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Research paper

Harmonic Elimination of Cascaded Multilevel Inverter using Metaheuristic Optimization Methods

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Abstract

The harmonic elimination of multilevel inverters is a complicated task that includes nonlinear transcendental equations. With the increase in the level of the multilevel inverter, the no of variables of the equation also increases which makes the problem more complicated. Metaheuristic optimization algorithms play an important role in finding out optimum switching angles required for elimination of harmonics in a lesser computational time avoiding multiple local minima. This paper deals with the harmonic elimination of cascaded multilevel inverter using whale optimization algorithm. The whale optimization method has the ability to escape local minima and it takes less time of computation of results. Results are verified theoretically by taking an example of a 15-level cascaded H-bridge inverter fed from equal d.c.sources. The above scheme well minimizes lower order harmonics and gives better output voltage and a low total harmonic distortion.

Keywords*: Selective harmonic elimination (SHE), cascade multilevel inverter (CMLI), whale optimization technique (WOA), Separate D.C. Sources (SDCS).*

1. Introduction

Multilevel inverters have generated a lot of attention among researchers in the power industry sector due to its ability to increase the output voltage levels making it fit for medium and large power applications and various applications in FACTS devices, traction, high-voltage d.c transmission system,etc[1].

2. Literature Review

The H bridge inverter could previously produce voltage levels such as +V, 0, -V. The output of a single bridge inverter may contain a harmonic content of more than 5 percent which may create problems in various applications like electric drives, etc. The solution to this problem is given by multilevel inverters. This basic unit consisting of an H bridge switching technique is extended to other circuits that can generate combined output voltage levels or multilevel.[2] Multilevel inverter topologies are classified into three different types such as neutral point clamped, flying capacitor (FC) and cascaded multilevel inverter (CHB).Among the conventional multilevel inverters, cascaded multilevel inverter has a lot of scope for the application in the power energy sector due to its improved quality output waveform and it's unique structure which utilizes connection of independent dc sources (SDCS) to each of the module in order to obtain high power output voltage levels without compromising the quality of the output. Each H-Bridge operates with a different switching scheme which is used for controlling harmonics. The output phase voltage is given by the addition of all voltages formed by H bridges These converters exhibit greater efficiency and better power quality than conventional 2-level inverters.[3] They have low voltage stress, more power handling capacity, etc. The utility of a multilevel inverter (MLI) is to attain the near sinusoidal output voltage from several D.C sources which has least harmonic component. Cascading of H bridge inverters is an important topology because it requires a very lowest amount of components in comparison to diode-clamped and FC type multilevel inverters .of water quality and status conditions of
It does not employ diodes for the voltage generation as employed in the other conventional multilevel inverter topologies and due to which the number of components required is significantly reduced at higher output voltage levels. Its modular structure, simple switching technique and lesser space requirement increases its importance in various applications. In CMLI, if 'a' is the number of d.c.sources of the H bridge joined in cascade, then the output phase voltage is 2a+1 levels and the line voltage is 4a+1.[4] Each H-Bridge operates at a different delay angle resulting in a staircase waveform of the output phase voltage. By implementing appropriate modulation schemes to CMLI, a near sinusoidal output voltage waveform can be obtained.[5] The harmonics of any system are divided into two categories i.e. lower order harmonics and higher order harmonics. In order to eliminate lower order harmonics such as 3, 5, 7,11,13,17 and19 the size of the filter components increases due to which there is an increase in cost and weight[6]. Hence as the method is not suitable, the solution to eliminate lower order harmonics is given by SHE equations for a multilevel inverter. In comparison to lower order harmonics, the higher order harmonics can be eliminated by connecting a low size filter. As the output voltage in CMLI is obtained by the combination of many SDCS to get the desirable a.c. value, hence it is essential to minimize the harmonics within the prescribed limits of IEEE standards.[7] The paper is presented as follows. In section II mathematical equations of SHE are given followed by the

introduction of WOA is section III followed by WOA flowchart in IV. The results of SHE problems using WOA are discussed in section V. followed by conclusion.

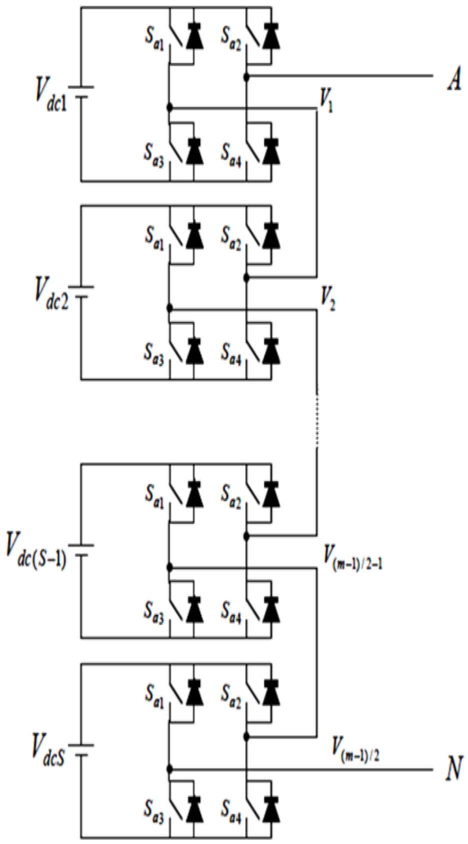

Fig 1: CMLI

3. Methodology

3.1. Equations for Selective Harmonics Elimination in a Cascade Multilevel Inverter:

The output voltage waveform is given by

$$V(wt) = \left\{\sum_{n=1,3,5...}^{\infty} \frac{4V_{dc}}{n\pi}(\cos(n\alpha_k)\sin nwt)\right\} \quad (1)$$

Where n is the harmonic number and constraints of with a constraints $0 \le \alpha_i \le 90^0$.There are many applications where the harmonic content is desirable at a value of less than or equal to 5 percent of its1st harmonic component. In SHE-PWM technique the switching angles are used to set the amplitude of the fundamental Harmonic component and cancel lower order harmonics at fundamental frequency .The output voltage waveform obtained in a cascaded multilevel inverter is a stepped waveform which is closer to sinusoidal wave form. Hence the harmonics those are to be eliminated are odd harmonics. For the elimination of n-1 harmonics, n numbers of switching angles are to be generated[8].In a balanced 3-phase circuits, the third harmonics is compulsorily cancelled and that's way it is possible to reject a very large number of the lower order harmonics at a lower switching frequency. The best firing angles are determined from a set of non-linear transcendental equations which reject lower order harmonics from output voltage of the inverter. . In this paper the best switching angles are calculated with the application of Whale optimization algorithm so that the harmonics are minimized. In this paper a 15 level inverter having equal voltage sources in the input is taken for study. The delay angles equations required for a seven source cascaded multilevel inverter that will eliminate 5,7,11,13,17,19 harmonics are given by equation(2)and(3) [9]. Modulation index 'M' is the proportion the 1st harmonic voltage to the utmost voltage obtained.

$$\left(\sum_{i=1}^{k}\cos(\alpha_i) - 7M\right)^2 = \epsilon_1$$
$$\left(\frac{4}{5\pi}\sum_{i=1}^{k}\cos(5\alpha_i)\right)^2 = \epsilon_2$$
$$\left(\frac{4}{7\pi}\sum_{i=1}^{k}\cos(7\alpha_i)\right)^2 = \epsilon_3$$
$$\left(\frac{4}{11\pi}\sum_{i=1}^{k}\cos(11\alpha_i)\right)^2 = \epsilon_4 \quad (2)$$
$$\left(\frac{4}{13\pi}\sum_{i=1}^{k}\cos(13\alpha_i)\right)^2 = \epsilon_5$$
$$\left(\frac{4}{17\pi}\sum_{i=1}^{k}\cos(17\alpha_i)\right)^2 = \epsilon_6$$
$$\left(\frac{4}{19\pi}\sum_{i=1}^{k}\cos(19\alpha_i)\right)^2 = \epsilon_7$$

Objective function is F (α_i) = $\epsilon_1 + \epsilon_2 + \epsilon_3 + \epsilon_4 + \epsilon_5 + \epsilon_6 + \epsilon_7 = 0$,
(3)

with a constraints $0 \le \alpha_i \le \frac{\pi}{2}$[10]

Modulation index $M = \frac{V_1 \pi}{4SV_{dc}}$ (4)

$THD = \sqrt{\left(\frac{\sum_k^{\infty} v_k^2}{v_1^2}\right)}$where k= 3, 5, 7, 11 … (5)

And v_1 is the 1st harmonic voltage and v_k is harmonic voltage with k is the harmonic number.

Whale optimization algorithm (WOA)

Whale optimization technique is based on the hunting activities of humpback whales. They are measured as the largest mammals in the Earth. The humpback whales are very brainy mammals that search for krill or minor fishes for food nearer to the sea. The interesting behavior about the humpback whales is their hunting method called bubble-net feeding methodThere are two exercises linked with their hunting technique, i.e. 'upward-spirals' and 'double- loops'. In the first exercise, humpback whales dive around 12 m down and then start to produce bubble in a spiral form around the prey and swim up near the surface. The second test comprises of 3 dissimilar steps: coral loop, lob tail, and capture loop, swimming around the target forming a unique bubble or 9 shaped paths. This unique actions of the humpback whales is the inspiration for this algorithm. The mathematical modeling of WOA is classified into three categories: encircling of prey, Bubble net hunting method and Search the prey[11][12][13]

3.2 Encircling Prey:

Humpback whales can identify theposition of target and enclose them. Since the position of the best possible answer in the search space is not identified, the WOA method assumes that the current best candidate result is the target prey or is close to the best values.

$$\vec{D} = |\vec{C}.\vec{X}*(t) - \vec{X(t)}| \quad (6)$$

$$\vec{X}(t+1) = \vec{X}*(t) - \vec{A}\cdot\vec{D} \quad (7)$$

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \quad (8)$$

$$\vec{C} = 2.\vec{r} \quad (9)$$

't' designates the current iteration, X^* is the position vector of the result attained and it is updated after every reiteration for getting improved outcomes. Equation (6) gives the absolute value, ‘a’ shrinks linearly from 2 to 0. ‘r’ is a random vector between [0.1]

3.3. Bubble Net Attacking Method:-

This method is the exploitation phase and the mathematical model of this method is as follows
(i). Shrinking encircling method:-
This performance is attained by shrinking the value of ‘a’ in equation (8).The function range of ‘A’ is also decreased by ‘a’. A will move from (X, Y) to (X*Y*) for 0≤A≤1.

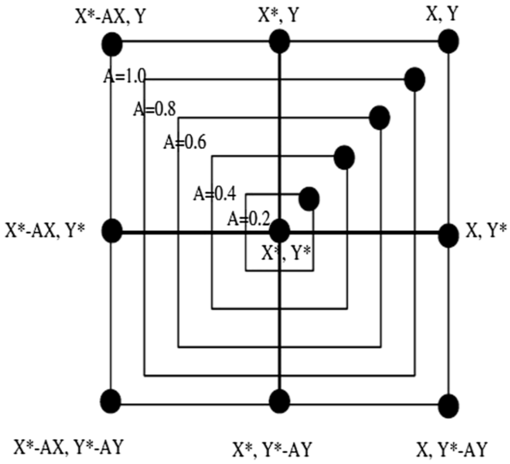

Fig 3: Bubble net search shrinking encircling mechanism

(Ii). Spiral Updating Position:-

Here the distance is first determined between the whale located at (*X*, *Y*) and target located at (X^*, Y^*). An equation for this spiral performance is then created between the position of whale and victim to imitate the spiral action of humpback whales. It is given by:

$$\vec{X}(t+1) = \vec{D} * e^{bl} \cos 2\pi l + \vec{X^*}(t) \quad (10)$$

$$\vec{D} = |X^*(t)' - \vec{X}(t)| \quad (11)$$

and shows the distance of i^{th} whale to prey position. ‘b' is a constant for defining the shape of logarithmic spiral,l is an incidental number [-1, 1] and is element by element multiplication. The humpback whales swim around the prey within a shrinking circle and along a spiral-shaped path concurrently. To model the performance of WOA, we take a chance of fifty percent between shrinking encircling method or spiral model for updating the location of whales. The mathematical model is given below

$$\vec{X}(t+1) = \vec{D} * e^{bl} \cos 2\pi l + \vec{X^*} \cdot \vec{D} \text{ If } P>0.5 \quad (12)$$

$$\vec{X}(t+1) = \vec{X^*} * (t) - \vec{A} \cdot \vec{D} \text{ If } P<0.5 \quad (13)$$

Here P is a arbitrary number between [0, 1]

3.3. Search for Prey:-

The overall best values are attained by updating has arbitrarily chosen search agent rather than the finest agent. Xrand is the arbitrary whales in present iteration. The symbol || denotes the absolute values. The equations are given as

$$\vec{X}(t+1) = \vec{X_{rand}} - \vec{A} \cdot \vec{D} \quad (14)$$

$$\vec{D} = |\vec{C}.\vec{X_{rand}} - \vec{X}| \quad (15)$$

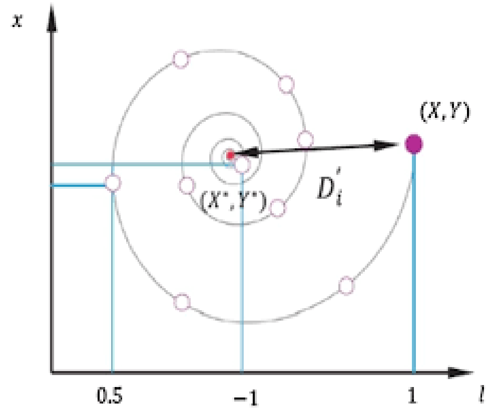

Fig 4: spiral updating position

3.4 Algorithm of Whale Optimization Technique:

1. State population size, parameters, maximum number of iterations
2. Set the repetition counter.
3. Fitness function $F(\alpha_i)$ is considered and preliminary population is generated arbitrarily
4. Search agent are estimated and finest search agent is assigned the job
5. Recurrence counter is increased t=t+1
6. All constrictions like a, A, C, P, etc are updated
7. Exploration and exploitation are applied as per the values of P and A.
8. Repeat step 5, 6, 7 till end criteria satisfies.
9. Write the answer
10. End

4. Results and Discussions:

Meta-heuristic techniques have turn into extraordinarily popular in past decades. This is due to their flexible nature and capability to avoid local minima. These two advantages initiate from the information that meta-heuristics consider and solve optimization problems by only looking at the responses. In this paper the problem is being solved by taking a swarm intelligent techniques i.e. the Whale optimization algorithm. It finds out the best optimal value of switching angles of the function given in equation-1 at various modulation index. As shown in figure-5, the program is run for several times and the finest outcomes were considered. The proposed algorithm solves the problem at a quicker speed of convergence, etc. For testing the above method, a 15 level inverter i.e. seven numbers of H-bridge inverter connected to a supply voltage of 48V in cascade. Optimum switching angles are generated at different modulation index with the help of above-mentioned algorithm. It can be seen from fig-6 that as the modulation index increases the angles also decreases objective to minimize THD while generating the fundamental component. The fundamental component of the line voltage increases is directly related with the modulation index (fig-7). It is observed in fig-8 that the line voltage THD has an inverse relation with the modulation index. The results are calculated up to 39th harmonics. The best results are obtained at a modulation index of 0.8 where the lower order harmonics is reduced below 2 percent and THD is around 3percent up to 39^{th} harmonics. The results show that the low-order harmonics in the line voltage are very lesser in magnitude and are suppressed. Because of the 120^0 phase shifts among voltages, all third harmonics in line voltages are very small. The harmonic spectrum of combined phase voltage shows that *5th*, *7th, 11th*, and *13th*, $17^{th}$and 19^{th} harmonics are less than 0.5% of the fundamental component. This minimization of harmonics in 15 level inverter and above makes it suitable for various industrial applications. The THD in line to line voltage as computed systematically up to 19^{th} harmonics and the results obtained are given in table2.The overall THD is calculated up to 39^{th} harmonics and the results are given in the table. Higher order harmonics are of very less in magnitude in comparison to the lower order harmonics and can be eliminated easily suitable filters. It is observed that results are improved with WOA algorithm well below the limits of 5%. The above-mentioned algorithm takes very less time to converge. Fig 7 shows the line voltage and at optimum switching angles and a modulation index of Ma=0.8. At each modulation index, the program was run many times for finding out the optimum switching angles and the graph of the best convergence is taken. It is clear that the above algorithm converges faster and has the ability to escape local minima. It can be seen from the convergence curve that whale optimization algorithm give the best convergence with less number of iterations. The convergence curve also give us the information about the fastness of the algorithm in giving suitable results. The details of the whale optimization algorithm is given in table-1.

Table1:

No of iterations	500
No of search agents	30
No of dimensions	7

Table2:

Modulation index	% of Lower order harmonics							Overall %THD
	3^{rd}	5^{th}	7^{th}	11^{th}	13^{th}	17^{th}	19^{th}	
0.6	0.14	1.4	1.5	1.1	1.1	1.4	1.4	5.2
0.7	0.03	0.4	0.2	0.6	0.3	0.2	0.29	3.4
0.8	0.07	0.7	0.2	0.3	0.8	1.1	1.04	3.1

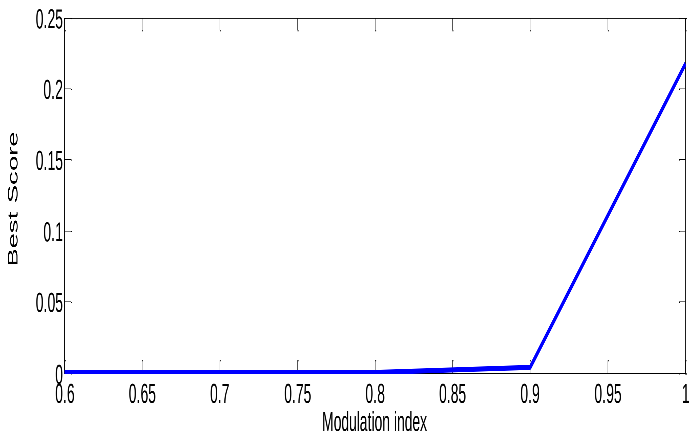

Fig-5: Best Score vs. Modulation Index

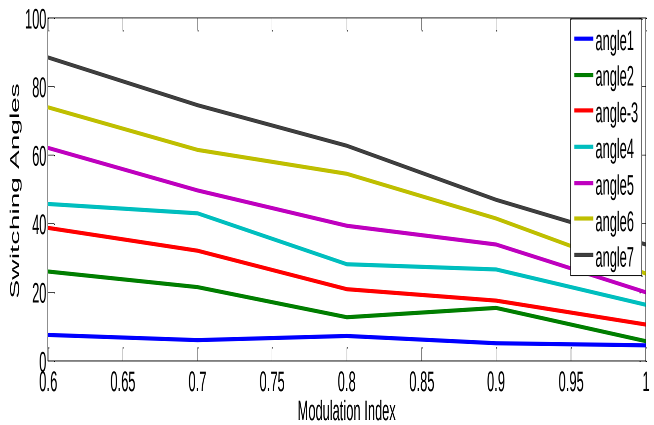

Fig-6: Switching angle vs. Modulation index

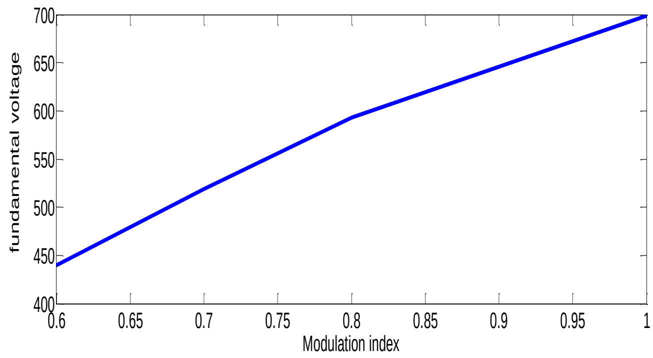

Fig-7: fundamental voltage vs Modulation index

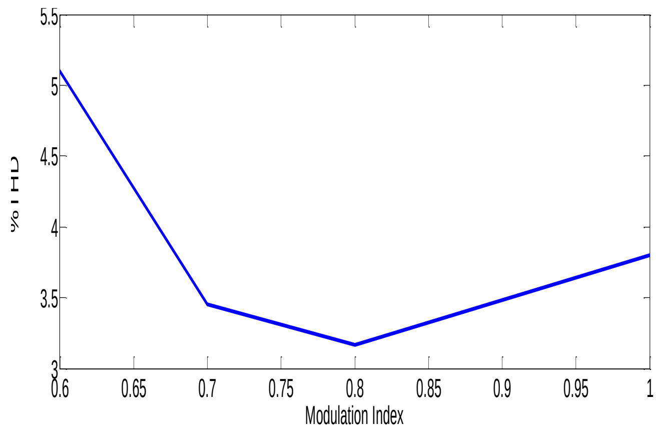

Fig 8: THD vs Modulation Index

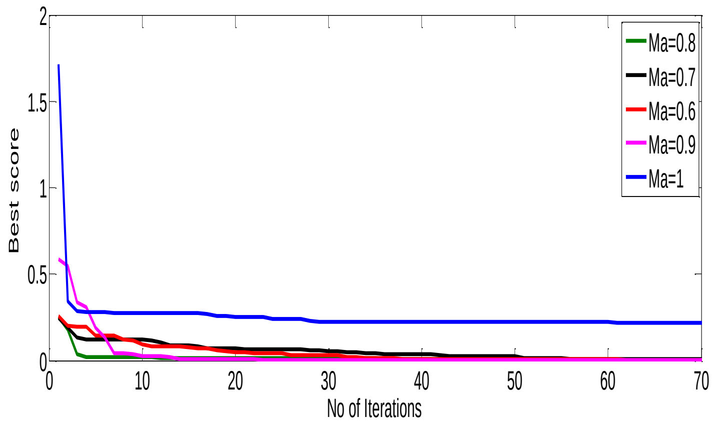

Fig-9: Convergence curve

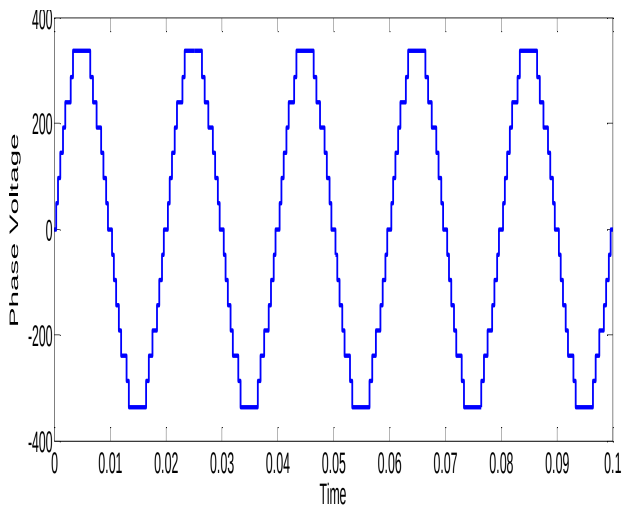

Fig-10: Phase voltage Waveform

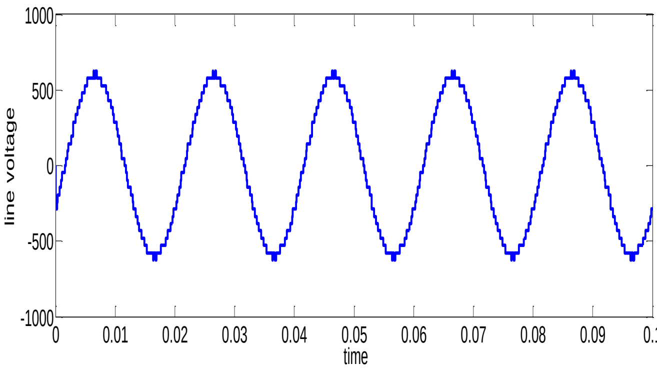

Fig 11: line voltage waveform

5. Conclusion

This paper represents the application of WOA which is relatively new technique. It has been fruitfully applied to the problem of switching angle optimization of a fifteen level inverter. The proposed WOA algorithm searches for all possible set of solutions to contribute the minimum THD. It can be resolved that the proposed WOA algorithm is capable to reject the desired harmonics while maintaining the fundamental output voltage. It is observed that healthier results are obtained with WOA algorithm. This study of 15 level inverter shows that it is suitable for STATCOM and drives applications. However by increasing the level of the inverter also increase the complexity of controlling of switching signals and control circuits.

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