Artificial Neural Network Based Harmonic Optimization of Multilevel Inverter to Reduce THD

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***Abstract*— A novel concept of application of Artificial Neural Networks (ANN) for estimating the optimum switching angles for the voltage and harmonic control of cascaded multilevel inverters is presented. In this paper, the neural network 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 Total Harmonic Distortion (THD) for a given 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. The ANN control algorithm is to be implemented using m-file program. Theoretical concepts have been validated in simulation results using artificial neural network technique which shows the high performance and technical advantages of the developed system.**

Keywords—multilevel inverter, artificial neural network, selective harmonic elimination, total harmonic distortion

I. INTRODUCTION

Nowadays, multilevel power inverters are widely used in AC motor drives, uninterruptible AC power supplies (UPS), high voltage and high power applications due to their lower switching frequency, lower switching losses, high voltage rating and lower electromagnetic interfaces (EMI) 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]. Several switching algorithm such as pulse width modulation (PWM), Sinusoidal Pulse Width Modulation (SPWM), space-vector modulation (SVM), selective harmonic eliminated pulse width modulation (SHEPWM) or programmed-waveform pulse width modulation (PWPWM) are applied extensively to control and determine switching angles to achieve the desired output voltage [4]-[5]. Among the mentioned techniques only SHE method is able to eliminate low order harmonics completely. 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 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. The advantages of this method are simple control circuit, controlling 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 seven-level cascaded multilevel inverter to validate the accuracy of estimated switching angles generated by proposed ANN system.

II. 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 Fig. 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. Each inverter generates quasi-square wave voltage waveform with different duty cycle ratios, which together form the staircase output voltage waveform as shown in Fig. 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.

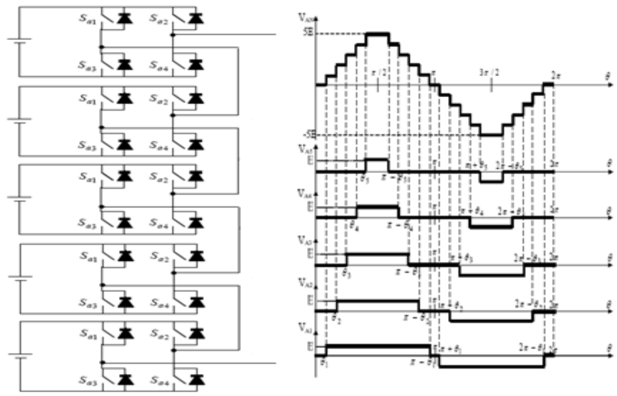

Figure 1. Multilevel Inverter and its Output Waveform

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 Fig. 1, have to be selected so that certain order harmonics are eliminated.

III. SELECTIVE HARMONIC ELIMINATION METHOD

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 Fig .1 is written as follows:

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

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

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

- 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

$$THD = \sqrt{\Sigma H_n^2}/H_1 \quad (3)$$

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.

$$\begin{aligned}
&\cos(\theta_1)+\cos(\theta_2)+\cos(\theta_3)+\cos(\theta_4)+\cos(\theta_5) = 3\pi M/4\\
&\cos(5\theta_1)+\cos(5\theta_2)+\cos(5\theta_3)+\cos(5\theta_4)+\cos(5\theta_5) = 0\\
&\cos(7\theta_1)+\cos(7\theta_2)+\cos(7\theta_3)+\cos(7\theta_4)+\cos(7\theta_5) = 0\\
&\cos(11\theta_1)+\cos(11\theta_2)+\cos(11\theta_3)+\cos(11\theta_4)+\cos(11\theta_5) = 0\\
&\cos(13\theta_1)+\cos(13\theta_2)+\cos(13\theta_3)+\cos(13\theta_4)+\cos(13\theta_5) = 0 \quad (4)
\end{aligned}$$

The modulation index for the multilevel waveform is given as

$$M = h_1/ sV \quad (5)$$

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].

IV. THE ARTIFICIAL NEURAL NETWORKS (ANN)

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. 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. 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]-[10].

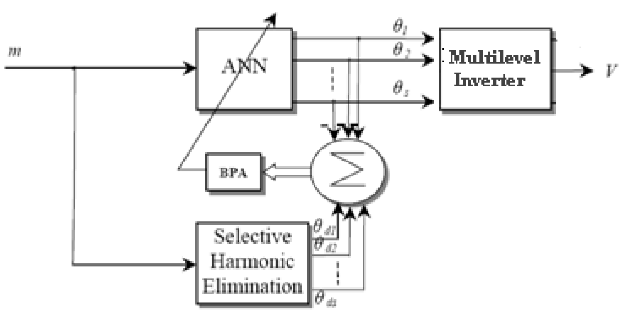

Figure 2. Back Propagation Algorithm

The training algorithm (BPA) is summarized in Fig.2.

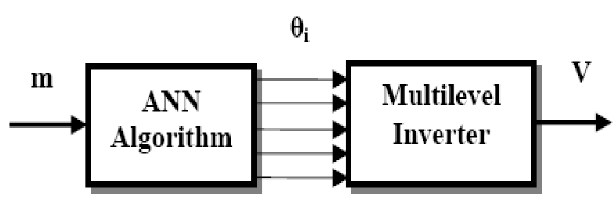

Figure 3. ANN Control of Inverter

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 Fig. 3.

V. 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 I. SWITCHING ANGLES GENERATED BY ANN FOR 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 II. SWITCHING ANGLES GENERATED BY ANN FOR 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

Fig. 4 shows the simulation results for the output voltage waveform of 7-level inverter for M = 0.8 and the load current waveform of inverter is shown in Fig. 5.

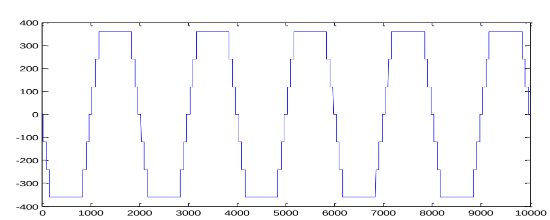

Figure 4. Output Voltage of 7-Level Inverter

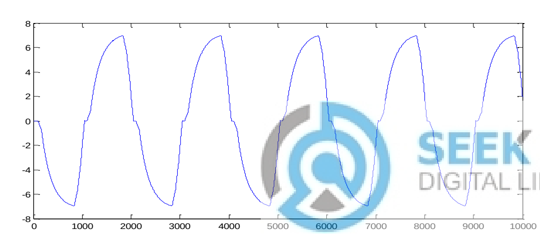

Figure 5. Load Current of 7-Level Inverter

Fig. 6 shows the simulation results for the output voltage waveform of 11-level inverter for M = 0.8 and the load current waveform of inverter is shown in Fig. 7.

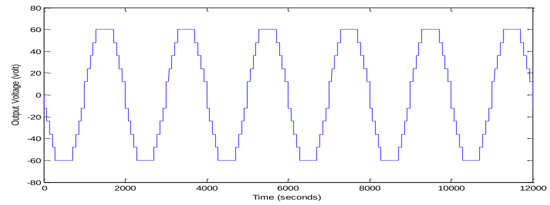

Figure 6. Output Voltage of 11-Level Inverter

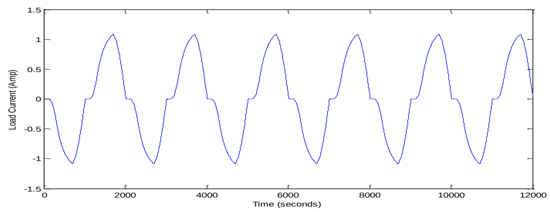

Figure 7. Load Current of 11-Level Inverter

The FFT spectrum up to 40 harmonics for 7-level and 11-level inverters is shown in Fig. 8 and Fig. 9 respectively.

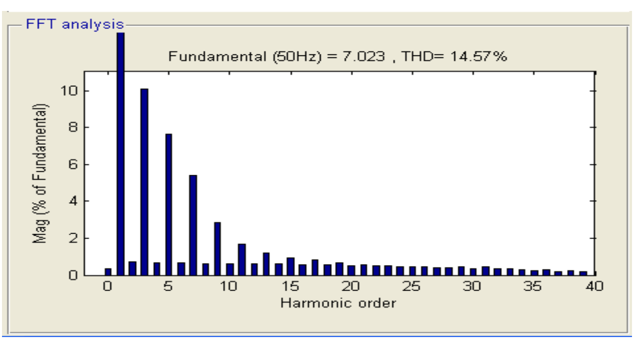

Figure 8. FFT Analysis of 7-Level Inverter

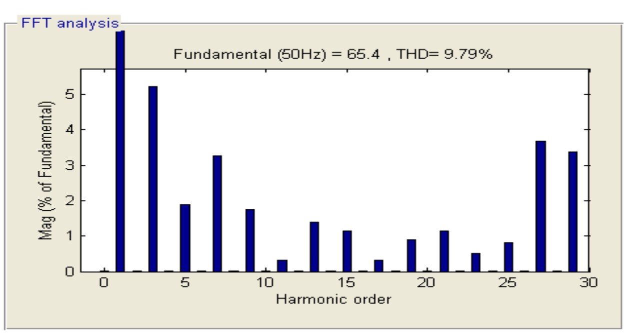

Figure 9. FFT Analysis of 11-Level Inverter

The THD analysis of 7-level & 11-level inverter is shown in Fig. 10 and Fig. 11 respectively. This shows the variation of Total Harmonic Distortion with respect to simulation time, in 7- level and 11-level Inverter without using filter circuit.

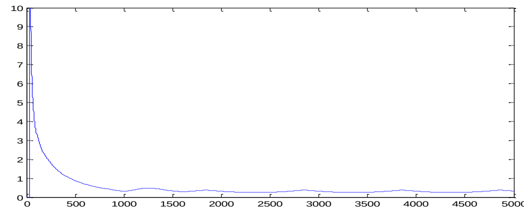

Figure 10. THD Analysis of 7-Level Inverter

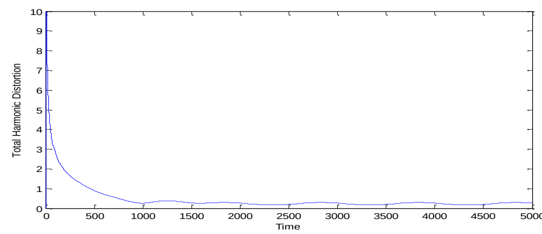

Figure 11. THD Analysis of 11-Level Inverter

TABLE III. THD COMPARISON OF 7-LEVEL AND 11-LEVEL INVERTERS

No. of Levels	Total Harmonic Distortion
7- Level Inverter	14.57%
11-Level Inverter	9.79%

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.

VI. CONCLUSION

In this paper, the use of the ANN is proposed to solve the selective harmonics elimination problem in PWM inverters. The paper successfully demonstrates the validity of feed forward neural networks for the estimation of optimum switching angles of staircase waveform generated by multilevel inverters. This technique allows successful voltage control of the fundamental as well as suppression of a selective set of harmonics. In the first part, the switching angles for seven-level and eleven-level inverter is calculated based on SHE strategy in order to cancel the 5, 7,11 and 13 harmonics and to control the fundamental of the AC output voltage given by this considered inverter. Then, an ANN is trained offline to reproduce these switching angles without constrain for any value of the modulation index. For a real-time control, it is enough to implement the obtained network after the training process. Simulation results are compared for a seven-level and eleven-level inverter to validate the accuracy of proposed approach to estimate the optimum switching angles which produce the lowest THD among the all possible set of solutions. The estimation principle can be extended to high level inverters.

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