carrier-based PWM,

space vector PWM, and SHEPWM [2]. SHEPWM eliminates certain harmonics that can reduce distortions and improve power quality.

The SHE is a mathematical technique that generates the required switching angles by solving nonlinear equations [3]. These nonlinear equations are obtained from the Fourier series expression of the output voltage waveforms for CHBMLI. Newton Raphson (NR) and Dragonfly Algorithm (DA) can be used to find the optimum switching angles for a CHBMLI by solving non-linear equations [4-5]. The Newton-Raphson method represents an iterative technique through which, from nonlinear equations, the roots can be obtained. It is a very suitable method for exploitation because it refines and continuously improves known solutions to give better overall performance. It has no mechanisms to study the entire solution space, therefore, it can never guarantee global optimum.

The Dragonfly algorithm is a nature-inspired technique. This algorithm iteratively changes or refines the switching angles to converge to a solution that gives minimum total harmonic distortion (THD). The Dragonfly algorithm effectively explores the solution space to find the optimal switching angle which minimizes the THD. It finds a global optimum rather than a local optimum solution. Since it is a metaheuristic, the Dragonfly algorithm requires more iterations to converge to an optimum or near-optimum solution [6]. Instead of directly optimizing the complex objective function using the Dragonfly Algorithm, a look-up table is created with every entry containing a pair of input and output to train the ANN model effectively using the neural fitting tool in MATLAB software [7]. The ANN model is trained with the data set and the outputs will be predicted for a given input [8]. These predicted values are then used in 5-level and 7-level CHBMLIs. The harmonic spectrum of the resulting voltage waveform is taken out to analyse the harmonic content. This refines the overall efficiency and effectiveness of the optimization process by reducing the computational burden and improving the quality of the solution.

This paper presents the implementation of the Newton Raphson and the Dragonfly algorithms with

ANN for effective harmonic elimination in the output waveform of 5 and 7-level CHBMLI as shown in Fig.1.

This research paper is organized as follows:

Section-1: Explains gives an overview of this paper including the block diagram of the system.

Section-2: Explains the total control methodology of CHBMLI and its basic operation. And gives details about the SHEPWM technique.

Section-3: Explains the implementation of Newton Raphson and the Dragonfly algorithms with ANN and explains their application within the context of solving SHEPWM equations for CHBMLI.

Section-4: this section presents about the results and discussions with literature, and

Section-5: It presents the conclusions

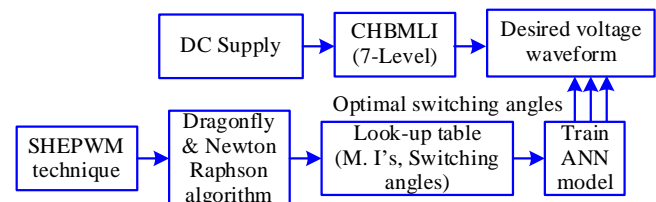


Fig. 1: Block Diagram of ANN-Based Dragonfly and Newton Raphson Algorithm

2. Test system

2.1 Cascaded Multi level inverter

Because of its advantages, multilevel inverters are much preferred by many industrial applications. They can handle higher voltage and power levels better than 2-level inverters. MLI, compared to the 2-level inverter, produces a more sinusoidal waveform.

The MLI reduces the voltage stress on each power device by dividing its total voltage among these devices, and every device handles just a fraction of the total output voltage.

Different topologies of multilevel inverters are

- Cascaded H-bridge MLI,
- Diode clamped MLI,
- Flying capacitor MLI.

The cascaded MLI has several advantages over the other two MLIs. Cascaded MLIs have fewer components, lower weight, and less cost. In the cascade 5-level inverter, two single-phase full-bridge (H-Bridge) inverters are connected in series to produce the required output voltage as shown in Fig. 2. Adding the

outputs of each single-phase H-bridge inverter provides the overall output. This circuit will give the following output voltage: $V_{out} = V_1 + V_2$. If there are m DC sources, then in a CHBML inverter. There are $L = 2m + 1$ voltage levels. The number of switching angles required for an L -level multilevel inverter is given by $n = (L - 1)/2$. The switching table of proposed system is shown in Table.1.

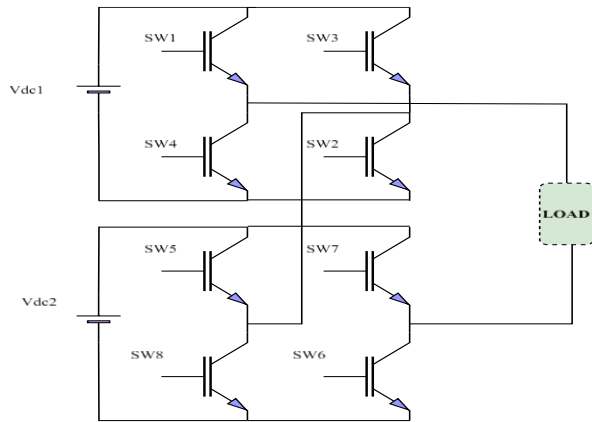


Fig. 2: 5-Level Inverter Circuit

Table. 1: Switching Sequence of 5-Level CHB Inverter

Switches Turn On	Voltage Level
S1, S2, S5, S6	+2Vdc
S1, S2, S6, S8	+Vdc
S1, S3, S5, S7	0
S3, S4, S5, S7	-Vdc
S3, S4, S7, S8	-2Vdc

2.2. SHE-PWM Technique

SHEPWM is a method applied in power electronics to control inverter output by eliminating some of the harmonics in the waveform. In this technique, the most appropriate switching angles of inverter switches are computed with the help of sets of nonlinear transcendental equations. These nonlinear transcendental equations have been derived from a Fourier analysis of the desired output waveform for eliminating specific harmonic frequencies. In the SHEPWM technique, the inverter output voltage of the CHBMLI is represented by using an equation (1-3)

$$f_n(t) = (t) = + \sum_{n=0}^s (A_n \cos(n\omega t) + V_n \sin(n\omega t)) \quad (1)$$

$$A_0 = \frac{1}{2\pi} \int_0^{2\pi} f(t) dt; A_0 \text{ is the DC component} \quad (2)$$

$$A_n = \frac{1}{\pi} \int_0^{2\pi} f(t) \sin n\omega t dt; \\ A_n \text{ represent even harmonics} \quad (3)$$

$$V_n = \frac{1}{\pi} \int_0^{2\pi} f(t) \cos n\omega t dt; V_n \text{ is odd harmonics} \quad (4)$$

Because of odd quarter wave symmetry, even-order harmonic amplitudes become zero. For a 5-level inverter, the above expression (4) become

$$V_{fun} = \frac{4V_{dc}}{n\pi} [\cos(\alpha_1) + \cos(\alpha_2)]$$

$$V_{3rd} = \frac{4V_{dc}}{3\pi} [\cos(3\alpha_1) + \cos(3\alpha_2)]$$

$$V_{5th} = \frac{4V_{dc}}{5\pi} [\cos(5\alpha_1) + \cos(5\alpha_2)]$$

$M = \frac{\pi V_1}{4nV_{dc}}$ (n -number of DC sources; V_i is the amplitude of the fundamental component of the output voltage)

$$\cos(\alpha_1) + \cos(\alpha_2) - 2M \quad (5)$$

$$\cos(3\alpha_1) + \cos(3\alpha_2) = 0 \quad (6)$$

$$\cos(5\alpha_1) + \cos(5\alpha_2) = 0 \quad (7)$$

To eliminate the third harmonic equation (6) should equate to zero and equation (5) to the modulation index. To eradicate the fifth harmonic equation (7) to zero and equation (5) to the modulation index. The modulation index ranges from 0 to 1, and switching angles (α_1 & α_2) range from 0 to 90 degrees [$0 \leq \alpha_1 \leq \alpha_2 \leq \frac{\pi}{2}$]. For higher-order multilevel inverters, deriving nonlinear equations that determine the optimal switching angles can be computationally expensive and challenging. As a result, numerous algorithms are employed to resolve the equations.

3. Proposed method

3.1 The Newton-Raphson method

The Newton-Raphson method is an iterative technique, effective in determining the roots of nonlinear equations. This technique is highly dependent on initial estimation. Incorrect initial estimation can lead the algorithm to diverge, convert

slowly, or even converge to a different root than the desired one. The computation of the switching angles for all possible combinations using the Newton-Raphson method becomes complex when more levels are to be added to the inverter. In such cases, optimization algorithms can be used instead. The solution for SHEPWM-based polynomial equations using the Newton-Raphson method involves the following steps.

- **Initial Guess:** Assume the initial guess for the switching angles. Jacobian and nonlinear system matrices: Find the Jacobian matrix DF and compute the nonlinear system matrix F.
- For 7-level, it requires 3 switching angles (α_1 , α_2 , and α_3)
- The solutions should meet the following conditions $0 \leq \alpha_1 \leq \alpha_2 \leq \alpha_3 \leq \frac{\pi}{2}$
- **Compute $\Delta\alpha$:** On every iteration compute $\Delta\alpha$:

$$\Delta\alpha = \frac{\delta F^j}{\delta \alpha} * (B - F^j)$$
 Convergence check: if $\Delta\alpha=0$ then end; otherwise go to the next step.
- **Update Angles:** Update new commutation angles as (8) below

$$\alpha(k+1) = \alpha(k) + \Delta\alpha(k) \quad (8)$$
 where k is the number of the iteration.
- **Repeat:** if $\Delta\alpha \neq 0$, go back to step 2 and repeat.

Using the steps mentioned above gives the switching angles at different modulation indices. The disadvantage of the Newton-Raphson method is that the difficulty and complexity increase with the increase in the number of levels because computing the Jacobian matrix becomes very difficult. Compared to the Newton-Raphson approach, the Dragonfly Algorithm has advantages. The global optimization strategy and population-based approach of the Dragonfly Algorithm allow it to efficiently handle the higher dimensionality and complexity of optimization problems that multilevel inverters present.

3.2 Dragonfly Algorithm

The Dragonfly Algorithm follows the principles of swarm intelligence and is inspired by the self-organized collective behaviors of dragonflies, like hunting strategies, migration for food, and predator-avoiding techniques. The dragonfly population is

divided into a migration swarm and a feeding swarm. Migration swarm refers to the situation where dragonflies are in a huge group, and fly a long distance in a unified direction in search of a better area to feed or to avoid unfavorable weather. This behavior during their migration gives them the advantage of traveling easily and increases their survival chance in case of any threats. The high cohesiveness of dragonflies in an active swarm or migration setting represents good coordination or communication. In this case, each dragonfly acts like an agent interacting with every other agent to exchange information obtained about the food sources or threats. By effective communication, the swarm will converge towards optimal or best solutions.

However, the swarm has a low alignment, meaning the individual dragonflies have less tendency to adjust their flight directions towards the global best solution found within the swarm. This balance is good for exploitation. In a feeding swarm, the dragonflies congregate in small groups and have to travel shorter distances, enabling the exploration of nearby areas thoroughly. It possesses low cohesion and high alignment, making it good for exploration. Dragonflies can explore in the solution space and find better solutions. Thus, exploration and exploitation of areas are possible with the dragonfly algorithm, resulting in the optimal solution. The parameters of this algorithm are presented in Table.2.

The different steps of the Dragonfly Algorithm for optimization are as follows.

- Initialization:** Initialize a Random Population of dragonflies.
- Evaluate Objective Function:** Based on the dragonfly position, the objective function of optimization will generate the fitness value for the solution. Update the weights according to iteration number and randomness
- Levy Flight Movement:** Levy flights are random flights that allow the dragonfly to explore the search space at any moment when the information in the location is insufficient. An operation to allocate a new position to the dragonfly is needed in cases where a dragonfly fails to find a neighboring individual with the highest fitness value or in the absence of a neighbor.
- Swarm behavior:** A dragonfly finds a neighbor individual or while in the company of a neighbor

having the highest fitness value, it executes swarm behavior: separation, alignment, and cohesion, including attraction towards food and distraction from enemies.

- i. **Separation:** The tendency for dragonflies to keep a certain distance between themselves to prevent overcrowding within the swarm allows better exploration.
- ii. **Alignment:** The fact that dragonflies can align the direction of their movement with neighbors in a swarm allows the swarm to share information regarding any known food locations, thus optimizing overall system performance.
- iii. **Cohesion:** Cohesion refers to the extent to which each dragonfly in a swarm holds on to each other and cooperates to achieve a common objective, the food resources, which leads to more rational performance.
- iv. **Attraction:** Attraction means that the dragonfly moves toward food, enabling them to explore and utilize available food resources.
- v. **Distraction:** This makes the dragonfly, through its behavior of distractibility, avoid danger by diverting its motion and helps in exploring new regions. This will ensure its survival in the long term because it's always in search of safer zones with minimal threats.
- e. **Position Update:** Dragonflies update their positions by group behaviors such as Levy flight patterns or swarm interactions. Before updating the position of dragonflies, the step factor needs to be calculated, describing their movement and the position vector, which represents the current location.
- f. **Termination Criteria:** Repeat step 'b' followed by steps 'c' and 'd', until termination is reached, depending upon the neighbor's presence.
- g. **End:** Once all the procedures are completed, the food position consists of the set of desired switching angles.
- h. The best switching angles for different modulation indices can be obtained at the end of all steps.

The dragonfly algorithm requires large numbers of iterations because the algorithm fine-tunes the switching angles iteratively to converge upon a solution where the THD is minimum. Applying the

dragonfly algorithm to solve real-world optimization problems may be time-consuming and computationally demanding. Therefore, by running the Dragonfly Algorithm for different modulation indices, a lookup table is developed. This data set is used to train an Artificial Neural Network. The ANN model is created by using the data that links a switching angle to a modulation index and is useful in predicting the best switching angle for any modulation index to enhance speed and effectiveness.

Table. 2: Parameters of the dragonfly algorithm

S.no	Parameters	Values
1.	Number of agents	100
2.	Number of iterations	200
3.	Separation factor	0.6
4.	Alignment factor	0.8
5.	Cohesion factor	0.5
6.	Food attraction factor	0.9
7.	Enemy distraction factor	1

3.3 Artificial Neural Network

ANNs have been inspired by the structure and functioning of the human brain. Information is passed in the human brain from one neuron to the other with the help of synapses. In ANNs, the information is passed via multiple interconnected artificial neurons or nodes arranged in layers. This hierarchy of an ANN allows it to learn complicated details by processing data through a series of hidden layers. The first layer of the ANN is the input layer, which is made of neurons that receive the input data as shown in Fig. 3. Hidden layers of a neural network fall between the input and output layers. Additional hidden layers allow ANNs to model and represent the most complicated nonlinear patterns within the data. The number of hidden layers to be used for the Artificial Neural Network is case-dependent on the complexity of the task and the number of available training data. Few hidden layers are sufficient for simple tasks with small datasets. More complex tasks, associated with large data sets, typically consist of multiple hidden layers. During forward propagation, the output layer uses the output from the last hidden layer to make the final outputs. Now, in each hidden or output neuron, a weighted sum of the inputs is computed after which a bias is applied, and the result is passed through an activation function.

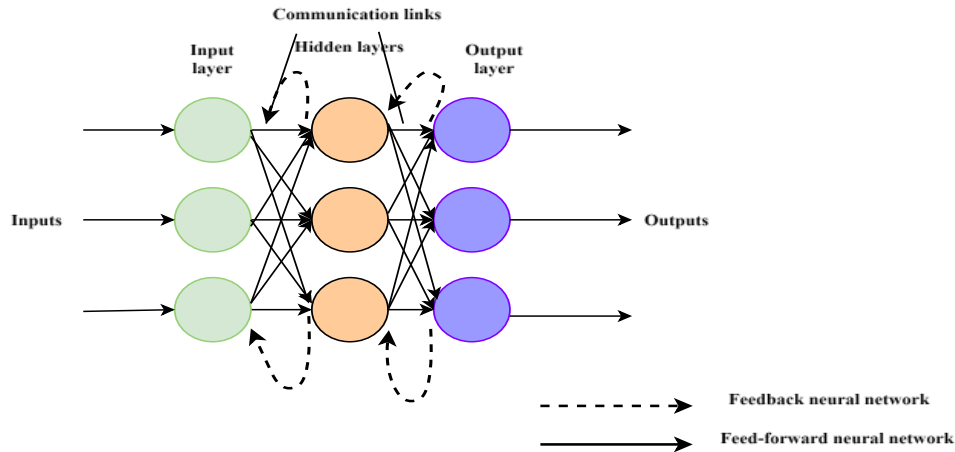


Fig. 3: ANN architecture

3.4. Training of the ANN

The ANN model is trained using a Neural Fitting Tool in MATLAB software. The Neural Fitting Tool of MATLAB software solves input-output fitting problems using a two-layered feed-forward neural network. By following the steps below, train the Neural Network,

Step-1. Collection of Data: A dataset is created by running the Dragonfly algorithm and Newton Raphson for different modulation indices and listing corresponding switching angles. Now, data would be split into 3 sets: training set, validation set, and testing set. Also, the percentage in the distribution of a given dataset would now be 70% for training and 15% for validation, leaving the remaining 15% for testing.

Step-2. Network Structure: Feedforward neural networks are used for fitting. Determine the number of hidden layers and neurons in the network. The number of hidden layers has a greater impact on the learning capability of the network.

Step-3. Network Training: To train the artificial neural network (ANN) model the Levenberg-Marquardt algorithm is leveraged as it works best with small- to medium-sized datasets.

Step-4. Testing of the Model: After training the ANN model using NFT in MATLAB, plot regression, and performance data.

Save the trained neural network and export it to a Simulink block. An imported neural network inside a Simulink model estimates optimum switching angles based on a specified modulation index. The 5-level and 7-level CHBMLIs then utilize the predicted angles. The

CHBMLI inverters consist of IGBTs, PWM pulse generators, and Direct current (DC) input voltage sources. The simulation runtime is set, and the simulations are run. After that, the obtained voltage waveform is analyzed for its harmonic content and THD based on FFT analyses

4. Results and Discussions

The 5-level and 7-level MLI simulation models were designed in MATLAB/Simulink using pulse generators, DC voltage sources, and Insulated Gate Bipolar Transistors (IGBTs). A 100V supply is provided to each H-bridge DC input, and an R load is used. These models were simulated to observe their performance using FFT analyses. The scope is connected to the voltage measurement block, which is parallel to the load, and the current measurement block is connected in series with the load. After running the simulation, the following outputs were obtained. The output voltage and current waveforms of 7 level CHBMLI are shown in Fig. 4 and Fig. 5, respectively.

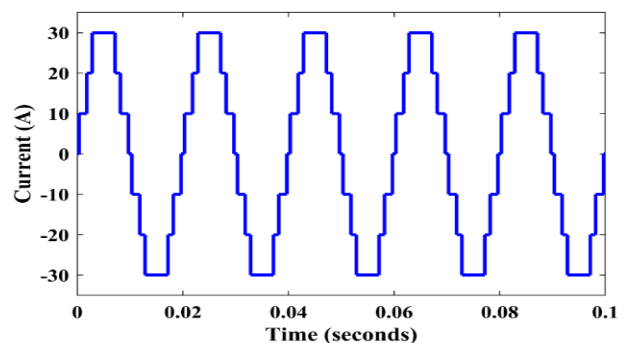


Fig. 4: Output voltage waveform of 7-level CHBMLI

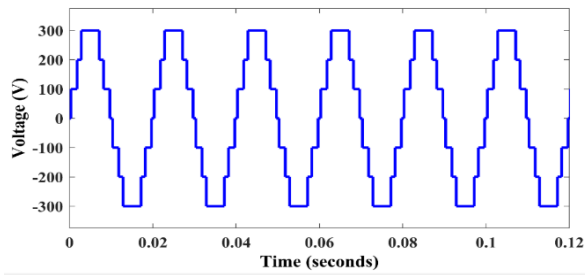


Fig. 5: Output current waveform of 7-level CHBMLI

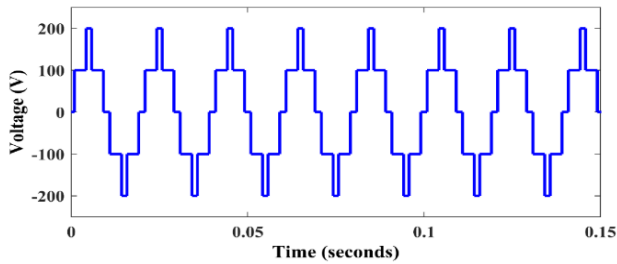


Fig. 6: Output voltage waveform of 5-Level inverter

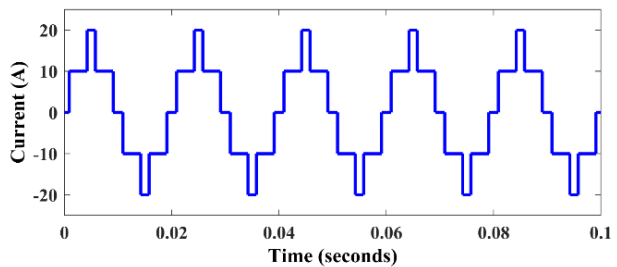


Fig. 7: Output current waveform of 5-level CHBMLI

The following is the FFT analysis on 5 and 7-level MLIs using the dragonfly algorithm and dragonfly algorithms with and without ANN. The output voltage and current waveforms of 5-level CHBMLI are shown in Fig. 6 and Fig. 7, respectively. FFT analysis on a 7-level inverter using the Dragonfly algorithm without ANN is 9.18 % as shown in Fig. 8 and with ANN is 8.84 % as depicted in Fig. 9.

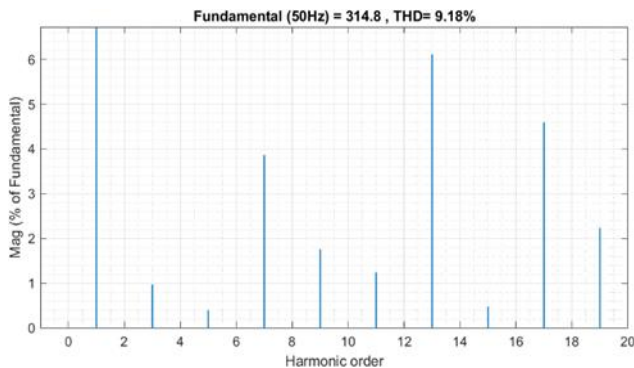


Fig. 8: FFT analysis on a 7-level inverter using the Dragonfly algorithm without ANN

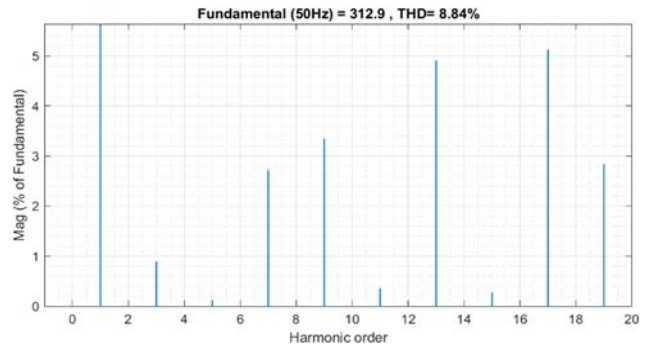


Fig. 9: FFT analysis on a 7-level inverter using the Dragonfly algorithm with ANN

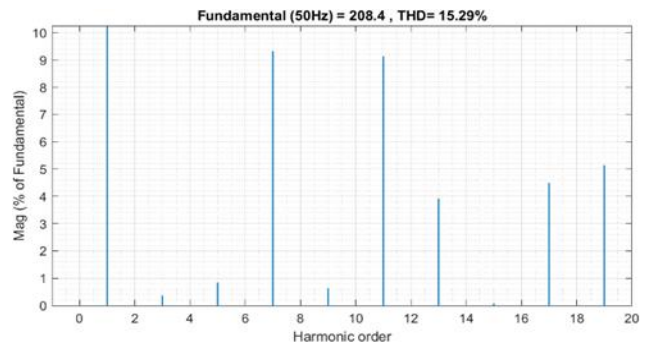


Fig. 10: FFT analysis on a 5-level inverter using the Dragonfly algorithm without ANN

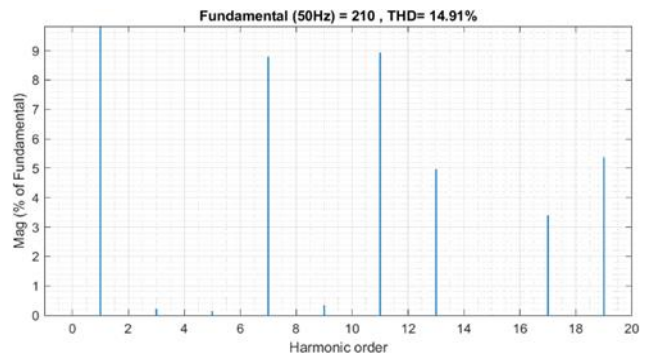


Fig. 11: FFT analysis on a 5-level inverter using the Dragonfly algorithm with ANN

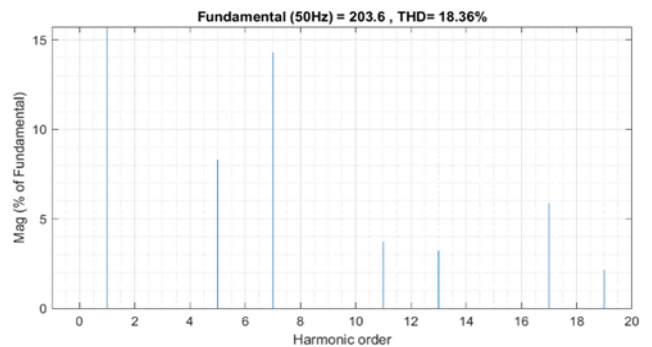


Fig. 12: FFT analysis on a 5-level inverter using Newton Raphson without ANN

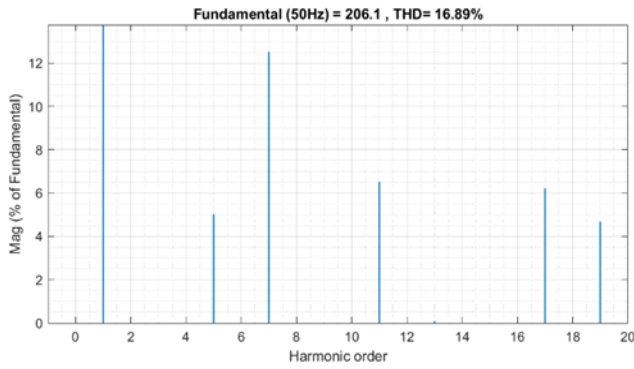


Fig. 13: FFT analysis on a 5-level inverter using Newton Raphson with ANN

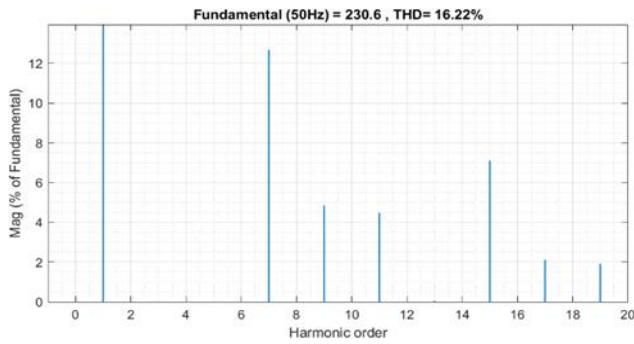


Fig. 14: FFT analysis on a 7-level inverter using Newton Raphson without ANN

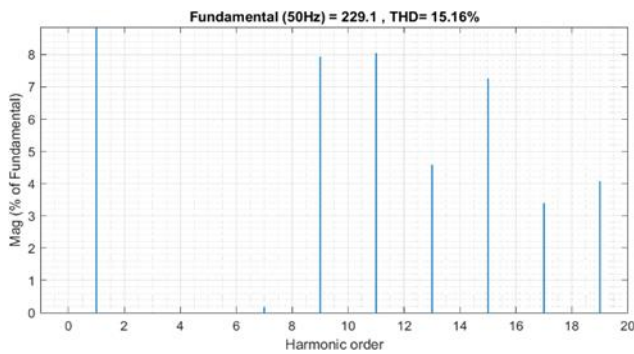


Fig. 15: FFT analysis on a 7-level inverter using Newton Raphson with ANN

Table. 3: FFT analyses for 5-level and 7-level inverters using Dragonfly and Newton-Raphson algorithms, with and without ANN

S.no	Algorithm	% THD of 5-Level CHBMLI	% THD of 7-Level CHBMLI
1.	Newton Raphson algorithm	18.36%	16.22%
2.	ANN-based Newton Raphson algorithm	16.89%	15.16%
3.	Dragonfly algorithm	15.29%	9.18%
4.	ANN-based dragonfly algorithm	14.91%	8.84%

Fig. 10 depicts the FFT analysis of 5 level inverter using the Dragonfly algorithm without ANN shows a THD of 15.29% and with ANN it is depicted in Fig. 11, which shows a THD of 14.91%. The FFT analysis of 5-level inverter using the Newton Raphson method without ANN shows a THD of 18.36% and with ANN it is 16.89% as shown in Fig. 12 and Fig. 13, respectively. Similarly, Fig. 14 and Fig. 15 shows a THD of 16.22% and 15.16 % Newton Raphson method without ANN and with ANN, for 7-level inverter respectively. Fig. 16 shows the THD versus modulation index for 7-level inverter using Newton Raphson and Dragonfly algorithms and Fig. 17 shows the THD versus modulation index using Newton Raphson and Dragonfly algorithms for 5-level inverters. The results comparison with various methods is shown in Table.3.

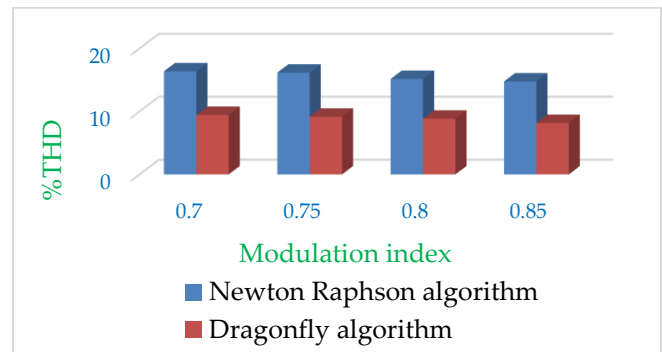


Fig. 16: Variation of %THDs with modulation index for a 7-level inverter using Dragonfly and Newton-Raphson algorithms with ANN

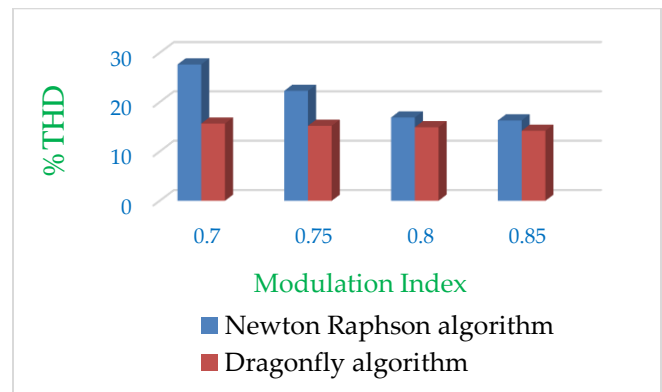


Fig. 17: Variation of %THDs with modulation index for a 5-level inverter using Dragonfly and Newton-Raphson algorithms with ANN

5. Conclusion

In this paper, the SHEPWM technique is employed to reduce selected low-order harmonics in 5-level and

7-level CHBMLI using both the Newton-Raphson and Dragonfly algorithms to determine optimal switching angles. A look-up table is created by applying these algorithms to various modulation indexes. The table trained an ANN, enabling the ANN to produce the optimal switching angle for a given modulation index. ANN model is trained using a Neural Fitting Tool in MATLAB software. The simulation is performed using MATLAB SIMULINK software for both 5-level and 7-level CHBMLI configuration. For a 5-level inverter, using the Dragonfly algorithm, the %THD decreased from 15.29% (without ANN) to 14.91% (with ANN). And, using the Newton-Raphson algorithm, the %THD increased from 18.36% (without ANN) to 16.89% (with ANN). For a 7-level inverter, using the Dragonfly algorithm, the %THD reduced from 9.18% (without ANN) to 8.84% (with ANN). And, using the Newton-Raphson algorithm, the %THD decreased from 16.22% (without ANN) to 15.16% (with ANN). It is observed that the ANN is more beneficial since it results in lower THD, and the Dragonfly Algorithm gives lower THD compared to the Newton-Raphson algorithm. Hence, the ANN-based Dragonfly Algorithm can effectively minimize harmonics in inverter systems.

Conflict of interest: The authors declared “No conflict of interest”

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