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Research Article

Selective harmonic elimination in multi-level inverters by using neural networks

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ABSTRACT

In this study, it is aimed to eliminate the harmonics selected by the selective harmonic elimination (SHE) method in a 7-level cascade multilevel inverter using artificial neural networks (ANNs). A control algorithm has been developed in which the 3rd and 5th harmonics or 5th and 7th harmonics can be eliminated according to the selection while adjusting the output voltage amplitude of the inverter. The required switching angles for SHE are calculated in real time using ANN. These angles were first obtained offline training of ANN using Newton-Raphson method. ANN was trained in MATLAB® environment according to the obtained data. The resulting ANN algorithm and practical implementation using the STM32F429 ARM microcontroller® and inverter switching was provided. Experimental results of the system with RL load were tested.

1. Introduction

Inverters are electrical power converters that convert DC voltage to AC voltage and are used in many areas such as motor drivers and renewable energy grid integration. In this area, multi-level inverters stand out more than traditional two-level inverters due to their advantages such as low total harmonic distortion (THD) value, better power quality, higher amplitude of the fundamental component and better electromagnetic compatibility [1]. Multilevel inverters can be regarded as voltage synthesizers where the desired output voltage is generated by the independent smaller DC voltage. Increasing the number of DC voltage sources causes the converter output voltage to reach an almost sinusoidal waveform.

Multilevel topologies are classified into three major categories as diode-clamped, flying capacitor, and cascading multilevel structures. Stepped multi-level structures are preferred more with their many advantages over other topologies. The most important advantage of cascading multilevel topology over diode-clamped and flying capacitors is its simplicity. While diode-clamped and flying capacitor configurations require more capacitors and diodes, cascading topology requires more isolated DA sources. Hence the complexity of the control strategy for controlling the voltage across each capacitor is the main drawback in flying capacitors and diode clamp converters. Requiring more insulated voltage sources may be disadvantageous depending on the type of application. However, they provide advantages in photovoltaic applications or applications in battery powered systems due to the independent nature of the sources [2].

There are many switching methods that are divided into two groups according to the switching frequency of multi-level inverters. Classical carrier-based Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Modulation (SVM) are some of the high frequency methods. Selective Harmonic Elimination (SHE) method is available as the low frequency method. SHE method is preferred over high frequency methods because it provides better harmonic profile and lower switching loss [3]. The main problem in the SHE method is to find the desired output voltage and the angles required to eliminate the selected harmonics. The challenge here is

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the complexity of solving higher-order nonlinear equations that need to be solved to calculate switching angles. There are many algorithms such as Newton-Raphson (NR), Sequential Quadratic Programming (SQP), Result Theory, Homotopy Algorithm, Genetic algorithm (GA), PSO and Harmony Search Algorithm (HSA) to find these angles [4]. However, solving the equations with these algorithms is very time consuming and difficult to implement in real-time for today's microprocessor speeds. Therefore, the necessary angles in applications are obtained offline by using these algorithms and a lookup table is created [5, 6]. While this method is applicable for basic applications, when the flexibility of the application increases, such a lookup table will require an amount of memory and fast processing that can easily exceed the processor capacity. The idea of using artificial neural networks (ANN) to overcome this problem has been proposed in recent years.

Artificial neural networks are a computing technology inspired by the information processing technique of the human brain. ANN has artificial nerve cells similar to human nerve cells. These cells determine at what rate the data received with the elements they have will be transmitted to the next cell. Therefore, cell elements should be updated until the desired input-output value is reached for ANN training.

ANN has a very fast calculation capability as a result of a good training. This feature has enabled it to find a place in power electronics applications where processing speed is very critical [7]. ANN can be trained according to the needs of each study with many training methods [8]. In SHE applications, the ANN must calculate the switching angles in real time. Therefore, ANN should be trained on an angle table obtained by old methods.

There are some SHE implementations made using ANN. The most common studies are studies that provide constant output voltage at variable input voltages, which are more suitable especially for solar systems [9, 10]. In these studies, the equation coefficients to be solved are constantly changing due to variable cell voltages. Therefore, angle samples taken for ANN training can be quite large. Another study is applications that give variable output voltage for constant input voltage, made for applications that require variable output voltage such as motor control [11, 12]. Since the equation coefficients are constant in these studies, ANN training gives better results than other studies.

In the literature, studies in general have been carried out for a single purpose, especially connecting the output voltage to the network. In this study, an inverter design that can be used for many different applications is realized. For a 7-level inverter, up to two harmonics can be eliminated simultaneously. Since the multiples of three (triple) harmonics are not important in systems connected to the grid, it is sufficient to eliminate the 5th and 7th harmonics. However, 3rd harmonic is a major disadvantage for single phase motor drive applications. For this, the options to eliminate 3rd and 5th or 5th and 7th harmonics, which can be selected depending on the application, are presented to the user with an interface. In addition, fixed and variable frequency options are offered by considering the V / f control, which is frequently used in motor drive applications. In this study, a 7-level inverter design, which includes all these features, has been implemented. Thus, unlike other studies, a different perspective has been brought to this field with an inverter design that can be used for many purposes.

2. System Introduction and Working Principles

In the study, two different harmonic selection, in which 3rd and 5th or 5th and 7th harmonics are eliminated, two different frequency options for constant and V / f control, and a control system that includes modulation index change options for variable output voltage, providing the appropriate output waveform. 7-level level inverter control has been implemented. The cascaded inverter is obtained by serially connecting the H-Bridge circuits powered by independent DC sources as shown in Figure 1. This inverter output is provided by switching angle control for each bridge circuit as seen in Figure 2.

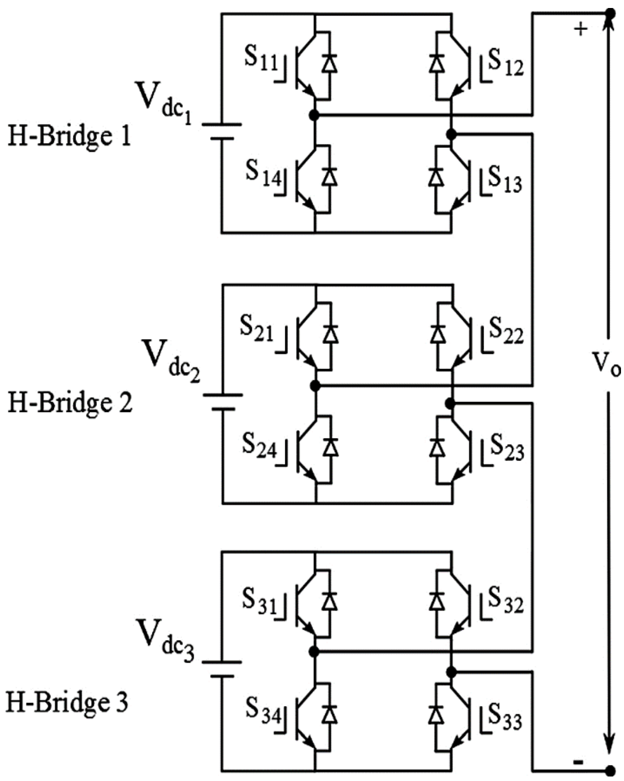


Figure 1. Single phase cascade h-bridge multilevel inverter

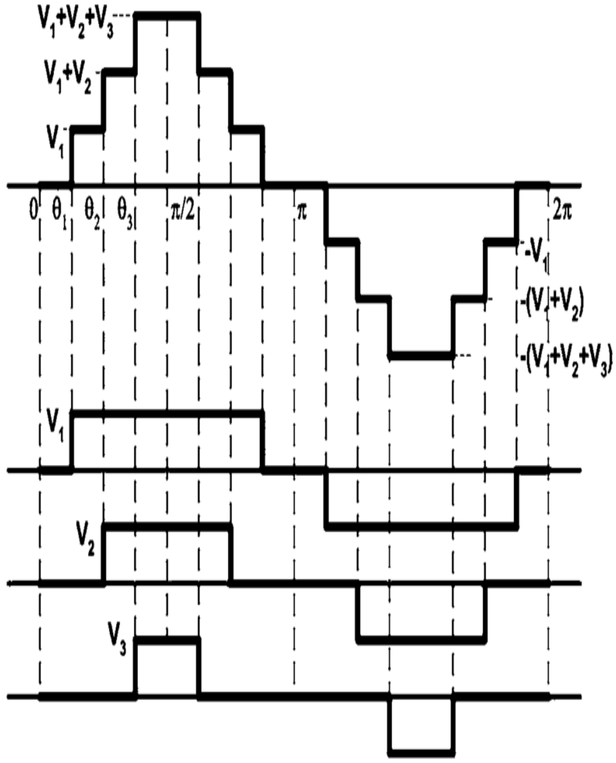


Figure 2. Staircase voltage waveform for single-phase multilevel inverter.

Fourier series expansion for the output waveform in Figure 2 is as in Equation (1).

$$V_{out}(\omega t) = \sum_{n=1,3,5\ldots}^{\infty} b_n \sin(n\omega t) \quad (1)$$

bn is given by:

$$b_n = \sum_{n=1,3,5\ldots}^{2N-1} (V_{dc1}\cos(n\alpha_1) + V_{dc2}\cos(n\alpha_2) + \cdots$$

$$+V_{dcL-1}\cos(n\alpha_{L-1}) + V_{dcL}\cos(n\alpha_L) + \cdots \quad (2)$$

For equal and constant source, bn is given by;

$$b_n = \sum_{n=1,3,5\ldots}^{2N-1} V_{dc}(\cos(n\alpha_1) + \cos(n\alpha_2) + \cdots$$

$$+\cos(n\alpha_{L-1}) + \cos(n\alpha_L) + \cdots \quad (3)$$

Where,

$V_{dc} = V_{dc1} = V_{dc2\ldots\ldots} = V_{dcL}$

L = number of dc sources for each full H-bridge inverter cell,

N = number of switching angles,

n =1, 3, 5, … odd harmonics (2N-1).

Harmonic equations including the basic voltage equation are derived from Equation (3). In the SHE method, as seen in Equation (4), the desired value for the basic component is assigned and the harmonic equation to be eliminated is set to zero. The desired output voltage and harmonic elimination can be achieved with the switching angles that give the solution of these equations.

$$\begin{gathered}\cos(\alpha_1) + \cos(\alpha_2) + \ldots\cos(\alpha_L) = m \\ \cos(3\alpha_1) + \cos(3\alpha_2) + \ldots\cos(3\alpha_L) = 0 \\ \cos(5\alpha_1) + \cos(5\alpha_2) + \ldots\cos(5\alpha_L) = 0 \\ \cos(7\alpha_1) + \cos(7\alpha_2) + \ldots\cos(7\alpha_L) = 0 \\ \cos(n\alpha_1) + \cos(n\alpha_2) + \ldots\cos(n\alpha_L) = 0\end{gathered} \quad (4)$$

Where:

Modulation index, $m = V_1/(4V_{dc}/\pi)$,L is the number of dc sources.

The main challenge is solving these nonlinear equations. An iterative algorithm such as the Newton-Raphson method is traditionally used to solve these equivalents. However, since the angle calculation is not possible in the output voltage frequency with this algorithm, it cannot be performed in real time. As stated before, angle tables calculated offline are useless because they can easily exceed the microcontroller memory. This problem has been solved by using ANN. ANN has the ability to do the same process faster by being trained with the input-outputs of time consuming transactions. Figure 3 shows the structure of a single neuron in ANN. For a single neuron, the processing charge has the power of very fast processing since it consists of passing the input value multiplied by the weight value through a transfer function and transmitting it to the next neuron as in Equation (5).

$$o_j = \varphi\left(\sum_{k=1}^{n} w_1 x_1 + \theta_j\right) \quad (5)$$

The training of ANN is based on updating the weights and bias values that make up its structure until it gives the most reliable result.

In the study, it is aimed to design a 7-level multilevel inverter. The following options are provided for the inverter output waveform; variable output voltage in the range of 40% -90% modulation index (m = 1.2-2.7) for the fundamental component, elimination of 3rd-5th harmonics or 5th-7th harmonics in this modulation index range, fixed output frequency according to selection or variable output frequency in V/f ratio. For these options, the angle calculation was made in MATLAB® using the Newton-Raphson method. ANN training was carried out in MATLAB® environment with the calculated data. The obtained ANN algorithm is implemented on the STM32F429 microcontroller® and switching signals are obtained. A printed circuit board was designed for the 7-level inverter design and the system was tested on an RL load.

3. System Simulation Analysis

Two different ANN structures were trained for two different harmonic elimination options (3rd - 5th and 5th - 7th). Two different data sets are required for these trainings. Using the Newton-Raphson method in MATLAB® environment, 151 data were obtained with a modulation index sampling interval of 0.01 for each option in the range of 1.2-2.7 modulation index.

ANN training was carried out using nftool neural network tool in MATLAB® environment. As seen in Figure 4, the general structure of ANNs consists of an input representing the modulation index, eight neurons and three outputs representing the switching angles.

Levenberg-Marquardt algorithm using the least mean square error approach was used to train the network. Mean square error and regression analysis were used as training performance criteria. Figure 5 shows the performance results obtained in both networks, respectively.

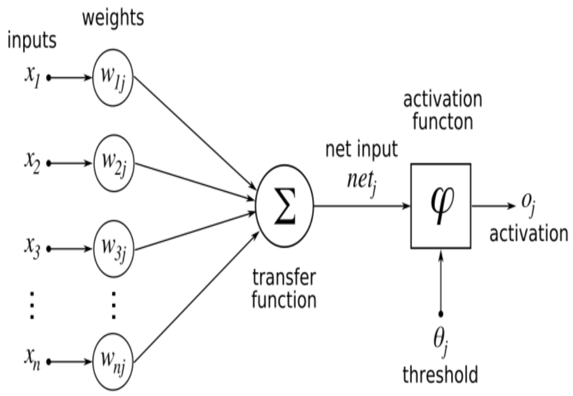


Figure 3. Structure of Single Neuron [13]

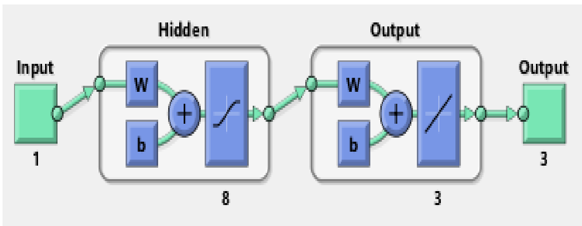


Figure 4. Artificial Neural Network Structure [14]

Results

	Samples	MSE	R
Training:	105	3.23715e-4	9.99583e-1
Validation:	23	3.47780e-4	9.99546e-1
Testing:	23	3.76651e-4	9.99537e-1

(a)

Results

	Samples	MSE	R
Training:	121	7.22040e-5	9.99838e-1
Validation:	15	9.51942e-5	9.99772e-1
Testing:	15	2.71884e-5	9.99938e-1

(b)

Figure 5a. ANN Performance Parameters for a) 3rd - 5th Harmonic, b) 5th - 7th Harmonic

The fact that the mean square error is very low and the regression number is very close to 1 means that both networks are well trained. The trained ANNs were compiled in the microcontroller compiler by creating an algorithm to be used on the microcontroller. Figure 6 shows the ANN algorithm.

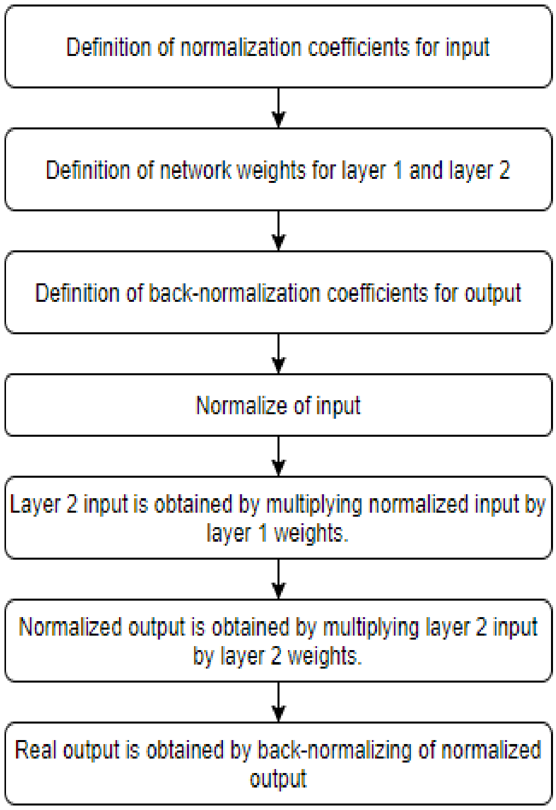


Figure 6. ANN Algorithm

4. Hardware Design

Our inverter is formed by connecting three H-Bridge circuits in series. A total of 4 MOSFETs are used in each circuit, and a gate driver circuit is required to switch these MOSFETs.

However, since the reference voltage for the source leg of the upper MOSFETs is not the ground of the circuit, a technique called bootstrap method is used to increase the voltage between the gate-source to a sufficient level during switching with the used capacitor.

The H-Bridge circuit was designed using the IR2110 driver integrated working with this technique. Figure 7 shows the gate driver circuit for a single module.

This circuit requires three different supply voltages: 25V for the input voltage, 15V and 5V for the IR2110 integrated. For this, other voltages were obtained from 25V input voltage with 7815 (15V) and 7805 (5V) integrations.

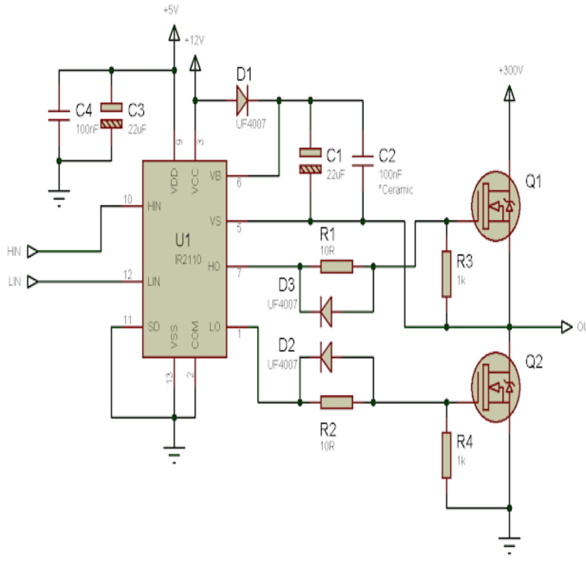


Figure 7. Gate Driver Circuit

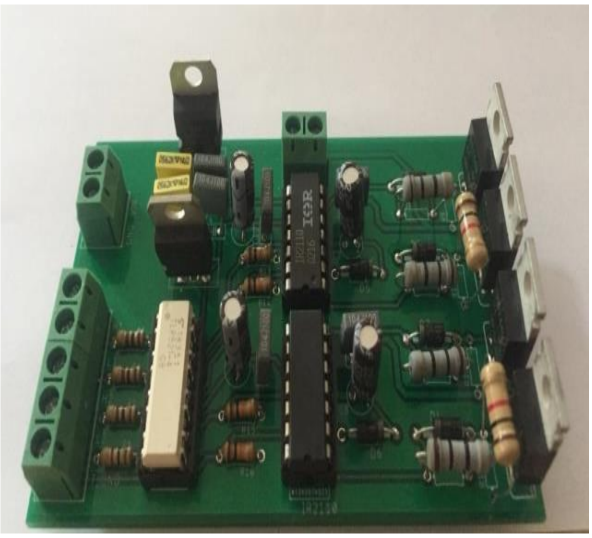


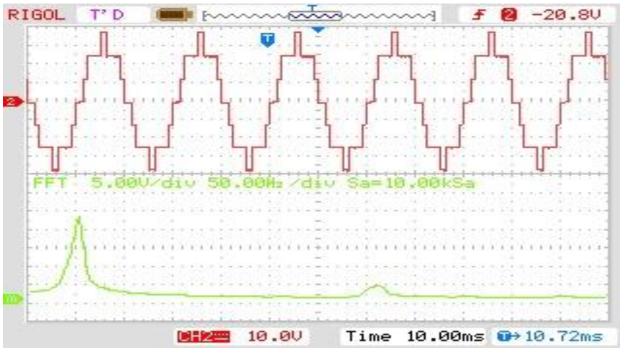
Figure 8. Printed Circuit Board design for H-Bridge

In addition, TLP521-4 integrated circuit is used for isolation between microcontroller and IR2110. Three H-Bridge circuits were obtained by drawing printed circuit in Eagle program.

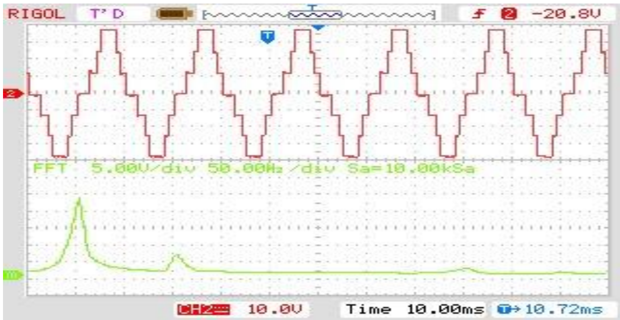
5. Experimental Results

The system was tested with RL load at 20kΩ and 1mH. Three power supplies produce 25V for each circuit, isolated from each other. The output voltages were taken over 10kΩ due to the volt/div restriction of the oscilloscope and half the output voltage (37Vpeak) was measured.

In Figure 9.a, waveforms and fast Fourier transform measurements are given in the modulation index of 2.0 for the situation where the 3rd and 5th harmonics are eliminated, and the 5th and 7th harmonics are eliminated in Figure 9b. As can be seen, the angles provided by both ANNs and the targeted harmonics have been eliminated.



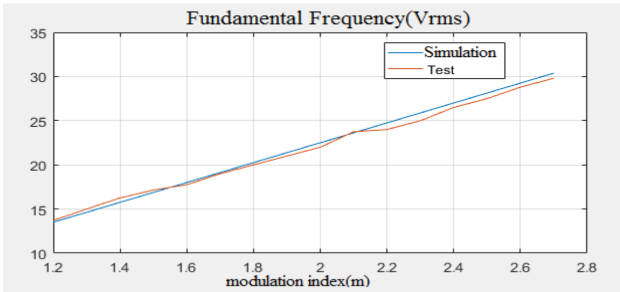
(a)



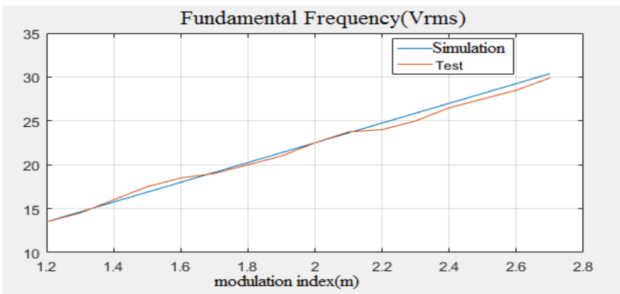
(b)

Figure 9. Wave and FFT Output in a) 3-5 (2.0 Mod. Index) Option, b) 5-7 (2.0 Mod. Index) Option

The fast Fourier transform measurements of the system output were made and the results obtained in the simulation environment were compared with the MATLAB® environment, and the V_{rms} values for the fundamental component and the harmonics they destroy were given as graphs in the range of 1.2-2.7 modulation index. Figure 10 shows the graphics for the fundamental frequency, respectively. As can be seen, with small differences, the result of the experiment follows the simulation result.

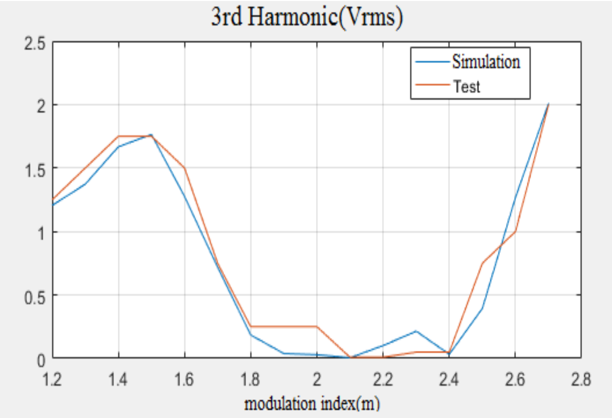


(a)

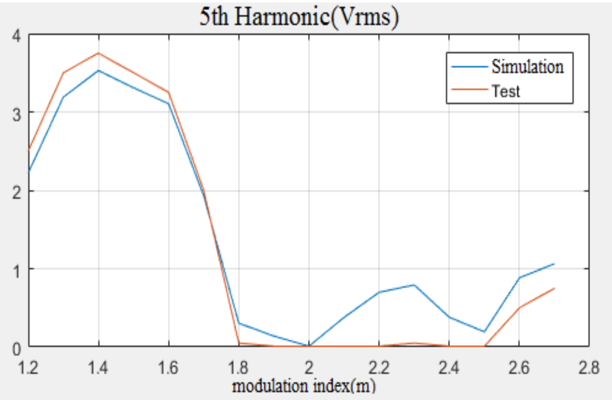


(b)

Figure 10. Comparison of Fundamental Frequency in a) 3-5 Option, b) 5-7 Option

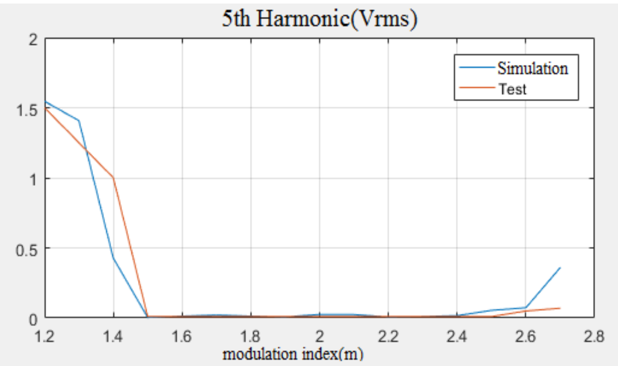


(a)

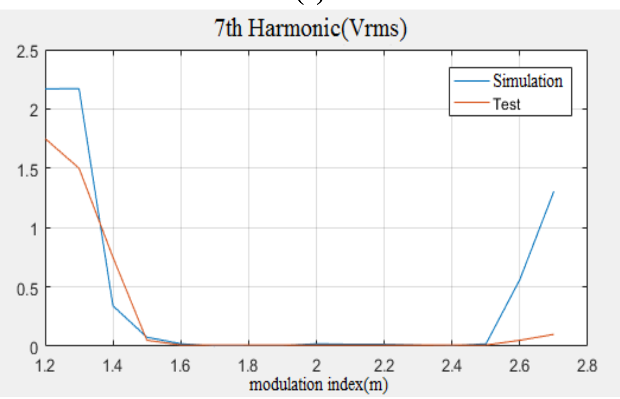


(b)

Figure 11. Comparison of 5th Harmonic in a) 3-5 Option, b) 3-5 Option



(a)



(b)

Figure 12. Comparison of 7th Harmonic in a) 5-7 Option, b) 5-7 Option

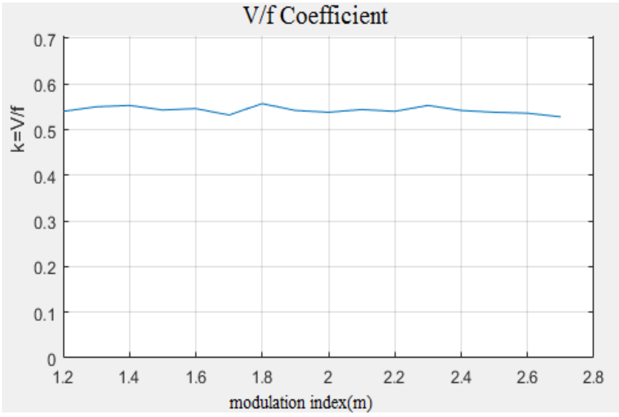


Figure 13. V/f Coefficient in Changeable Frequency Option

Figure 11 shows the graphs obtained for harmonics eliminated in 3-5 option. The experiment results follow the simulation. Full elimination could only be achieved between 1.8-2.5 indices.

In Figure 12, the graphs obtained for harmonics eliminated in 5-7 option are given. Full elimination was achieved between indices 1.5-2.6. In this respect, the situation where 5th-7th harmonics are eliminated provides better performance.

Although there is little difference between the results, in general, the simulation and test results are very close to each other. Since the Newton-Raphson method did not provide results for every modulation index, complete harmonic elimination could not be achieved at certain intervals.

Finally, measurements were taken for V/f control option. As seen in Figure 13, the V/f ratio could be fixed despite very small changes that may occur due to noise and measurement errors.

6. Conclusion

In this study, harmonic elimination has been achieved by using SHE method for 7-level cascade multilevel inverter. The most important contribution of this study was the real-time application of the SHE method using ANN. Offline angle tables used in traditional SHE methods can both exceed the memory and limit the flexibility of the system. A trained ANN has a very fast processing capacity due to its simple structure. Using this feature, angles can be calculated in every period with a speed much higher than the output frequency range of 25Hz-50Hz. In the study, the inverter interface offers two different harmonic options, 3rd – 5th, 5th – 7th and a fixed frequency and variable frequency in V/f ratio.

In addition, the option of changing the output voltage in the 40% -90% modulation range is offered. The weakness of this study is that it cannot achieve complete elimination for each modulation index. To overcome this problem, training data instead of the Newton-Raphson method can be solved by another solution algorithm. As can be seen from the regression value and the results obtained, ANN training is extremely successful.

Considering a new research topic on this project, a system in which the same operations are performed against variable input voltages can be considered.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

Ö. Akın developed the methodology and planned the study. İ. Özer worked on artificial neural network design and software implementation. H. Ünlü performed the hardware design and performance analysis.

References

1. Santhi, R., Giridharan, K., Kannabhiran, A., *A survey on voltage source multi level inverter topologies.* IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI), 2017. p. 1262-1271.
2. Kar, P. K., Priyadarshi, A., Karanki, S. B., *A modified single phase H-bridge multilevel inverter topology for photovoltaic applications*. in National Power Electronics Conference (NPEC) 2017: Pune, India. p. 340-345.
3. Sahu, N., and Londhe, N. D., *Optimization based selective harmonic elimination in multi-level inverters*. in National Power Electronics Conference (NPEC) 2017*:* Pune, India. p. 325-329.
4. Sharma, A., Singh, D., Pandey, V., Gao, S., *Selective harmonic elimination for cascaded H-bridge MLI using GA and NR-Method*. in International Conference on Electrical and Electronics Engineering (ICE3) 2020: Gorakhpur, India. p. 89-94.
5. Halim, A. W., Azam, T. N. A. T., Applasamy, K., Jidin, A., *Selective harmonic elimination based on newton-raphson method for cascaded H-bridge multilevel inverter*. International Journal of Power Electronics and Drive Systems (IJPEDS), 2017. **8**(3): p. 1193-1202.
6. Chatterjee, A., Rastogi, A., Rastogi, R., Saini, A., and Sahoo, S. K., *Selective harmonic elimination of cascaded H-bridge multilevel inverter using genetic algorithm.* in Innovations in Power and Advanced Computing Technologies (i-PACT) 2017: Vellore, India. p. 1-4.
7. Bose, B. K., *Neural Network Applications in Power Electronics and Motor Drives—An Introduction and Perspective.* IEEE Transactions on Industrial Electronics, 2007. **54**(1): p. 14-33.
8. Kumar, J., Gambhir, J., Kumar, A., *Control of switching angles for a CMLI using ANN*. in Engineering and Computational Sciences (RAECS) 2014, Panjab University Chandigarh: India. p. 1-6.
9. Aravind, P. S., Alexander, S. A., *Harmonic minimization of a solar fed cascaded H bridge inverter using artificial neural network*. in International Conference on Energy Efficient Technologies for Sustainability 2013: Nagercoil, India. p. 163-167.
10. Filho, F. J. T., Tolbert, L. M., Ozpineci, B., *Real time selective harmonic minimization for multilevel inverters using genetic algorithm and artificial neural network angle generation*. Proceedings of The 7th International Power Electronics and Motion Control Conference, 2012. p. 895-899.
11. Fakhry, M. G., Massoud, A., Ahmet, S., *Quasi seven-level operation of multilevel converters with selective harmonic elimination*, in 2014 26th International Conference on Microelectronics (ICM): Doha, Qatar. p. 216-219.
12. Yang, K., Hao, J., and Wang, Y., *Switching angles generation for selective harmonic elimination by using artificial neural networks and quasi-newton algorithm*, in 2016 IEEE Energy Conversion Congress and Exposition (ECCE): Milwaukee, WI. p. 1-5.
13. Cybenko, G, *Approximation by superpositions of a sigmoidal function.* Math. Control Signal Systems, 1989. **2**(4): p. 303–314.
14. Oluwasegun K. M., Ojo O. A., Ola O. T., Birur A., Cuddy J. and Chan K., *Development of artificial neural network models for predicting weld output parameters in Advanced fusion welding of a magnesium alloy*. American Journal of Modeling and Optimization. 2018. **6**(1): p. 18-34.