Comparative Analysis of PWM Techniques for Multilevel Inverter Control Using ANN

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ABSTRACT
This paper proposes a comparative analysis of sinusoidal PWM and selective harmonic elimination PWM for the control of cascaded multilevel inverters. A novel concept of application of Artificial Neural Networks (ANN) for estimating the optimum switching angles for cascaded multilevel inverters is presented. In this paper, the ANN is trained off-line using the desired switching angles given by the classic harmonic elimination strategy to any value of the modulation index. After training the proposed ANN system, a large and memory-demanding look-up table is replaced with trained neural network to generate the optimum switching angles with lowest THD for a range of modulation index. This technique can be applied to multilevel inverters with any number of levels. As an example, a seven-level and eleven-level inverter is considered and the optimum switching angles are calculated, in order to eliminate the odd harmonics and to reduce THD. To verify these goals, the system is simulated on MATLAB/ Simulink. The ANN control algorithm is implemented using m-file program. Theoretical analysis of the proposed algorithm with neural networks is provided, and simulation results of SPWM and SHE-PWM techniques are compared to show the improved performance and technical advantages of the developed system.

General Terms
Multilevel inverter, Pulse width modulation, Back-propagation Algorithm, Modulation index

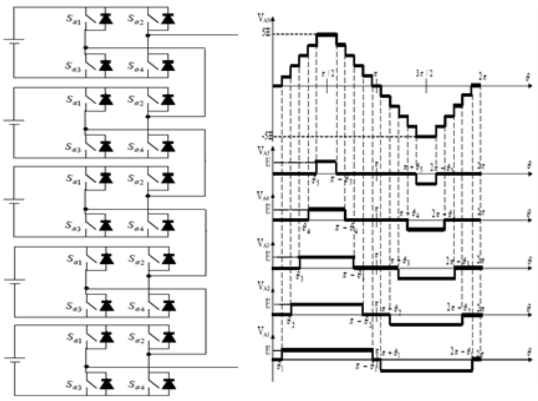
Keywords
Artificial neural network (ANN), sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), Total Harmonic Distortion (THD)

1. INTRODUCTION
Multilevel power conversion has been receiving special attention in the past few years for high voltage and high power applications due to their lower switching frequency, lower switching losses and high voltage rating than conventional two level inverters [1-3]. In most cases, low distortion sinusoidal output voltage waveforms are required with controllable magnitude and frequency. Numerous topologies and modulation strategies have been introduced and studied extensively for utility and drive applications in the recent literatures. In the family of multilevel inverters, topologies based on series connected H-bridges are particularly attractive because of their modularity and simplicity of control [1-2]. Moreover, various modulation strategies such as Sinusoidal PWM (SPWM), Space-Vector PWM (SVPWM), Non-sinusoidal PWM and Selective Harmonic Elimination (SHE) have been suggested for multilevel inverters to decrease the undesired harmonics and control the output voltage of inverter [4-5]. The sinusoidal pulse width modulation (SPWM) is one of the most popular modulation technique used in wide range of industrial application where power switching inverter is employed. Among the mentioned techniques only SHE method is able to eliminate low order harmonics completely [2, 6]. In the SHE method, mathematical techniques such as iterative methods or mathematical theory of resultant can be applied to calculate the optimum switching angels such that lower order dominant harmonics are eliminated [3, 4]. The application of ANN is recently growing in power electronics and electric drives area. In the control of dc–ac inverters, ANNs have been used in the voltage control of inverters for ac motor drives. A feed forward ANN basically implements nonlinear input-output mapping. For any chosen objective function, the optimal switching pattern depends on the desired modulation index. In this paper, a new training algorithm is developed which is used as an alternative for the switching angles look-up table to generate the optimum switching angles of multilevel inverters. This method controls the magnitude of output voltage continuously versus modulation indexes and there is no need to any lookup table after training the ANN. Without using a real time solution of nonlinear harmonic elimination equation, an ANN is trained off-line using the desired switching angles given by solving of the harmonic elimination equation by the classical method, i.e., the Newton Raphson method. Back Propagation training Algorithm (BPA) is most commonly used in the training stage. After the termination of the training phase, the obtained ANN can be used to generate the control sequence of the inverter. The simulation results are presented in MATLAB/Simulink software package for a single-phase cascaded multilevel inverter to validate the accuracy of estimated switching angles generated by proposed ANN system. A comparison with respect to THD between results obtained by SPWM and SHE-PWM technique for a range of modulation index is presented which evidently shows the greater advantage of controlling the inverter by SHE-PWM technique.

2. CASCADED MULTILEVEL INVERTERS
The cascaded multilevel inverter is one of several multilevel configurations. It is formed by connecting several single phase H-bridge inverters in series as shown in Figure 1 for 11-level inverter. Each H-bridge has its own isolated DC source. Each separated DC sources is connected to H-bridge inverter

and can produce voltages of *0*, *+V* and *–V*, where *V* is the voltage of its DC bus.

Figure 1: Multilevel Inverter and its Output Waveform



Each inverter generates quasi-square wave voltage waveform with different duty cycle ratios, which together form the staircase output voltage waveform as shown in Figure 1. The synthesized voltage waveform is, therefore, the sum of the inverter outputs. The number of output phase voltage levels in a cascade multilevel inverter is then 2*s*+1, where *s* is the number of isolated dc sources. With enough levels and appropriate switching algorithm the multilevel results in an output voltage waveform which is almost sinusoidal. Three phase configuration can be formed by connecting three numbers of these inverters in *Y* or Δ [1]. For harmonic optimization, the switching angles θ_1, θ_2, θ_3, θ_4,and θ_5 (for a 11-level inverter) shown in Figure 1, have to be selected so that certain order harmonics are eliminated.

3. COMPARISON OF SPWM AND SHE-PWM TECHNIQUE

In the sinusoidal pulse width modulation (SPWM) technique, generation of the desired output voltage is achieved by comparing the desired reference waveform (modulating signal) with a high-frequency triangular carrier wave. Low ratio of carrier frequency to modulation frequency is the best form of modulation for high power application.

The Selective Harmonic Eliminated PWM (SHE PWM) technique is used to find appropriate switching angles namely θ_1, θ_2, θ_3,…, θ_s so that the (s-1) odd harmonics can be eliminated and control of the fundamental voltage is also achieved. The Fourier series expansion for the quarter-wave symmetric staircase waveform as shown in Figure 1 is written as follows:

$$V_{out}(\omega t) = \sum_{n=1}^{\infty} [(\frac{4V}{n\pi}) \sum_{k=1}^{s} \cos(n\theta k)] \sin(n\omega t) \qquad (1)$$

Where, θ_k is the switching angles, which must satisfy the following condition: $\theta_1, \theta_2, \theta_3, \ldots\ldots\ldots, \theta_s < \pi/2$

s is the number of H-bridge cells
n is odd harmonic order
And, V is the amplitude of dc voltages

The harmonic components in the waveform can be describes as follows:

- the amplitude of dc component equals zero
- the amplitude of the fundamental component, *n* = 1, and odd harmonic component are given by

$$h_1 = (\frac{4V}{\pi}) \sum_{k=1}^{s} \cos(\theta_k) \text{ and } h_n = (\frac{4V}{n\pi}) \sum_{k=1}^{s} \cos(n\theta_k) \qquad (2)$$

- the amplitude of all even harmonics equals zero

Thus, only the odd harmonics in the quarter-wave symmetric multilevel waveform need to be eliminated. The switching angles of the waveform will be adjusted to get the lowest output voltage THD. The total harmonics distortion (THD) is mathematically given by

$$THD = \sqrt{\Sigma \frac{H_n^2}{H_1}} \qquad (3)$$

In order control the fundamental amplitude and to eliminate the 5th, 7th, 11th, & 13th lower order harmonics, the nonlinear transcendental equations set (4) must be solved and the five switching angles θ_1, θ_2, θ_3, θ_3 and θ_5 are calculated offline to minimize the harmonics for each modulation index in order to have a total output voltage with a harmonic minimal distortion rate.

$$\begin{aligned}
&\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) + \cos(\theta_5) = \frac{5\pi M}{4} \\
&\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) + \cos(5\theta_5) = 0 \\
&\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4) + \cos(7\theta_5) = 0 \qquad (4) \\
&\cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4) + \cos(11\theta_5) = 0 \\
&\cos(13\theta_1) + \cos(13\theta_2) + \cos(13\theta_3) + \cos(13\theta_4) + \cos(13\theta_5) = 0
\end{aligned}$$

The modulation index for the multilevel waveform is given as

$$M = \frac{h_1}{sV} \qquad (5)$$

Where, h_1 is the amplitude of the fundamental component. From equation, varying the modulation index value can control the amplitude of the fundamental component and the other s-1 nonlinear equations, which are the undesirable harmonic components, can be eliminated. These equations are solved by Newton-Raphson method [1-3].

In the natural sinusoidal PWM strategy, a large number of switching is required, with the consequent increase of switching losses. With the method of Selective Harmonic Elimination, only selected harmonics are eliminated with the smallest number of switching. This technique is very suitable for inverters control. By employing this technique, the low THD output waveform without any filter circuit is possible. Another approach uses the artificial neural networks to learn these switching patterns; afterwards the trained ANN can be used to estimate the optimum switching angles of inverter [8, 9].

4. ARTIFICIAL NEURAL NETWORK IMPLEMENTATION

The implementation of the feed forward neural network is done to generate the switching angles based on the SHE strategy in order to cancel the 5th, 7th and 11th harmonic and to control the fundamental of the AC output voltage given by this considered inverter.

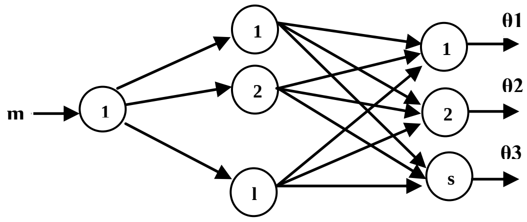


Figure 2: ANN Structure

The ANN to be used for the generation of the optimal switching angles has a single input neuron fed by the modulation index, one hidden layer and *s* outputs where each output represents a switching angle as shown in Figure 2. This set of angles is required to eliminate the 5th, 7th, 11th and 13th harmonics, etc, given by equation (4).

The ANN is trained by the back-propagation algorithm of the Mean Square Error (MSE) between the output and the desired value. The training set for the network has been produced off-line by solving these nonlinear equations using Newton-Raphson method. To implement this algorithm, MATLAB programming is used which in turn makes the process fast and easy. When a set of input values are presented to the ANN, step by step calculations are made in the forward direction to drive the output pattern. The mean square error MSE) generated for the set of input patterns is minimized by gradient descent method altering the weights one at a time starting from the output layer [8-11].

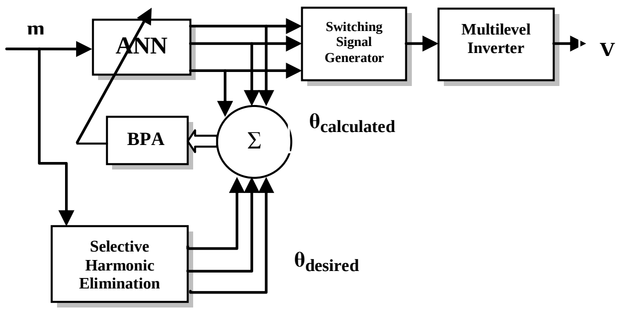


Figure 3: ANN Back-Propagation Algorithm

The training algorithm (BPA) is summarized in Figure 3.

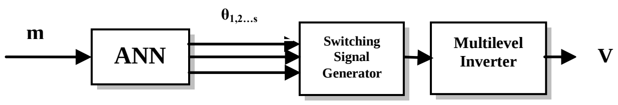


Figure 4: ANN Control of Inverter

The ANN control algorithm is implemented using m-file program. After the termination of the training phase, the obtained ANN can be used to generate the control sequence of the inverter as shown in Figure 4.

5. SIMULATION RESULTS

From the simulation results using neural network, it is clear that the 5th, 7th, 11th and 13th harmonics are strongly suppressed and their magnitudes are negligible relatively to the fundamental component. The obtained switching angles for various values of modulation index using ANN for 7-level and 11-level inverter is shown in Table I and Table II respectively.

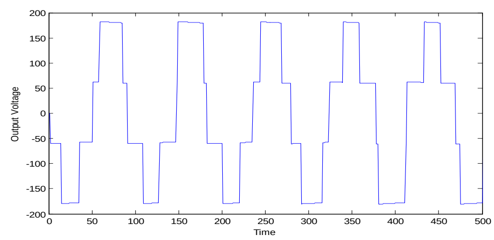
Table 1: Switching Angles Generated By ANN (7-Level)

Modulation Index (M)	Switching Angles		
	θ1 (rad.)	θ2 (rad.)	θ3 (rad.)
0.6	0.1434	0.2851	1.4763
0.65	0.1526	0.3487	1.4455
0.7	0.1615	0.4107	1.4155
0.75	0.1701	0.4710	1.3864
0.8	0.1783	0.5298	1.3581
0.85	0.1863	0.5868	1.3307
0.9	0.1939	0.6422	1.3041
0.95	0.2013	0.6960	1.2783
1.0	0.2084	0.7480	1.2533

Table 2: Switching Angles Generated By ANN (11-Level)

Modulation Index (M)	Switching Angles				
	θ_1 (rad.)	θ_2 (rad.)	θ_3 (rad.)	θ_4 (rad.)	θ_5 (rad.)
0.6	0.0330	0.0665	0.5189	0.6717	0.7935
0.65	0.0423	0.1094	0.4929	0.6686	0.8402
0.7	0.0510	0.1494	0.4686	0.6658	0.8840
0.75	0.0591	0.1868	0.4458	0.6635	0.9249
0.8	0.0668	0.2216	0.4246	0.6615	0.9631
0.85	0.0740	0.2539	0.4048	0.6599	0.9988
0.9	0.0807	0.2840	0.3864	0.6586	1.0320
0.95	0.0870	0.3118	0.3692	0.6576	1.0630
1.0	0.0929	0.3377	0.3532	0.6568	1.0919

Figure 5 shows the simulation results based on SPWM technique for the output voltage waveform of 7-level inverter



for M = 0.6 and the load current waveform of inverter is shown in Figure 6.

Figure 5: Output Voltage of 7-Level SPWM Inverter

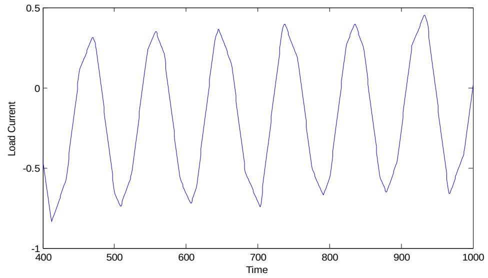


Figure 6: Load Current of 7-Level SPWM Inverter

Figure 7 shows the simulation results based on SHE-PWM technique for the output voltage waveform of 7-level inverter for M = 0.8 and the load current waveform of inverter is shown in Figure 8.

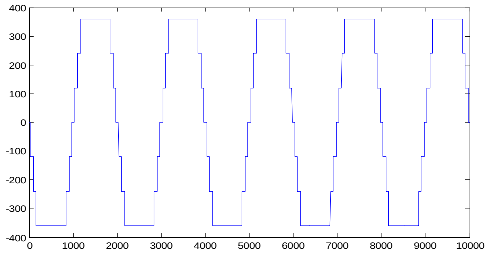


Figure 7: Output Voltage of 7-Level SHE-PWM Inverter

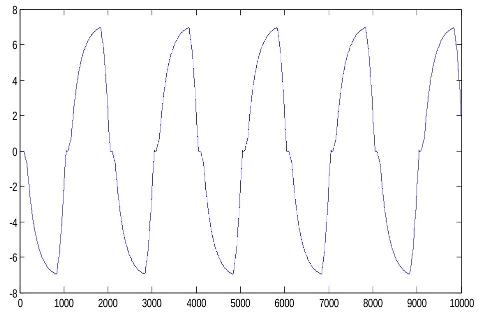


Figure 8: Load Current of 7-Level SHE-PWM Inverter

The FFT spectrum for SPWM and SHE-PWM based 7-level inverter is shown in Figure 9 and Figure 10 respectively.

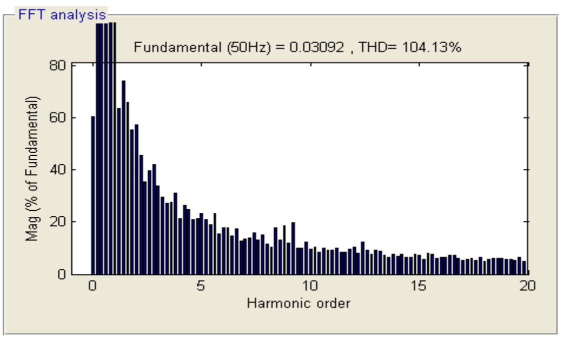


Figure 9: FFT Analysis of 7-Level SPWM Inverter

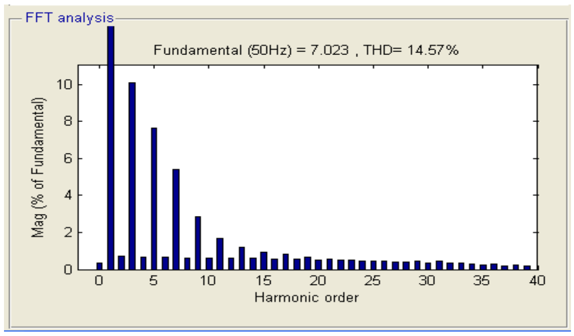


Figure 10: FFT Analysis of 7-Level SHE-PWM Inverter

The THD analysis of 7-level SPWM and SHE-PWM based inverter is shown in Figure 11 and Figure 12 respectively. This shows the variation of Total Harmonic Distortion with respect to simulation time in 7- level inverter without using filter circuit.

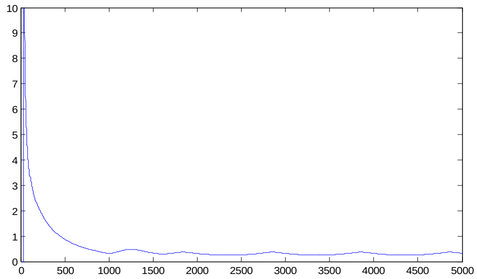


Figure 11: THD Analysis of 7-Level SPWM Inverter

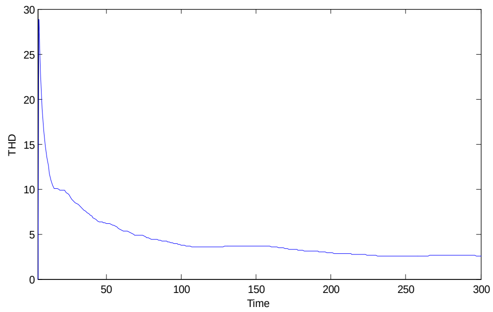


Figure 12: THD Analysis of 7-Level SHE-PWM Inverter

From simulation performed on different level of inverter, it is found that, as the number of levels is increased from 7 to 11 in the inverter with linear load i.e. resistive, or non-linear load i.e. RL load, quality of output waveform improves i.e. harmonic contents are less as shown in Table III.

Table 3: THD Comparison of SPWM and SHE-PWM

No. of Levels of Inverters	Total Harmonic Distortion	
	SPWM	**SHE-PWM**
7- Level Inverter	104.13%	14.57%
11-Level Inverter	92.47%	9.79%

The comparisons between SPWM and SHE-PWM techniques is performed by varying number of levels of inverter for certain value of modulation index which shows the greater advantage of controlling the inverter by SHE-PWM technique.

6. CONCLUSION

In this paper, the comparative analysis of the SPWM and SHE-PWM scheme for the control of multilevel inverter is performed. The SPWM method used in multilevel inverters is more complex because large number switching is required as compared to SHE-PWM method. In this paper, the THD analysis and FFT analysis of seven-level and eleven-level inverter is done based on SPWM and SHE-PWM strategy in order to control the output voltage of the considered inverter. Simulation results of both the inverter control techniques using ANN are compared to validate the accuracy of proposed approach. The paper successfully demonstrates the use of ANN to solve the selective harmonics elimination problem in PWM inverters to obtain lowest THD among the all possible set of solutions. The estimation principle can be extended to high level inverters.

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