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Grey Wolf Optimized Modified Selective Harmonic Elimination PWM in Multilevel Inverter with Lesser Number of Switches

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Abstract— In this paper, a modified SHEPWM for multilevel inverter with lesser number of switches to minimize dominant lower order harmonics and switching losses is proposed. In SHE PWM, nonlinear transcendental equations with switching angles can be developed and these equations are calculated by using any numerical method or any optimization algorithm to find optimum value of these switching angles. Main drawback of selective harmonic elimination is while dealing with increased level of inverters optimization of switching angles is not available for some values of modulation index and this will increase undesired harmonics. A modified SHEPWM optimized by grey wolf optimization algorithm is proposed in this paper for reduced switch 17 and 53 level inverter. Fitness function in modified SHEPWM comprises of fundamental component of voltage and lower order harmonics to derive switching angles. Simulation results using MATLAB/SIMULINK are presented for 17 and 53 level inverter and switching losses and THD are compared with conventional selective harmonic elimination..

Keywords- Total harmonic distortion; grey wolf optimization; lower order harmonics; selective harmonic elimination; reduced switch type multilevel inverters.

I. INTRODUCTION)

Sinusoidal voltages are required for the applications like distributed generation, FACT devices, HVDC transmission, variable frequency drives, power quality enhancement devices etc. This requirement for sinusoidal voltages with less harmonic distortion led to development of advanced multilevel inverters with modular structure [1]. Compared to two and three level, multilevel inverters provide reduced harmonic distortion, low voltage stress and less electromagnetic inference. Main drawback of the multilevel inverter is increase in switching losses and hence reduced efficiency due to increase in number of switches. By reducing lower order harmonics of output voltage of multilevel inverter (MLI) reduces switching losses and improves efficiency. MLIs convert DC voltage into staircase bidirectional output voltage with low switching frequency or high switching frequency. Topology of MLIs depends on no. of DC sources, no. of switches, required voltage levels and their application [2].

Switching operation controlled by specific pulse width modulation decide performance of multilevel inverters in reducing THD. Sinusoidal PWM, space vector PWM and selective harmonic elimination PWM are modulation strategies that can be used for conversion process of DC to AC in MLIs [3]-[4]. Phase shifted and level shifted carrier modulation [5] are types of sinusoidal pulse width modulation. SVPWM and SPWM are high frequency modulation strategies. Due to increase in frequency and hence increase number of switching instants from ON to OFF and vice versa per one fundamental period, increases switching losses. In case of SVPWM, complexity of switching strategy is more if number of levels are more [6]. To reduce switching instants per fundamental period and to reduce switching losses selective harmonic elimination is beneficial [7].

Low frequency selective harmonic elimination based PWM reduces switching losses and improves efficiency and hence reduces rating and size of filter required at AC side which filters undesired harmonics. In SHEPWM, nonlinear transcendental equations with switching angles can be developed and these equations are solved by using optimization algorithm to find optimum value of these switching angles. These pre-optimized switching angles for total range of modulation index can be well-kept-up in lookup table and used to generate switching pulses [8].

Academics and scholars have made significant work in recent times in planning and processing several algorithms and solution approaches to attain best and diverse solutions with a wide range of SHE PWM designs. Newton Raphson method is the most discussed approach in literature with iterative calculation in minimizing the transcendental equations of SHEPWM [9]. It is simple in using and converges within less time but requires correct forecast of initial values. But convergence of equations depends on correct forecast of initial values and hence this algorithm is restricted to limited switching angles [10]. Predicting algorithm for initial values in Newton Raphson method using equal area algorithm is proposed in [11]. Resultant theory-based approach in [12], walsh functions in [13], phase shift technique in [14], Chebyshev method in [15] are proposed techniques in literature. As the initial values are to be predicted in these numerical methods, these methods are undependable and complex. In walsh function method transcendental equations can be transformed into linear equations by means of walsh transformation matrix.

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The drawbacks due to numerical methods can be eliminated by using meta heuristic optimization algorithms in finding optimum switching angles. Genetic algorithm is used as optimization algorithm in finding switching angles in huge amount of research papers [16]. Whale optimization algorithm [17], differential harmony search algorithm [18], bacterial foraging algorithm [19], BAT algorithm [20], ant colony optimization [21] are some of optimization algorithms proposed by researchers in recent times. Whale optimization algorithm and differential harmony search algorithms are not effectively eliminating lower order harmonics due to local optima and slow convergence. The performance of genetic algorithm depends on prospect of crossover and mutation. Wrong choice of input constraints like crossover and mutation constants in genetic algorithm will diminish its performance and optimization. An hybrid approach with GA and PSO is proposed in [22]. An online switching calculation using artificial neural network is proposed in [23]. Flower pollination algorithm based SHEPWM is proposed in [24].

Main drawback of these methods for selective harmonic elimination, by solving nonlinear equations, is while dealing with increased level of inverters optimization of switching angles is not available for some values of modulation index and this will increase undesired harmonics. Hence, proposed method in this paper reduces total harmonic distortion by optimizing the fitness function comprises of fundamental component of voltage and lower order harmonics to derive switching angles. Fitness function is optimized by grey wolf optimization algorithm. This process of optimization imitates the communal order of grey wolves and their chasing behavior. GWO algorithm shows highly competitive results compared to other optimization algorithms [25]. Exploration ability of GWO is tremendous and this reduces chance of local optima. Hence GWO is chosen as optimization algorithm in this work. The paper is organized as follows modified selective harmonic elimination is illustrated in section 2. Multilevel inverter configuration with switching strategies is presented in section 3. Grey Wolf optimization and its procedure for SHEPWM with flowchart is depicted in section 4. Section 5 presents simulation results for 17 level and 53 level reduced switch MLIs with modified SHEPWM. In Section 6, concluded the paper and outstanding literature on SHEPWM is presented.

II. MODIFIED SELECTIVE HARMONIC ELIMINATION

Variable frequency drives, distributed generators, FACTS devices, power quality conditioners adopt multilevel inverters as converting devices because of reduced THD. But while choosing switching frequency of PWM of inverters should be limited because electromagnetic inference and switching losses have to be considered due to which performance of inverts will be affected. SHEPWM method is advantageous as switching frequency is low and THD will be reduced in MLIs. Improved harmonic profile with better fundamental magnitude and reduced switching losses due to fundamental switching frequency are main benefits of SHEPWM. This method reduces THD by reducing lower order harmonics. This can be possible by optimizing switching angles from a fitness function comprises of nonlinear equations using any optimization algorithm.

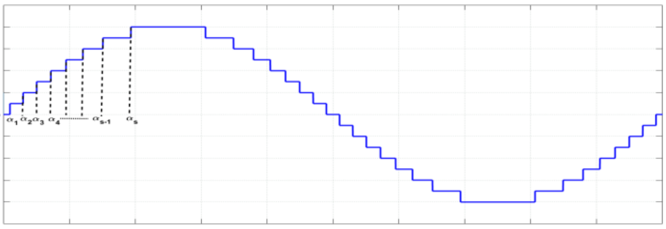

Fig.1. Output Voltage levels of MLI with switching angles

Switching angles with stepped voltage waveform of MLI is presented in Figure1 and can be expanded as shown in (1)

$$u(t) = u_0 + \sum_{h=1}^{\infty} a_h \cos(h\omega t) + \sum_{h=1}^{\infty} b_h \sin(h\omega t) \tag{1}$$

Where u_0 is a DC component a_h is cosine component and b_h is sine component

Due to quarter wave symmetry [26] $u_{dc} = 0$, $a_h = 0$ and for even harmonic order $b_h = 0$

For odd harmonic order b_h is given as show in (2)

$$b_h = \frac{4u_{dc}}{h\pi}[\cos(h\alpha_1) + \cos(h\alpha_2) + \cos(h\alpha_3) + \ldots + \cos(h\alpha_s)] \tag{2}$$

u_{dc} is the DC voltage of MLI

Converted voltage of MLI is given as shown in (3)

$$u(t) = \sum_{h=1}^{\infty}\left[\frac{4u_{dc}}{h\pi}\sum_{k=1}^{s}\cos(h\alpha_k)\right]\sin(n\omega t) \tag{3}$$

By calculating values of switching angles $\alpha_1, \alpha_2, \ldots, \alpha_s$ such that sine coefficients other than fundamental component in above equation become zero then THD will be reduced. This can be possible by solving nonlinear equations (4) using any optimization algorithm, optimized switching angles can be generated.

$$\begin{gathered}
\cos\alpha_1 + \cos\alpha_2 + \ldots + \cos\alpha_{s-1} + \cos\alpha_s = sM_i \\
\cos 3\alpha_1 + \cos 3\alpha_2 + \ldots + \cos 3\alpha_{s-1} + \cos 3\alpha_s = 0 \\
\cos 5\alpha_1 + \cos 5\alpha_2 + \ldots + \cos 5\alpha_{s-1} + \cos 5\alpha_s = 0 \\
. \\
. \\
\cos(2s-1)\alpha_1 + \cos(2s-1)\alpha_2 + \ldots + \cos(2s-1)\alpha_{s-1} + \cos(2s-1)\alpha_s = 0 \\
0 < \alpha_1 < \alpha_2 < \alpha_3 \ldots < \alpha_{s-1} \le \frac{\pi}{2}
\end{gathered} \tag{4}$$

Where modulation index M_i is given as $M_i = \frac{\pi u_1}{4 s u_{dc}}$ and u_1 is the amplitude of fundamental component

For a seventeen-level inverter, angles to be optimized are $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_8$ and non-linear equation are given as in (5)

$$\begin{aligned}
&\cos\alpha_1+\cos\alpha_2+\cos\alpha_3+\cos\alpha_4+\cos\alpha_5\\
&+\cos\alpha_6+\cos\alpha_7+\cos\alpha_8=8M_i\\
&\cos 3\alpha_1+\cos 3\alpha_2+\cos 3\alpha_3+\cos 3\alpha_4\\
&+\cos 3\alpha_5+\cos 3\alpha_6+\cos 3\alpha_7+\cos 3\alpha_8=0\\
&\cos 5\alpha_1+\cos 5\alpha_2+\cos 5\alpha_3+\cos 5\alpha_4\\
&+\cos 5\alpha_5+\cos 5\alpha_6+\cos 5\alpha_7+\cos 5\alpha_8=0\\
&\cos 7\alpha_1+\cos 7\alpha_2+\cos 7\alpha_3+\cos 7\alpha_4\\
&+\cos 7\alpha_5+\cos 7\alpha_6+\cos 7\alpha_7+\cos 7\alpha_8=0\\
&\cos 9\alpha_1+\cos 9\alpha_2+\cos 9\alpha_3+\cos 9\alpha_4\\
&+\cos 9\alpha_5+\cos 9\alpha_6+\cos 9\alpha_7+\cos 9\alpha_8=0\\
&\cos 11\alpha_1+\cos 11\alpha_2+\cos 11\alpha_3+\cos 11\alpha_4\\
&+\cos 11\alpha_5+\cos 11\alpha_6+\cos 11\alpha_7+\cos 11\alpha_8=0\\
&\cos 13\alpha_1+\cos 13\alpha_2+\cos 13\alpha_3+\cos 13\alpha_4\\
&+\cos 13\alpha_5+\cos 13\alpha_6+\cos 13\alpha_7+\cos 13\alpha_8=0\\
&\cos 15\alpha_1+\cos 15\alpha_2+\cos 15\alpha_3+\cos 15\alpha_4\\
&+\cos 15\alpha_5+\cos 15\alpha_6+\cos 15\alpha_7+\cos 15\alpha_8=0
\end{aligned} \tag{5}$$

Main drawback of selective harmonic elimination is while dealing with increased level of inverters optimization of switching angles is not available for some values of modulation index and this will increase undesired harmonics. Hence in proposed method total harmonic distortion is reduced by the fitness function comprises of fundamental component of voltage and lower order harmonics to optimize switching angles given as in (6)

$$f=\left|k_1\frac{u_{ref}-u_1}{u_{ref}}\right|^4+\sum_{s=2}^{s}\frac{1}{h_s}\left|k_2\frac{u_{h_s}}{u_1}\right|^2 \tag{6}$$

k_1 and k_2 are scaling gains, h_s is the harmonic order $h_2=3, h_3=5, h_4=7$ and so on. u_1 is fundamental magnitude of stepped voltage. u_{ref} is desired voltage. If chosen condition is not attained or switching angles are not optimized then value of fitness function will rise severely. Error between desired voltage and fundamental voltage is powered by four in the fitness function because the limitation for fundamental voltage is 1% according IEEE-519 harmonics standard. Ratio between lower order harmonics and fundamental value are powered by 2 because these harmonics should be limited to 2% of fundamental value. To define significance of lower order harmonics, this ratio is multiplied with $1/h_s$ to levy further importance. In this paper switching angles are obtained for SHE and modified SHE by Grey Wolf optimization algorithm for 17 level and 53 level inverters with reduced switches.

III. MULTILEVEL INVERTER CONFIGURATION WITH REDUCED SWITCHES

Arrangement of 17 and 53 level inverter with lesser number of switches is presented in Figure2 and 3. 4 unequal DC sources and 10 switching devices are required to convert DC voltage into 17 level staircase voltage. 10 unequal DC sources and 22 switching devices will form 53 level inverter. 17 level staircase bidirectional voltage is possible by connecting one main module with two DC sources of $3V_{dc}$ and 2 sub modules each consists of one dc source of u_{dc} in series. 53 level staircase bidirectional voltage is possible by connecting 0ne main module with two DC sources of $9V_{dc}$ and 8 sub modules each consists of one dc source of u_{dc} in series. Detailed analysis of 17 level and 53 level inverter with reduced number of switches and their switching strategy is presented in [27].

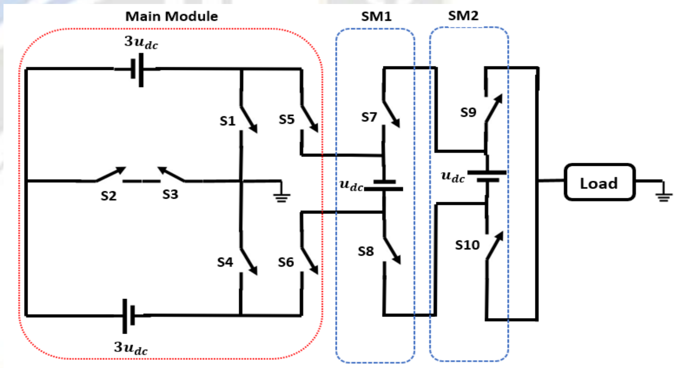

Fig.2. 17 level inverter

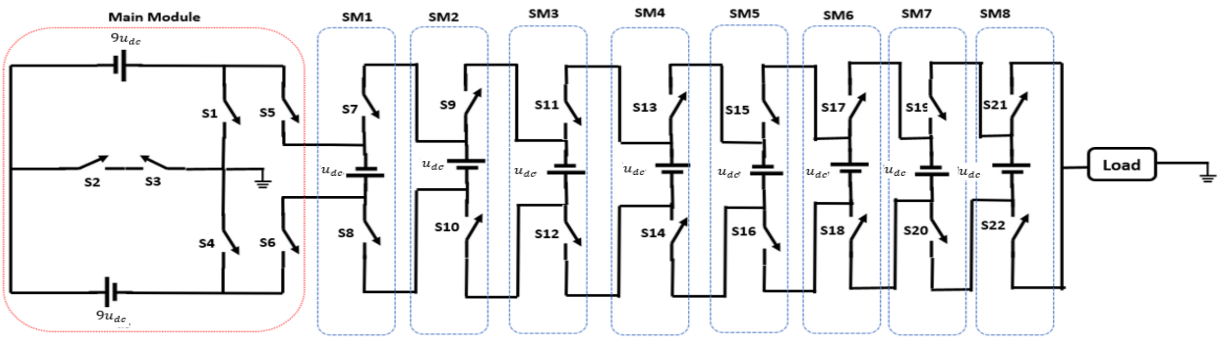

Fig.3. 53 level inverter

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IV. GREY WOLF OPTIMIZER (GWO)

Brilliant chasing method of grey wolves for prey and their communal order is the principle involved in GWO algorithm. These animals usually live and hunt in group with 4 to 18 members and called as pack. Their communal order is well maintained with a strict dominant hierarchy. Every pack is led by a breeding pair of male and female called as alpha and the decisions for the pack regarding hunting and other daily activities can be taken by this alpha pair. Usually, the decisions taken by alpha must be accepted by other members and this acceptance by members can be confirmed by holding their tails down. While taking these decisions alpha pair will follow other individuals of the pack. Shaping of pack and discipline are the main roles of alpha. In communal order next level is beta and the wolves in this level will help alpha to make decisions. Beta may be either female or male and if alpha turn aged or dies this beta will replace alpha. Main responsibilities of beta are maintaining discipline in pack, emphasizing alpha's orders and giving feedback to alpha regarding other members of pack. Next level in the order is delta and also called as subordinates. Delta group obey the orders of alpha and beta and these are functioned as detectives, guards, trackers and custodians. They look for limits of their region and alarm the pack when any danger is going to occur. Next level in the order is omega and these are poorest wolves in terms of strength in the pack. These wolves have to obey the order of other wolves in the pack.

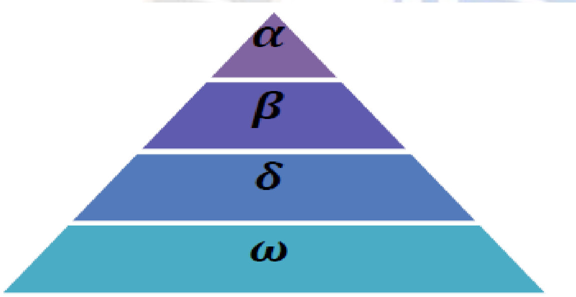

Fig.4. Communal order of Grey Wolves

Hunting of grey wolves involve three key stages including stalking and racing the prey, surrounding and distressing the prey and finally attacking the prey. Hunting behavior of grey wolves and their communal order are used to model GWO algorithm for optimization of a fitness function or any physical problem.

A. Mathematical model of GWO

In resemblance to communal order of pack of grey wolves in GWO algorithm first best solution is termed as alpha, second best solution is beta, third best solution is delta and residual solutions are termed as omega. Process of hunting or minimization of fitness function is directed by these four solutions.

Surrounding behavior to attack a prey by grey wolves can be expressed in GWO algorithm as shown in (7)

$$\vec{D} = \left|\vec{C}.\vec{X}_p(ite) - \vec{X}(ite)\right|$$
$$\vec{X}(ite+1) = \vec{X}(ite) - \vec{A}.\vec{D} \tag{7}$$

ite is the number of iteration, $\vec{X}_p$ is the vector of prey's positions, $\vec{X}$ vector of grey wolf's positions, $\vec{D}$ is a vector which specifies new positions of grey wolves. $\vec{A}$ and $\vec{C}$ are coefficients which re given as in (8)

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a}$$
$$\vec{C} = 2.\vec{r}_2 \tag{8}$$

$\vec{a}$ is a controlling parameter which reduces linearly from 2 to 0 while iterations are increasing, $\vec{r}_1$ and $\vec{r}_2$ are random vectors within the range of 0 and 1.

By adjusting or controlling the coefficient vectors $\vec{A}$ and $\vec{C}$ diverse positions in search space can be attained by grey wolves and new positions will make the prey to be reachable. Random vectors $\vec{r}_1$ and $\vec{r}_2$ will make the searching process as stochastic and will increase probability to reach optimum point. In an n dimensional search region grey wolves can shift in any position around the prey and the positions of grey wolves are calculated by equation (7). Prey can be surrounded by grey wolves and their every position is differentiated in search space. The process of searching or catching the prey is led by alpha (α). Beta (ß) and delta (δ) which are in next level in communal order provide support to α for hunting. In mathematical modeling to replicate this action α can be assumed as best candidate for the solution and ß and δ are expected to be having data about next best position required by α. Hence in every iteration, algorithm should save three best solutions attained till and make omega (ω) wolves to reach the best place in search space. This hunting process can be modeled as shown in (9), (10) and (11)

$$\vec{D}_\alpha = \left|\vec{C}_1.\vec{X}_\alpha - \vec{X}\right|$$
$$\vec{D}_\beta = \left|\vec{C}_1.\vec{X}_\beta - \vec{X}\right|$$
$$\vec{D}_\delta = \left|\vec{C}_1.\vec{X}_\delta - \vec{X}\right| \tag{9}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1\vec{D}_\alpha$$
$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2\vec{D}_\beta$$
$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3\vec{D}_\delta \tag{10}$$

$$\vec{X}(t) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{11}$$

Alpha (α), Beta (ß) and delta (δ) estimate the positions of omega (ω) wolves and prey before update their new locations which are able to surround and catch the prey. $\vec{A}$ is a vector with random values within the range of $[-2a, 2a]$ and a reduces linearly from 2 to 0 for every iteration. This will make grey wolves to reach prey and finally attack it. If $|A| > 1$, the grey wolf is required to deviate from the local optima or prey to search for better position or solution. If $|A| < 1$, then grey wolves attack the prey. GWO algorithm allows the search agent to renew its position using the positions of α, ß and ω. $\vec{C}$ is a vector with random values inside the array of $[0,2]$ and this component offers random weights for the prey to arbitrarily highlight or destress the impact of the prey in significant the distance. This supports GWO algorithm to display a more random performance during optimization, supporting exploration and escaping local optima. $\vec{C}$ is required consciously to deliver random values at all times in order to highlight exploration during initial and final iterations.

B. Process of GWO

In GWO algorithm initially a random population can be created within a predefined range. Possible positions of the prey are estimated by α, β and δ for each iteration. Depending on the distances from the prey α, β and δ values will be updated for every iteration. a decreases linearly from 2 to 0 for every iteration and this can be useful to highlight exploration and exploitation. If $|A| > 1$, the grey wolf is required to deviate from the local optima i,e. the candidate solution diverge from the optimum position and if $|A| < 1$, then grey wolves attack the prey i.e. the candidate solution converge into the optimum position. a and C are the two parameters which are to be adjusted in GWO optimization. As a value is decreasing for every iteration first half number of iterations are allotted to exploration in which $|A| > 1$ and last half number of iterations are allotted to exploitation in which $|A| < 1$. Adaptive values of vector $\vec{A}$, guarantees exploration and exploitation. The viable position of the prey can be located by candidate's solutions using proposed hunting method.

C. Pseudocode of GWO algorithm

Pseudocode of GWO algorithm

1. Initialization of number of candidates or grey wolves $\boldsymbol{n}$, Number of Iterations $\boldsymbol{ite}$
2. Initialize $\boldsymbol{a}, \vec{\boldsymbol{A}}$ $\boldsymbol{and}$ $\vec{\boldsymbol{C}}$
3. for $\boldsymbol{i = 1\ to\ n}$
4. Initialize $\boldsymbol{G} = \{\boldsymbol{s_1}, \boldsymbol{s_2}, \dots, \boldsymbol{s_n}\}$ randomly within the range of $\{\boldsymbol{lb}, \boldsymbol{ub}\}$
5. end for
6. Evaluate or find fitness value of each candidate or grey wolf $\boldsymbol{f(G)}$
7. Grade the candidates with respect to their fitness values such as $\boldsymbol{X_\alpha}$ the best solution, $\boldsymbol{X_\beta}$ the second-best solution and $\boldsymbol{X_\delta}$ the third best solution
8. While (stop criterion is not satisfied and ($\boldsymbol{ite} < \boldsymbol{maximum\ number\ of\ iterations}$) do
9. for $\boldsymbol{i = 1\ to\ n}$
10. Update the position of candidates by using Equation (7)
11. end for
12. renew $\boldsymbol{a}, \vec{\boldsymbol{A}}$ $\boldsymbol{and}$ $\vec{\boldsymbol{C}}$
13. Evaluate the function using each candidate and grade them
14. Renew the position of $\boldsymbol{X_\alpha}$, $\boldsymbol{X_\beta}$ and $\boldsymbol{X_\delta}$
15. Ite=ite+1
16. end while

D. Flow chart of GWO

Flowchart of the GWO algorithm for proposed MLIs using modified SHE is presented in Figure5. Figure6 presents optimized switching angles α_1 *to* α_8 for modulation indices from 0.01 to 1 in case of modified SHE for 17 level inverter. Values of switching angles are decreasing with increase in modulation index and these switching angles control the fundamental value of output voltage. Figure7 presents optimized switching angles α_1 *to* α_{26} for modulation indices from 0.01 to 1 in case of modified SHE for 53 level inverter. Total harmonic distortion for 17 level inverter comparison between GWO optimized selective harmonic elimination and GWO optimized modified selective harmonic elimination is presented in Figure8. THD is less in case of proposed modified SHE as fitness function comprises of both fundamental component and harmonics ratio. Figure9 presents THD of 53 level inverter in case of GWO optimized modified selective harmonic elimination

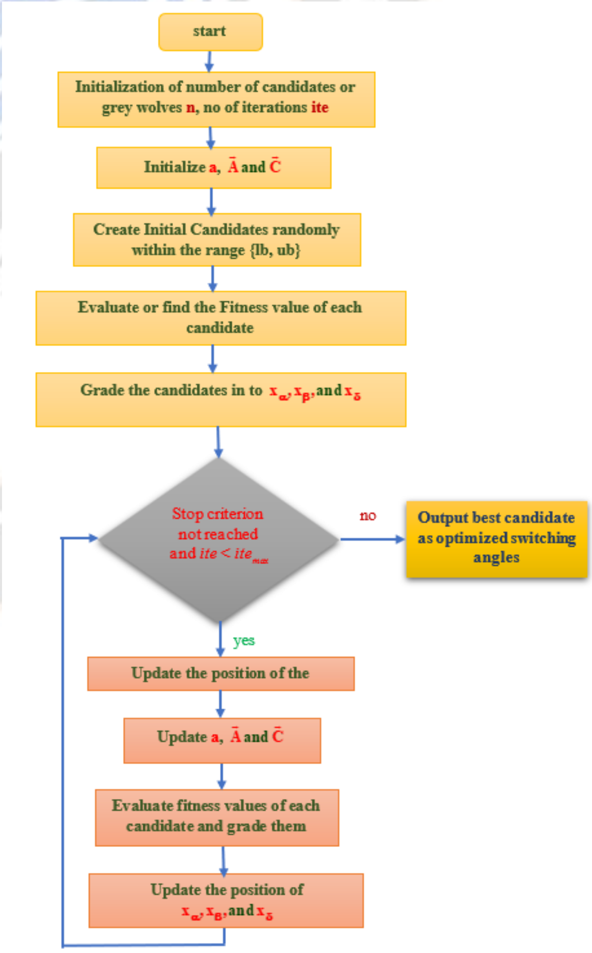

Fig.5. GWO optimization algorithm flow chart

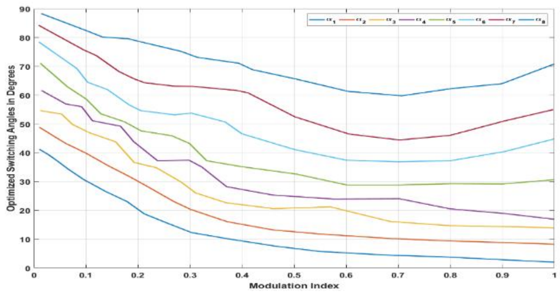

Fig.6. obtained switching angles from modified SHE for 17 level inverter

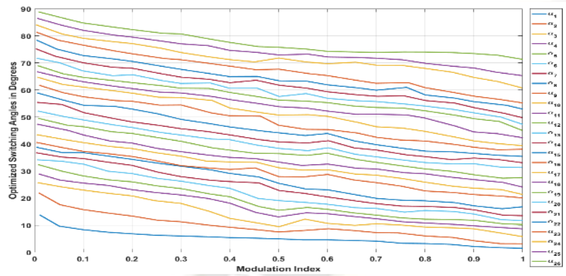

Fig.7. obtained switching angles from modified SHE for 53 level inverter

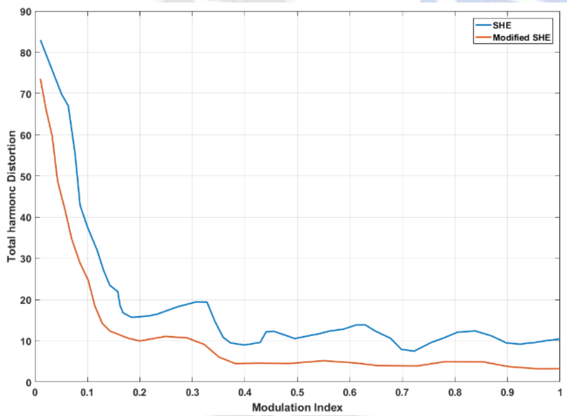

Fig.8. THD Vs MI for 17 level inverter for SHE and modified SHE

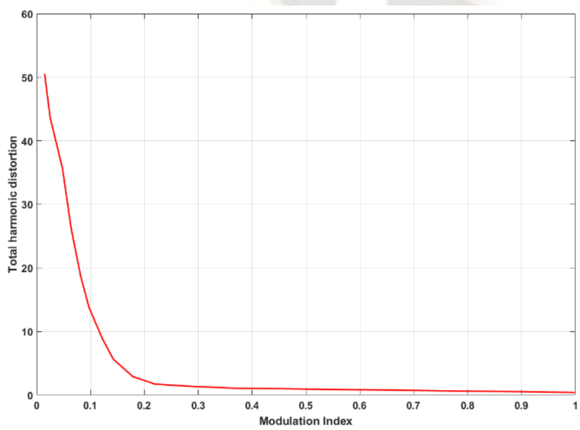

Fig. 9 . THD Vs MI for 53 level inverter for modified SHE

V. SIMULATION RESULTS

To check validation of proposed modified SHE algorithm using GWO for multilevel inverter with smaller no. of switches, simulations were implemented using MATLAB/SIMULINK on 17 level and 53 level inverters. 17 level output voltage is generated by simulating topology depicted in Figure2. DC voltage in each submodule is 100V and in main module voltage is 300V. Optimized switching angles by GWO optimized modified SHE for 17 level inverter is presented table 1. 53 level output voltage is generated by simulating topology depicted in Figure3. DC voltage in each submodule is 30V and in main module voltage is 270V. Optimized switching angles by GWO optimized modified SHE for 53 level inverter is presented in table 2. Figure10 shows the 17 level output voltage and load current with GWO optimized SHE PWM and THD of voltage and current is presented in Figure11. As shown in FFT analysis of voltage and current in Figure11 lower order harmonics (3^{rd}, 5^{th}, 7^{th}, 9^{th}, 11^{th}, 13^{th} and 15^{th}) of 17 level inverter are reduced and THD of voltage is 4.84% and current is 0.61%.

TABLE 1. OPTIMIZED SWITCHING ANGLES FOR MODIFIED SHE IN 17 LEVEL INVERTER

Switching Angles in Degrees	
α_1	3.6067
α_2	10.8171
α_3	18.2011
α_4	25.9758
α_5	34.2746
α_6	43.4884
α_7	54.4139
α_8	69.7154

TABLE 2. OPTIMIZED SWITCHING ANGLES FOR MODIFIED SHE IN 53 LEVEL INVERTER

Switching Angles in Degrees		**Switching Angles in Degrees**		**Switching Angles in Degrees**	
α_1	1.0996	α_{10}	21.4432	α_{19}	45.4416
α_2	3.2998	α_{11}	23.8454	α_{20}	48.6388
α_3	5.5167	α_{12}	26.2745	α_{21}	52.1099
α_4	7.7735	α_{13}	28.7582	α_{22}	55.8586
α_5	9.9653	α_{14}	31.3280	α_{23}	59.0297
α_6	12.2282	α_{15}	33.9515	α_{24}	64.7440

α_7	14.4986	α_{16}	36.6566	α_{25}	70.5436
α_8	16.7753	α_{17}	39.4326	α_{26}	78.8429
α_9	19.1005	α_{18}	42.3755		

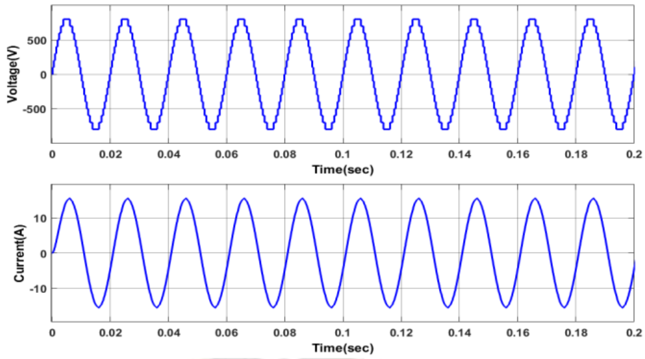

Fig.10. 17 level output voltage and load current with SHE

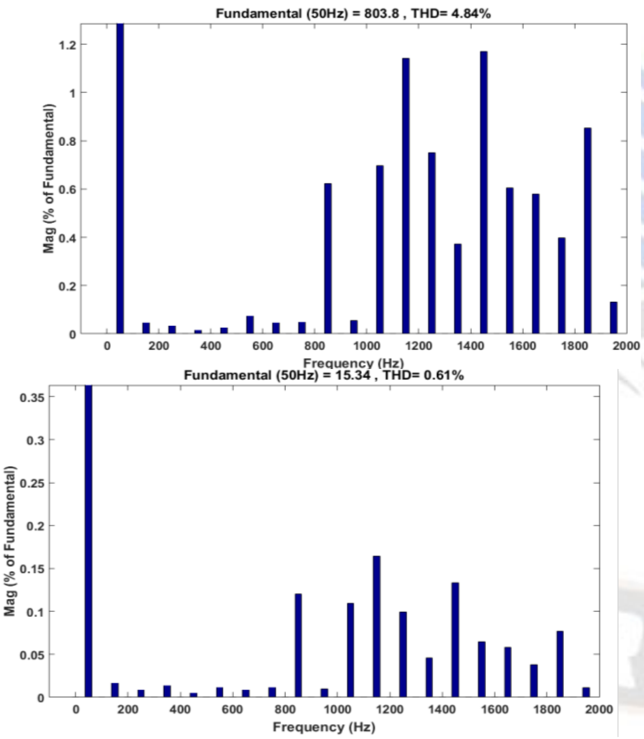

Fig.11. THD of output voltage and current with SHE

Figure12 presents voltage and current of 17 level inverter when the switching angles are optimized with GWO on modified SHE PWMwhen modulation index is 1 and load is 50Ω and 50mH. Figure13 presents THD of voltage and current. Due to proposed method THD of voltage is reduced to 3.23% from 4.84% and current THD is reduced to 0.4% from 0.61%. Figure14 presents output voltage and current for 53 level reduced switch multilevel inverter with switchung angle optimized by GWO for modified SHE PWM. 0.9% is the voltage THD and 0.06% is current THD and fundamental component of voltage is equal to 1 p.u. due to reduced lower order harmonics and reduced THD in modified SHE switching losses are less and hence efficinecy is more compared to NLC PWM [25] and conventional selective harmonic elimination. Efficiency of 17 level inverter and 53 level inverter are presented in Figure16.

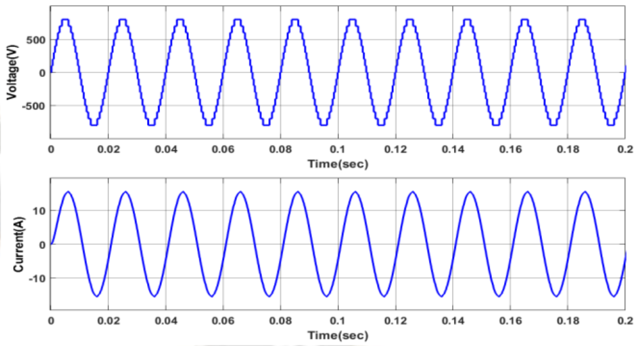

Fig.12. 17 level output voltage and load current with modified SHE

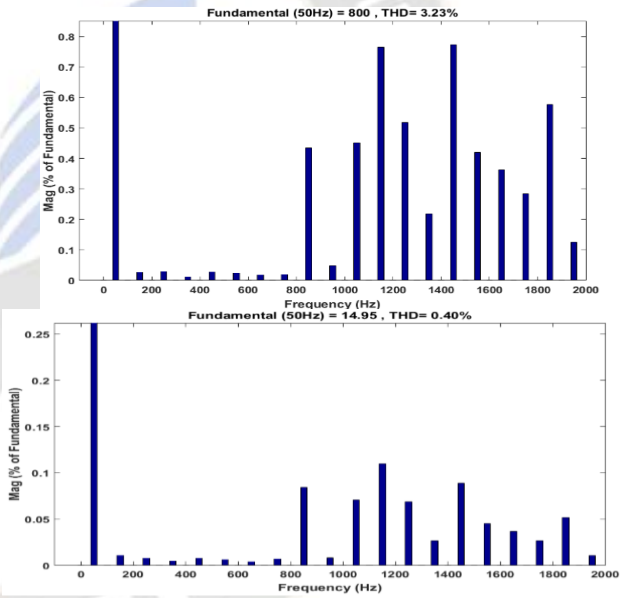

Fig.13. THD of output voltage and current of 17 level inverter with Modified SHE

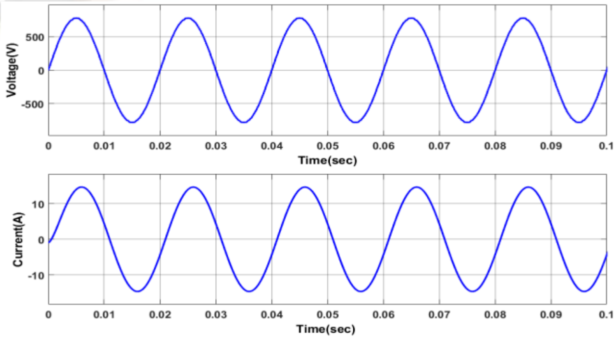

Fig.14. 53 level output voltage and load current with Modified SHE

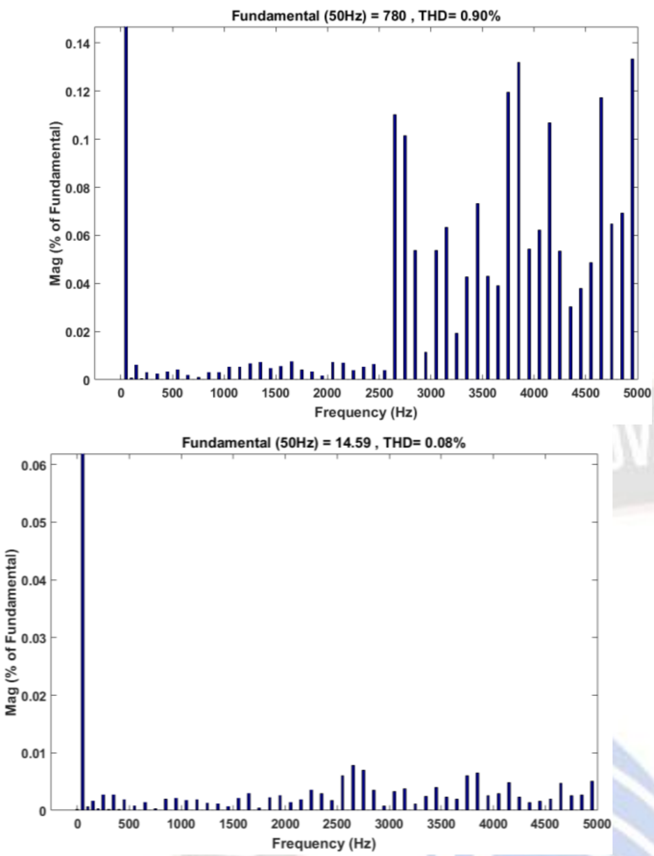

Fig.15. THD of output voltage and current of 53 level inverter with modified SHE

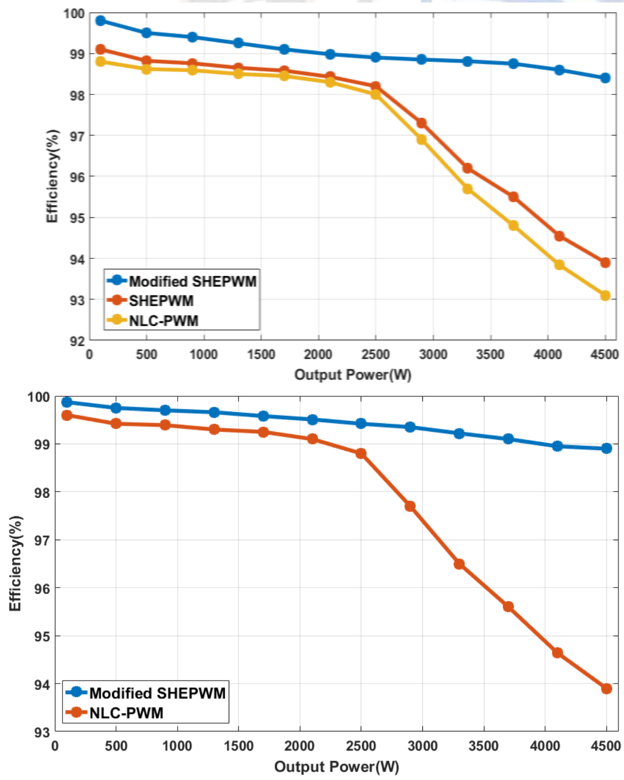

Fig.16. Efficiency for (a) 17 level (b) 53 level

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

VI. CONCLUSION

Modified SHEPWM strategy for multilevel inverter with a smaller number of switches is proposed to reduce switching losses and THD. Switching angles in SHEPWM and in modified SHEPWM are optimized by grey wolf optimization algorithm. This procedure of optimization imitates the communal order of grey wolves and their chasing behavior. Compared to other optimization algorithms, GWO algorithm shows highly competitive results. Exploration ability of GWO is tremendous and this reduces chance of local optima. Hence GWO is chosen as optimization algorithm in this work. 17 and 53 level inverters with reduced number of switches are examined and simulated to check the efficacy of presented optimization. Switching angles are determined and presented for whole range of modulation index. Switching frequency of PWM is low and almost equal to fundamental frequency. Due to this low frequency, switching losses are reduced and due to optimization of switching angles lower harmonics are reduced. Comparison of switching losses between SHEPWM and modified SHEPWM for 17 and 53 level inverter is presented.

VII. Copyright Forms and Reprint Orders

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