

A modified cascaded h-bridge multilevel inverter based on particle swarm optimisation (PSO) technique

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ABSTRACT

In this paper, modified multilevel inverter, via addition of an auxiliary bidirectional switch, based on Newton Raphson (NR) and Particle Swarm Optimization (PSO) techniques is presented. The NR and PSO techniques were employed for selective harmonics elimination (SHE) solution in a modified Cascaded H Bridge Multilevel inverter (CHB-MLI). The Selective Harmonic Elimination Pulse-Width Modulation (SHE-PWM) is a powerful technique for harmonic minimization in multilevel inverter. The NR and PSO techniques were used to determine the switching angles by solving the non-linear equations of the output voltage waveform of the modified CHB-MLI in order to control the fundamental component and eliminate some low order harmonics. The proposed NR and PSO techniques are capable to minimize the Total Harmonic Distortion (THD) of the output voltage of the modified inverter within allowable limits. This paper aims to modeling and simulation by MATLAB of the modified topology of the CHB-MLI for a single-phase prototype for 13-levels. The inverter offers less THD and greater efficiency using PSO control algorithm compared with the NR algorithm. The performance of the proposed controllers based on NR and PSO techniques is verified through simulation.

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1. INTRODUCTION

Multilevel power conversion was first introduced 25 years ago [1]. The general concept involves utilizing a higher number of active semiconductor switches to perform the power conversion in small voltage steps. There are several advantages to this approach when compared with traditional two-level power conversion. The smaller voltage steps lead to the production of higher power quality waveforms and also reduce the dv/dt stresses on the load and the electromagnetic compatibility concerns. Another important feature of multilevel converters is that the semiconductors are wired in a series-type connection, which allows operation at higher voltages. However, the series connection is typically made with clamping diodes, which eliminate over voltage concerns. Furthermore, since the switches are not truly series connected, their switching can be staggered, which reduces the switching frequency and thus the switching losses [2, 3]. The harmonic elimination techniques are utilized in multilevel inverters in order to lower harmonic content for improving the output waveform of the voltage inverter, reduce the size of the filter utilized and the level of electromagnetic interference (EMI). Numerous topologies can be used to realize those advantages and can generally be divided into three major categories, namely, diode clamped multilevel inverter DC-MLI, flying capacitor multilevel inverter FC-MLI and separated DC sources cascaded H-bridge CHB-MLI. The type of the MLI which uses a single DC source rather than multiple sources is called the diode-clamped MLI. While, the FC type is designed by series connection of capacitor clamped switching

cells. The CHB switches are connected in parallel and series in order to provide high power demand and high-power quality [4–10], [11, 12] Reduced number of switches with installation area and cost as well as simplicity of control system, with a high number of steps associated using a new topology of cascaded multilevel inverter (CHB-MLI) has been presented in [13]. A new topology for current source multilevel inverter (CSI) with reduced number of switches to generate desired output current based on sinusoidal pulse width modulation (SPWM) method has been presented in [14]. This topology employs $(n+7)/2$ switches and $(n-1)/2$ current-sharing inductors for an n-level CSI. A 5-level single-phase inverter has been developed by field-programmable gate array (FPGA) by [15]. The digital control technique is generated based on multi carrier PWM in Altera DE2 board, which has many features that implement the system design the simulation and experimental results have been consistent. A seven-level inverter has been simulated by [16] via implementation of PWM techniques to reduce total harmonic distortion (THD). This inverter is implemented on the principle of reducing numbers of switches, thus decreasing number of gate drivers in the circuit. The simulation circuitry basically incorporates DC supply and smaller (CHB-MLI) blocks connected in series to implement its desired stepped output waveform.

In this paper, a modified CHB-MLI based on auxiliary bidirectional switch controlled using NR and PSO techniques for optimisation of the output with 13-levels is implemented based on MATLAB Simulink. Most of the researchers had applied the PSO technique to the single phase conventional CHB-MLIs. The NR and PSO techniques are used to calculate switching angles with the capability to eliminate harmonics in the output of the modified CHB-MLIs. Finally, in this paper, is evaluated and validated through simulation results.

2. SWITCHING OPERATION MODES OF MODIFIED CHB-MLIS FOR 13-LEVELS

The switching mode operation of the proposed single-phase modified CHB-MLI for 13-levels can be illustrated in Figure 1. As previously mentioned, the proposed topology adopts a full-bridge configuration with an auxiliary circuit comprising four diodes and a switch which generates half-level DC bus voltage. Figure 2 shows the timing diagram or switching pattern for all switches employed in the modified CHB-MLI. The output voltages of the modified CHBMLI for 13 levels can be summarized as described in Table 1. The present work presents a 13-level PWM inverter with output voltages V_{dc} , $V_{dc}/2$, $V_{dc}/3$, $V_{dc}/4$, 0, $-V_{dc}/4$, $-V_{dc}/3$, $-V_{dc}/2$ and $-V_{dc}$. Surely that increasing the number of output levels of an inverter would reduce its harmonic content.

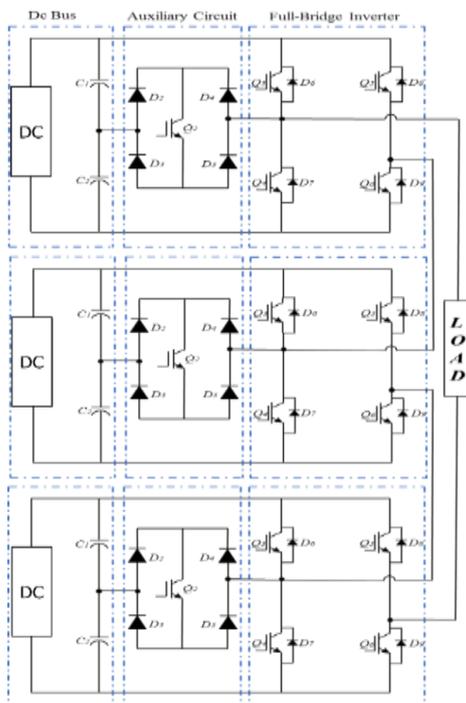


Figure 1. Proposal of modified CHB-MLI, single-phase 13-level topology

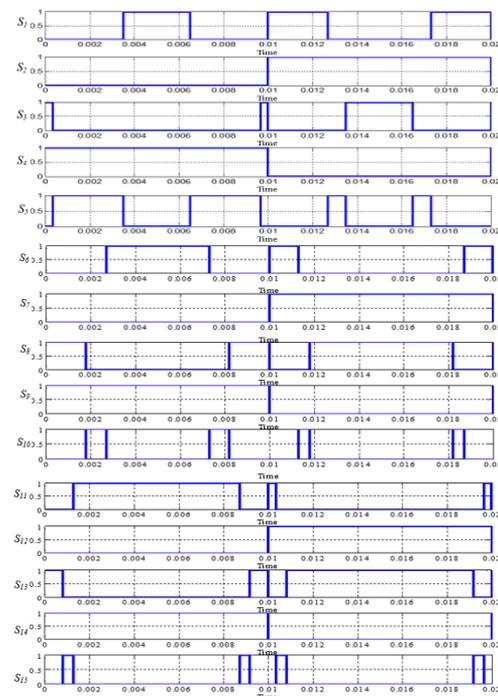


Figure 2. Switching pattern of modified CHB-MLIs for 13-levels

Table 1. Output Voltage for 13-level Inverter to the Switches' states On=1 and Off=0

Voltage State	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇	S ₈	S ₉	S ₁₀	S ₁₁	S ₁₂	S ₁₃	S ₁₄	S ₁₅	Vo
A	1	0	0	1	0	1	0	0	1	0	1	0	0	1	0	V _{dc}
B	1	0	0	1	0	1	0	0	1	0	0	0	0	1	1	V _{dc} /2
C	0	1	1	0	0	0	0	0	1	1	0	0	0	1	1	V _{dc} /3
D	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1	V _{dc} /4
E	0	0	0	1	1	0	0	0	1	1	0	0	1	1	0	V _{dc} /5
F	0	0	0	1	1	0	0	1	1	0	0	0	1	1	0	V _{dc} /6
G	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0
H	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0	0*
I	0	1	0	0	1	1	1	0	0	0	1	1	0	0	0	-V _{dc} /6
J	0	1	0	0	1	0	1	0	0	0	1	1	0	0	0	-V _{dc} /5
K	0	1	0	0	1	0	1	0	0	1	0	1	0	0	1	-V _{dc} /4
L	0	1	1	0	0	0	1	0	0	1	0	1	0	0	1	-V _{dc} /3
M	0	1	1	0	0	0	1	1	0	0	0	1	0	0	1	-V _{dc} /2
N	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0	-V _{dc}

3. ANALYSIS OF THE PROPOSED TOPOLOGIES OF THE MODIFIED CHB-MLI FOR 13-LEVELS

A. Fourier Series for the Output Voltage of the Proposed Modified CHB-MLI for 13-Level:

The equations for 13-levels based on the Fourier series are described below [20]:

$$f(t) = f_{\theta_1}(t) + f_{\theta_2}(t) + f_{\theta_3}(t) + f_{\theta_4}(t) + f_{\theta_5}(t) + f_{\theta_6}(t) = \sum_{n=1,3,5}^{\infty} \frac{2V_{dc}}{n\pi} [(V_{dc1} \cos(n\theta_1) + V_{dc2} \cos(n\theta_2) + V_{dc3} \cos(n\theta_3) + V_{dc4} \cos(n\theta_4) + V_{dc5} \cos(n\theta_5) + V_{dc6} \cos(n\theta_6)] \sin(n\omega t) \tag{1}$$

where:

V_{dci} : Voltage of each voltage source that was in unity

θ_i : Switching angles

$i=1,2...6$.

From (1), six equations were resulted, one for controlling the fundamental component 1st and others for eliminating the 3th, 5th, 7th, 9th and 11th harmonics.

$$V_{AN} = V_{dc1} + V_{dc2} + V_{dc3}$$

$$b_n = \frac{2V_{dc}}{n\pi} \{ \cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \cos(n\theta_4) + \cos(n\theta_5) + \cos(n\theta_6) \} n = 1,3,5,7, \tag{2}$$

As shown in (2) has six variables ($\theta_1, \theta_2, \theta_3, \dots, \theta_6$), where $0 < \theta_1 < \theta_2 < \theta_3 \dots < \theta_6 < \pi/2$, and a solution set is obtained by assigning a specific value to the fundamental component, V_f , and equating the remaining equations to zero as given below:

$$\begin{aligned} V_1 \cos(\theta_1) + V_2 \cos(\theta_2) + V_3 \cos(\theta_3) + V_4 \cos(\theta_4) + V_5 \cos(\theta_5) + V_6 \cos(\theta_6) &= 6 m_i \\ V_1 \cos(3\theta_1) + V_2 \cos(3\theta_2) + V_3 \cos(3\theta_3) + V_4 \cos(3\theta_4) + V_5 \cos(3\theta_5) + V_6 \cos(3\theta_6) &= 0 \\ V_1 \cos(5\theta_1) + V_2 \cos(5\theta_2) + V_3 \cos(5\theta_3) + V_4 \cos(5\theta_4) + V_5 \cos(5\theta_5) + V_6 \cos(5\theta_6) &= 0 \\ V_1 \cos(7\theta_1) + V_2 \cos(7\theta_2) + V_3 \cos(7\theta_3) + V_4 \cos(7\theta_4) + V_5 \cos(7\theta_5) + V_6 \cos(7\theta_6) &= 0 \\ V_1 \cos(9\theta_1) + V_2 \cos(9\theta_2) + V_3 \cos(9\theta_3) + V_4 \cos(9\theta_4) + V_5 \cos(9\theta_5) + V_6 \cos(9\theta_6) &= 0 \\ V_1 \cos(11\theta_1) + V_2 \cos(11\theta_2) + V_3 \cos(11\theta_3) + V_4 \cos(11\theta_4) + V_5 \cos(11\theta_5) + V_6 \cos(11\theta_6) &= 0 \end{aligned} \tag{3}$$

where $m = V_1/(2V_{dc}/\pi)$, and it is related to the modulation index m_i by $m_i = m/s$, where $0 < m_i < 1$.

An objective function is then needed for the optimisation procedure selected as a measure of effectiveness of eliminating selected order of harmonics while maintaining the fundamental component at a pre-specified value. Therefore, this function is defined as:

$$F(\theta_1, \theta_2, \dots, \theta_s) = [\sum_{n=1}^s V_1 \cos(\theta_n) - m]^2 + [\sum_{n=1}^s V_2 \cos(3\theta_n)]^2 + \dots + [\sum_{n=1}^s V_s \cos(2s - 1)\theta_s]^2 \tag{4}$$

The optimal switching angles are obtained by minimising (4) subjected to the constraint $0 < \theta_1 < \theta_2 < \theta_3 < \theta_4 = \dots < \theta_s < \pi/2$, and consequently the required harmonic profile is achieved. The main challenge is the non-linearity of the transcendental set of (4), as most iterative techniques can be used with five and 13-levels of the modified CHB-MLI as shown in Figure 3 and each step is explained, General flowchart of the PSO of the modified CHB-MLI as shown in Figure 4.

3.1. NR Technique

The values of the switching angles $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$, and θ_6 can be chosen by solving the transcendental equations using a modulation index formula (5) to obtain the suitable.

$$mi = \frac{\pi V_f}{2V_{dc}} \quad (0 \leq mi \leq 1) \tag{5}$$

Where, mi is the modulation index

For the angles θ_7 until θ_{24} can be obtained by referring the output waveform of 13-levels of the modified CHB-MLIs theory in Figure 5. The procedure of detecting attributes and configuration of a system is called optimisation. For a 13-level single phase inverter, only five harmonics can be eliminated which are the 3rd, 5th, 7th, 9th, and 11th harmonics. Thus, the switching angles can be found by solving the transcendental equations by using NR technique. These switching angles are then examined for their corresponding THD given by:

$$THD_V = \frac{\sqrt{\sum_{n=1}^{\infty} V_n^2}}{V_1} \tag{6}$$

The effect of optimised angles for 13-levels are $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$, on the THD and the modulation index. By using MATLAB coding for number of iterations, it can be easily find that the modulation index is equal to 0.949 and the corresponding THD value of output voltage with 13-levels is equal to 6.18 %.

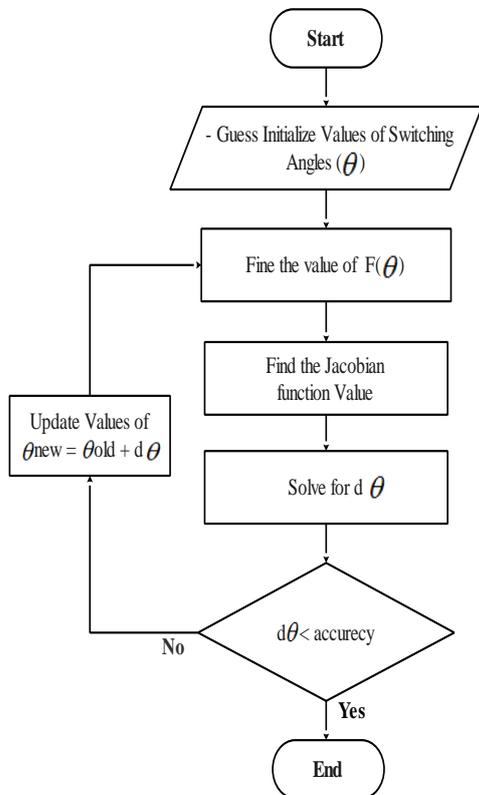


Figure 3. General flow-chart of NR of the modified CHB-MLIs

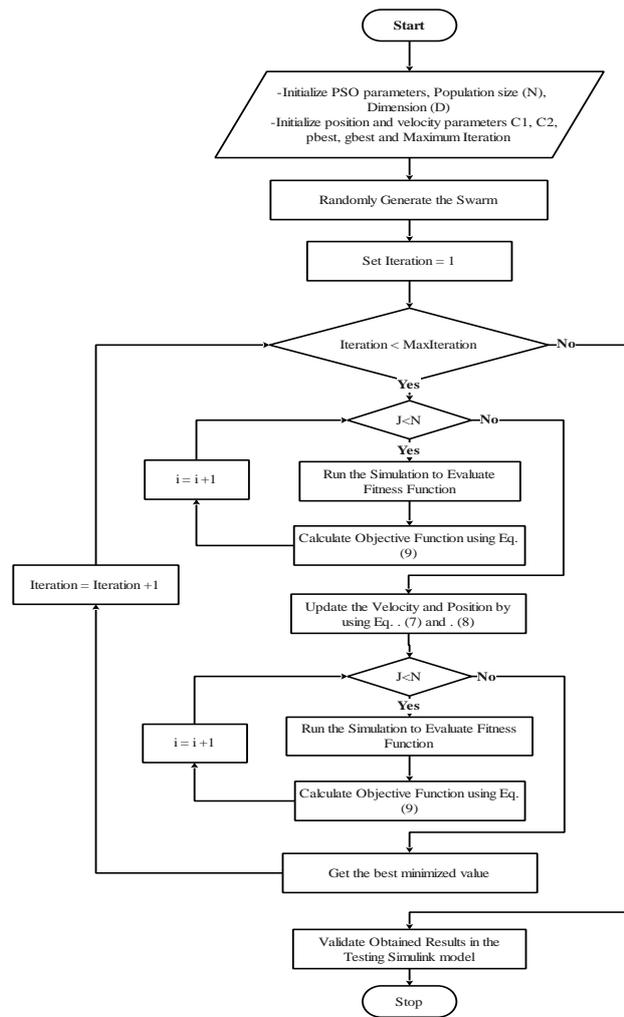


Figure 4. General flowchart of the PSO of the modified CHB-MLI

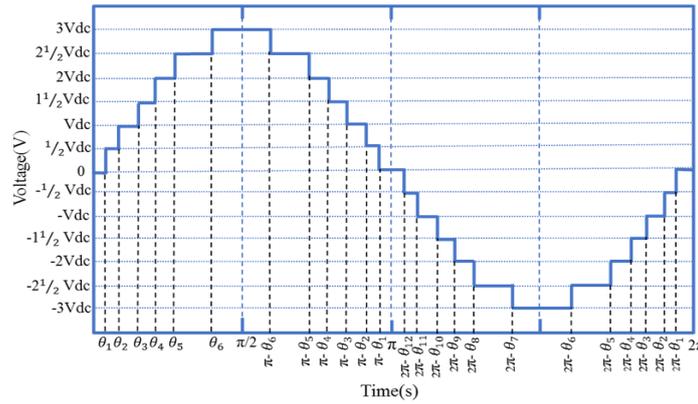


Figure 5. V_{ab} at low switching frequency of modified CHB-MLI, for 13-levels

3.2. PSO Technique

PSO has become a very popular technique in solving non-linear optimization problems. Among many types of evolutionary algorithms, particle swarm is preferred primarily because of its computational efficiency, simplicity and ability to avoid local optima. The PSO has the following key advantages over other evolutionary optimization techniques [17–20]. The PSO algorithm is required to solve nonlinear equations based on SHE algorithm for solving the transcendental equations in order to optimize best switching angles. The number of iteration in the algorithm is solved using MATLAB coding to get better angles for eliminating specific unwanted harmonics. The iteration PSO algorithm can be described by the following steps:

Step 1: Initialise the system parameters such as velocity vector V_i , location vector X_i , personal best particle vector P_i , particle inertia weight C_0 , and global best vector P_g . Assign the values of generations as 100, population size as 40, cognitive parameter C_1 as 0.5 and social parameter C_2 as 1.25.

Step 2: Check for the case $0 < (C_1 + C_2) < 2$ and $(C_1 + C_2)/2 < C_0 < 1$, if the two cases are satisfied then the system will be guaranteed to converge to a stable equilibrium point. If false, go to Step 1.

Step 3: Update the Velocity, $V_i(t + 1)$.

$$V_{ij}(t+1) = V_{ij}(t) + \gamma_{1i}(P_i - x_i(t)) + \gamma_{2i}(G_i - x_i(t)) \tag{7}$$

Step 4: Update the Position, $X_i(t + 1)$.

$$X_{ij}(t+1) = X_{ij}(t) + V_{ij}(t+1) \tag{8}$$

where i is the particle index, j is the index of parameter of concern to be optimized, x is the position of the i th particle and j th parameter, k is the discrete time index, V is the velocity of the i th particle and j th parameter, P is the best position found by the i th particle and j th parameter (personal best), G is the best position found by swarm (global best), C is a random uniform number between $[0,1]$ applied to the i th particle.

Step 5: Now, utilize the Fitness Function in order to evaluate the particle,

Here the switching angles $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$, and α_6 are chosen in such a way that the selective harmonics 3th, 5th, 7th, 9th, and 11th are eliminated. The corresponding transcendental equations are given by:

$$\begin{aligned} F(1) &= (\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_4) + \cos(\theta_4) + \cos(\theta_5) + \cos(\theta_6)) - ma. \\ F(2) &= (\cos(3 * \theta_1) + \cos(3 * \theta_2) + \cos(3 * \theta_3) + \cos(3 * \theta_4) + \cos(3 * \theta_5) + \cos(3 * \theta_6)). \\ F(3) &= (\cos(5 * \theta_1) + \cos(5 * \theta_2) + \cos(5 * \theta_3) + \cos(5 * \theta_4) + \cos(5 * \theta_5) + \cos(5 * \theta_6)). \\ F(4) &= (\cos(7 * \theta_1) + \cos(7 * \theta_2) + \cos(7 * \theta_3) + \cos(7 * \theta_4) + \cos(7 * \theta_5) + \cos(7 * \theta_6)). \\ F(5) &= (\cos(9 * \theta_1) + \cos(9 * \theta_2) + \cos(9 * \theta_3) + \cos(9 * \theta_4) + \cos(9 * \theta_5) + \cos(9 * \theta_6)). \\ F(6) &= (\cos(11 * \theta_1) + \cos(11 * \theta_2) + \cos(11 * \theta_3) + \\ & \quad \cos(11 * \theta_4) + \cos(11 * \theta_5) + \cos(11 * \theta_6)) \end{aligned} \tag{9}$$

Step 6: Check the constraints $0 \leq \theta_1 \leq \theta_2 \leq \theta_3 \leq \theta_4 \leq \theta_5 \leq \theta_6 \leq \pi/2$.

Step 7: Check for the case $P(x_i) < P(P_i)$, if $i = i + 1$ not satisfied then execute to Step 3.

Step 8: If the produced location of the particle is the best then update by change with the previous location as $P_i = X_i$.

Step 9: Update the global best location as $P_g = \min(P \text{ neighbor})$.

Step 10: Switching angles are optimized as the best. Accomplish the solution of the problem.

The general flowchart of the PSO of the modified CHB-MLI is shown in Figure 5.

4. MODELLING OF THE PROPOSED MODIFIED CHB-MLI

MATLAB/SIMULINK software was used to model the proposed topologies of the modified CHB-MLI for 13, levels. Figure 6 shows the circuit diagram of the proposed single-phase modified CHB-MLI for 13-levels. The configuration of this model consists of conventional inverter with 12 switches in addition to a 3-bi-directional switch. This paper aims to develop a PSO algorithm based on the SHE technique for getting the best firing angles for harmonics elimination and compare it with the conventional NR algorithm. The system operation was simulated at low switching frequency. In this simulation, the model; has three DC supply of 300V each. Generator pulse block is used to procedure the switching pattern for generating switching pulses necessary to control the switches of the MLI based on the NR and PSO algorithms. A resistor of 100k Ω will be used as a load to the proposed inverter model. The maximum output phase voltage of the modified CHB-MLI is 900 volts with frequency of 50Hz. The series connected DC bus capacitors C1 and C2 are 2500e-6F, which split the DC bus voltage for each cell into: $V_{DC}/2, 0, -V_{DC}/2$. The middle point n of the capacitors is defined as the neutral point.

5. SIMULATION RESULTS OF MODIFIED CHB-MLI FOR 13-LEVELS WITH $m_i=0.81$ USING NR AND PSO ALGORITHMS

In order to obtain the optimization of the output of the single-phase modified CHB-MLI with 13-levels, the switching angles based on the NR and PSO algorithms were calculated. Based on the simulation model, Figure 7, Figure 8 and Figure 9 show the timing diagram of the switches in the single-phase modified CHB-MLI of 13-levels. There are 3 cells available in the configuration of the proposed inverter shown in the methodology of Figure 6.

Each cell comprises five switches, including bi-directional switch, namely e.g. for the first cell has the switches S1, S2, S3, and S4 and the bi-directional switch S5. From these figures, it is noted that the 15 switches have equal switching periods using a switching frequency of 2500 Hz. The switching angles of the inverter were calculated using the NR technique with MATLAB code and the obtained switching angles are equal to $\theta_1=6.2542^\circ$, $\theta_2=14.3224^\circ$, $\theta_3=22.9152^\circ$, $\theta_4=32.044^\circ$, $\theta_5=48.0239^\circ$, and $\theta_6=62.6458^\circ$. These angles have used the SHE based on the NR technique in order to generate the output of the inverter waveform with time period of 0.02s, and m_i equal to 0.81.

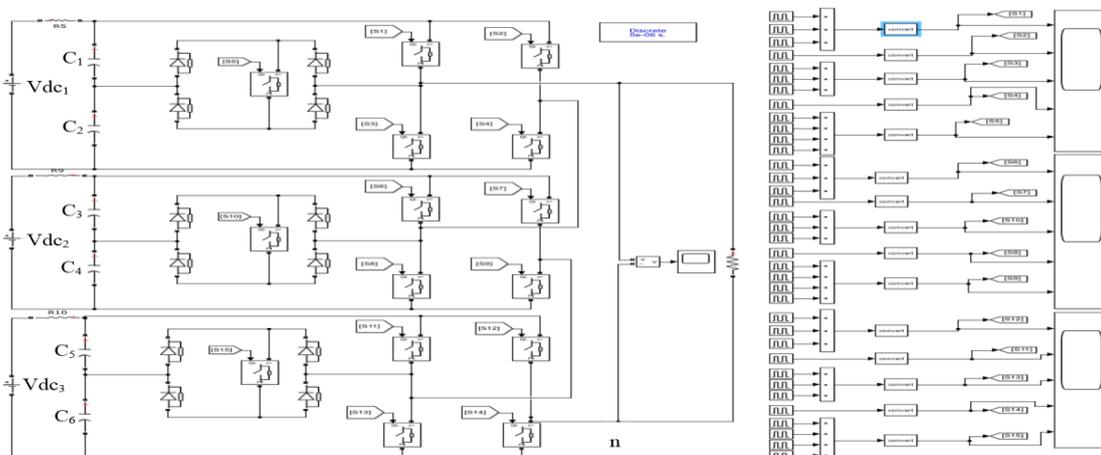


Figure Error! No text of specified style in document.6. Simulations of modified CHB-MLIs for 13-levels model

The obtained timing diagram for the optimization of output voltage waveform of the single-phase 13-level modified CHB-MLI using the NR technique has been produced as shown in Figure Error! No text of specified style in document.10. In order to eliminate the specific order harmonics of the inverter output, the SHE technique of the fundamental switching frequency scheme is used. In this paper, the single-phase modified CHB-MLI with equal DC sources based on the super capacitors [18, 19] is utilized. The output voltage harmonic spectra of the single-phase modified CHB-MLI using the NR were obtained through simulation as shown in Figure Error! No text of specified style in document.11. Figure Error! No text of specified style in document.11 shows the THDv value of the modified inverter output voltage-which equivalent to 6.59%.

The simulation results of timing diagram of the single-phase 13-level modified CHB-MLI based on the PSO technique can be shown in Figure Error! No text of specified style in document.12, Figure Error! No

text of specified style in document.13 and Figure Error! No text of specified style in document.14. The optimized switching angles obtained by using MATLAB simulation are equal to $\theta_1=4.4873^\circ$, $\theta_2=14.5441^\circ$, $\theta_3=24.5761^\circ$, $\theta_4=33.1991^\circ$, $\theta_5=45.82^\circ$, and $\theta_6=62.672^\circ$.

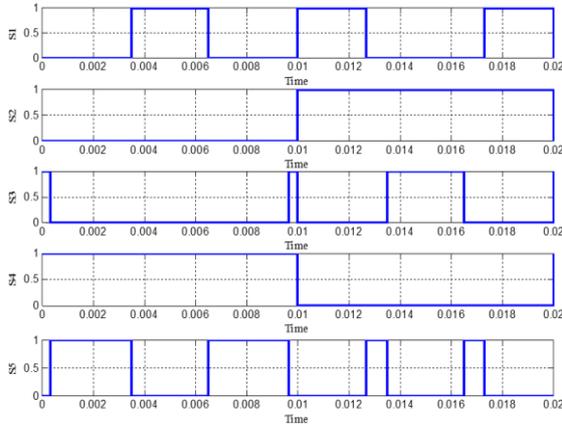


Figure 7. Timing diagram for cell 1 in 13 level inverter comprising S1-S5 switches with $m_i = 0.81$ using NR technique

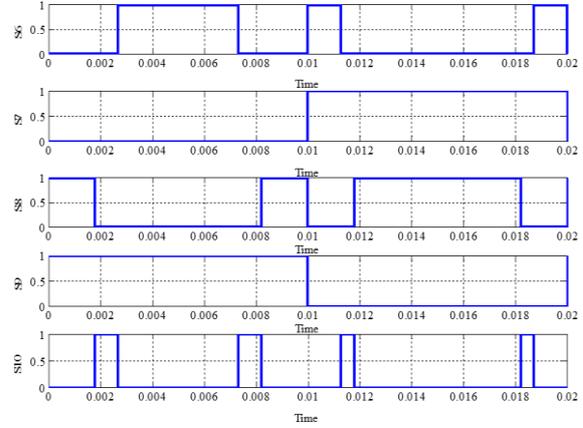


Figure 8. Timing diagram for cell 2 in 13 level inverter comprising S6-S10 switches with $m_i = 0.81$ using NR technique

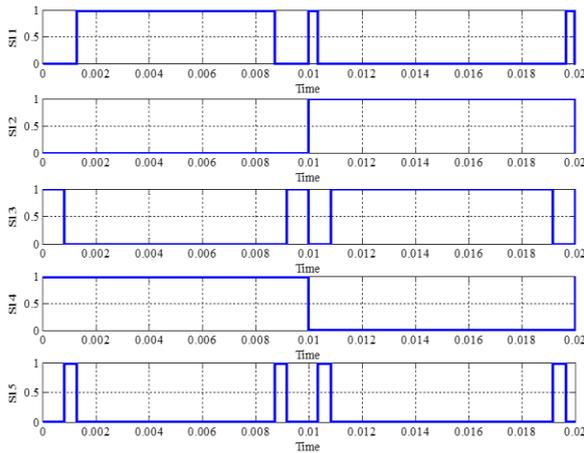


Figure 9. Timing diagram for cell 3 in 13 level inverter comprising S11-S15 switches with $m_i = 0.81$ using NR technique

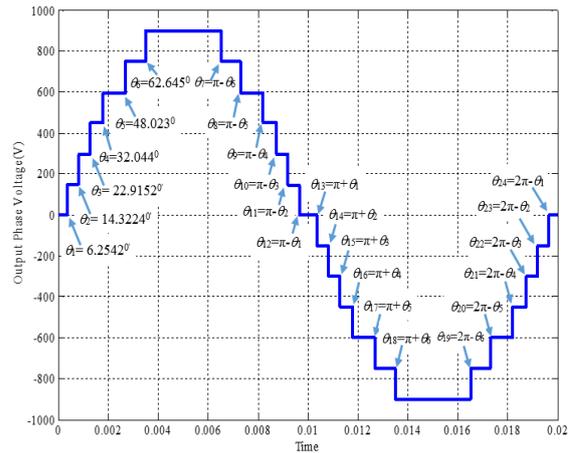


Figure 10. The optimization of output voltage waveform of the modified 13-level inverter with $m_i = 0.81$ using NR technique

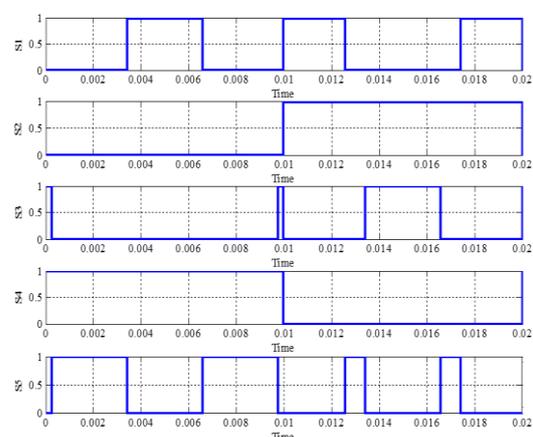
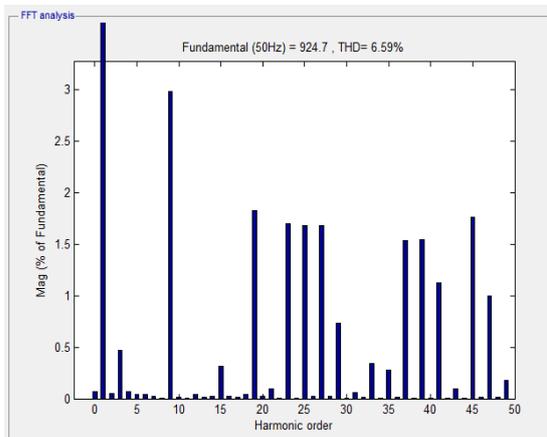


Figure 11. Harmonic spectrum of output voltage waveform of the modified CHB-MLI with $m_i=0.81$ using NR technique

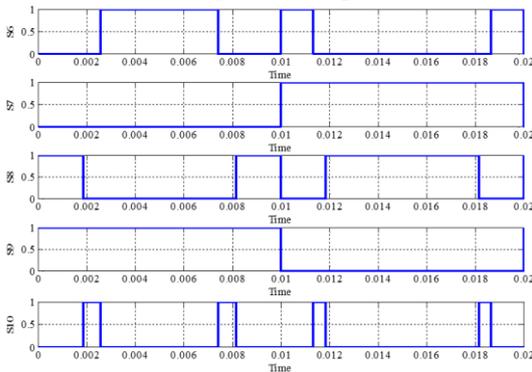


Figure 12. Timing diagram for cell 1 in 13 level inverter comprising S1-S5 switches with $m_i = 0.81$ using PSO technique

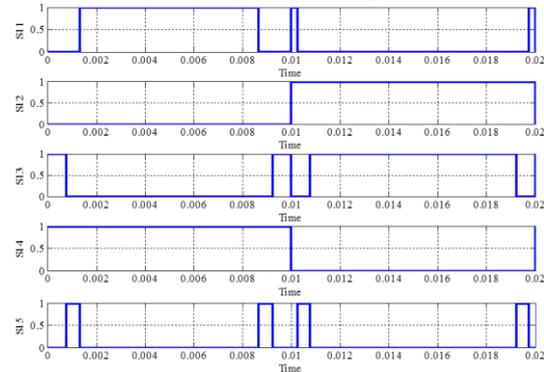


Figure 13. Timing diagram for cell 2 in 13 level inverter comprising S6-S10 switches with $m_i = 0.81$ using PSO technique

Figure 14. Timing diagram for cell 3 in 13 level inverter comprising S11-S15 switches with $m_i = 0.81$ using PSO technique

Figure Error! No text of specified style in document.15 shows the simulation results of the optimized output voltage waveform of the modified CHB-MLI using the PSO technique. It is shown that the optimized output voltage waveform of the inverter based on the PSO algorithm was smoother than that with the NR algorithm due to the inaccurate calculation of the switching angles using the NR technique in comparison with the PSO one. Figure Error! No text of specified style in document.16 shows the optimized harmonic spectrum of the output voltage waveform of the single-phase modified CHB-MLI using the PSO with its THD value equivalent to 5.16%. Overall values of the switching angles and THD shown in Figure 17.

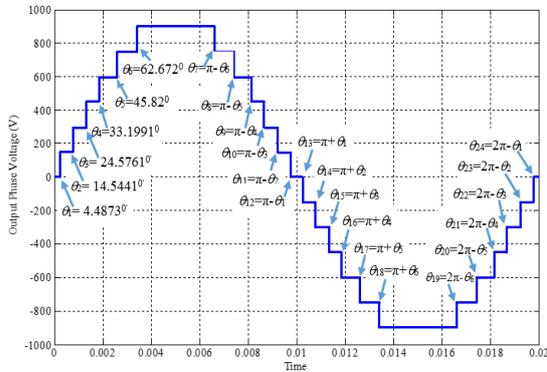


Figure Error! No text of specified style in document.15. Optimization of output voltage waveform of 13-level with $m_i=0.81$ using PSO technique

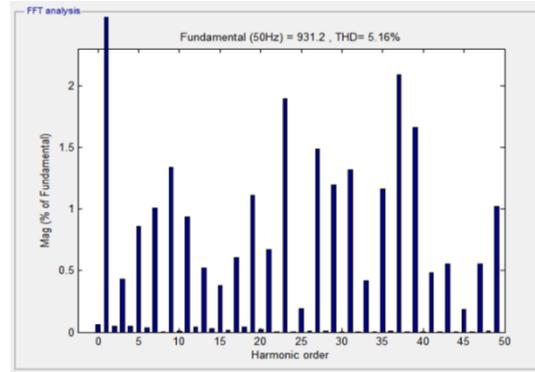


Figure 16. Harmonic spectrum of output voltage waveform of the modified CHB-MLIs with $M_i = 0.81$ using PSO technique

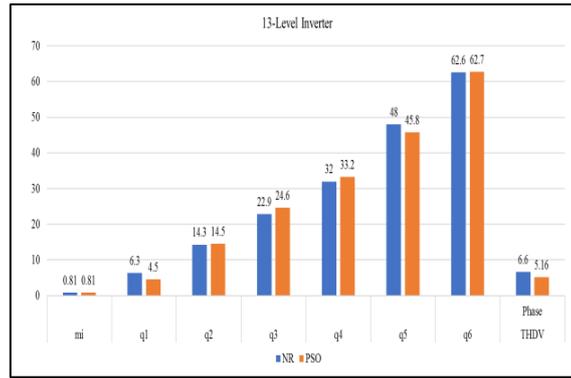


Figure 17. Overall values of the switching angles and THD for the output voltage of the modified CHB-MLI of 13-levels based on NR and PSO techniques

Table 2. Overall Values of m_i , Switching Angles and THD for Output Voltage of the Modified CHB-MLI for 13-levels based on NR and PSO Techniques

13-level	m_i	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	THD _v
NR	0.81	6.3	14.3	22.9	32.0	48.0	62.6	6.6
PSO	0.81	4.5	14.5	24.6	33.2	45.8	62.7	5.16

6. EFFICIENCY OF THE MODIFIED CHB-MLI

Actually, the efficiency of the inverter simply can be defined as the process of converting the DC power into an AC power during the conversion of the power in the system, and there are power losses available, these losses would change as a heat, making the inverter heated, and causing reduction in its operational life time. The drop in the inverter output power controlled with both algorithms NR and PSO will cause its efficiency to be reduced as shown in Figure **Error! No text of specified style in document.** 18, but the efficiency performance of the inverter under the PSO controller is better than the NR one due to effect of the optimization. The DC input power doesn't convert completely into AC output power; part of which is converted into losses. These losses are produced depending on the materials nature of inverter switches as well as the harmonic content, THD of its output. This makes inverter under the PSO control is better than the NR control.

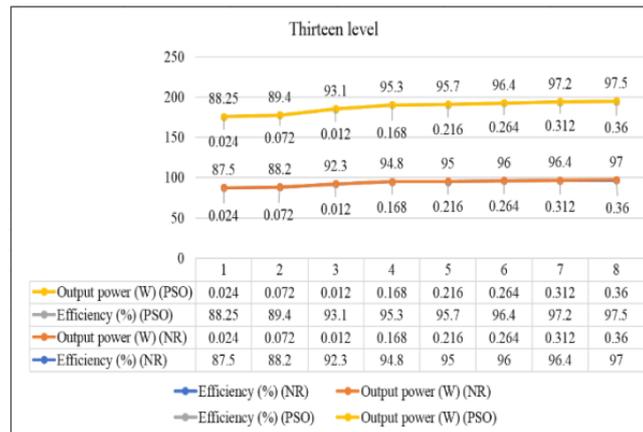


Figure 18. Efficiency of the 13-level modified CHB-MLI for versus technique PSO and NR

7. CONCLUSIONS

The simulation results showed that the higher level of the modified inverter will produce lower harmonics content in its output voltage waveform using the both NR and PSO techniques. However, the PSO technique produce lower content of harmonics (THD) compared to NR technique due to switching angles of the PSO technique is more accurate and thus, more efficient in eliminating lower order harmonics. Its proved that the proposed PSO technique produced the best switching angles. Voltage harmonics within an electrical power system

will cause power line carrier disorder, which leads to long distance operation of switching devices, load control, and metering to be less precise.

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