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Real-Time Robust Control of Multilevel Converters Using Artificial neural Networks (ANNs) and Particle Swarm Optimization (PSO) Algorithm

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ABSTRACT: Multilevel converters are considered today as the state-of-the-art power conversion systems for high power and power quality demanding applications. Multilevel converters using low and medium voltage switches, possible producing medium output voltage to accept. These converters also avoiding high levels of stress in rapid changes of voltage and cascading switches, thus provided higher output power. This paper presents the selective harmonic elimination and reduced output voltage distortion in a cascaded full-bridge multilevel inverter powered by varying DC input sources. To obtain the switching angles of ANNs is used in real-time conditions. The switching angles were chosen somehow that the fundamental harmonic was kept constant and the higher-order harmonics, in order to minimize THD, were minimized or eliminated. Thus, by this means, the problems related to such the uncertain input voltage inverter are largely solved. For ANN training from samples generated will be used to perform detailed simulations. In these samples to obtain the optimum switching angles of PSO algorithm is used.

KEYWORDS: Multilevel Inverter, Artificial Neural Networks, Switching Angles, Particle Swarm Optimization Algorithm, harmonic elimination.

I.INTRODUCTION

Power electronic converters on the base of semiconductor devices are applied today in many different branches of industry and other technical applications. Their power changes from mW to hundreds of MW. Multilevel converters are considered today as the state-of the-art power conversion systems for high power and power quality demanding applications. Multilevel converters using low and medium voltage switches, possible producing medium output voltage to accept. These converters also avoiding high levels of stress in rapid changes of voltage and connect switches in the series, thus provided higher output power. they are capable of handling high voltage with minimum voltage stress on switching devices, generate output voltage with minimum harmonic content, and generate low dv/dt and have a lower common mode voltage, which result in reduced stress on motor bearing in drive applications [1-3].

The Multilevel converters are one of the recent developments in power electronics technology to meet the high power, good spectral quality voltage requirements of industries. Based on the topology multilevel converters are classified as 1) Diode clamped multilevel converter; 2) Flying capacitor multilevel converter and 3) Cascaded multilevel converter.

The most attractive features of multilevel inverters are as follows [4]:

1. Generation of output voltages with extremely low distortion and lower.
2. Drawing input current with very low distortion.

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3. Generating smaller common-mode voltage, thus reducing the stress in the motor bearings. In addition, using sophisticated modulation methods, common mode voltages can be eliminated.
4. Operating with a lower switching frequency.

In this paper, the main purpose is using control feature of cascaded H-Bridge converters. A number of technical papers using selective harmonic elimination (SHE) or minimization have been reported for fundamental frequency operation using the most common multilevel (ML) inverter topologies [5–7]. Selective harmonic elimination (SHE) is a low switching frequency PWM method developed for traditional converters in which a few (generally from three to seven) switching angles per quarter fundamental cycle are predefined and pre-calculated via Fourier analysis to ensure the elimination of undesired low-order harmonics [8]. Basically in SHE, the Fourier coefficients or harmonic components of the predefined switched waveform with the unknown switching angles are made equal to zero for those undesired harmonics, while the fundamental component is made equal to the desired reference amplitude. This set of equations is solved offline using numerical methods, obtaining a solution for the angles.

Usually this method, a set of nonlinear equations must be solved, which may not always have a solution acceptable [9]. In this case, the equations are solved in a way that the amplitude of the harmonics to be zero, is minimal. In this case, this procedure is described as SHE (Selective Harmonic Mitigation) [10]. In cases that require rapid dynamic for converter, this method cannot be used.

For Cascaded H-Bridge Multilevel Inverter (CHB-MLI), this method is expressed as a Staircase Modulation technique that for this inverter is easy to implement [11, 12]. In this case, each cell must be specified conduction time.

The power converter output voltage improves its quality as the number of levels increases reducing the total harmonic distortion (THD) of the output waveforms. These properties make multilevel converters very attractive to the industry and, nowadays, researchers all over the world are spending great efforts trying to improve multilevel converter performances such as the control simplification [13] and the performance of different optimization algorithms in order to enhance the THD of the output signals [14], the balancing of the DC capacitor voltage [15], and the ripple of the currents [16]. For instance, nowadays researchers are focused on the harmonic elimination using pre-calculated switching functions [17], harmonic mitigation to fulfill specific grid codes [18], the development of new multilevel converter topologies (hybrid or new ones) [19], and new control strategies [20]. The most common multilevel converter topologies are the neutral-point clamped converter (NPC) [21], flying capacitor converter (FC) [22], and cascaded H-bridge converter (CHB).

A general classification of high power converters is shown in fig. 1. The most common topologies are cascaded H-Bridge topology that has been used in industrial applications [23]. Its construction makes it a perfect choice for selective control of harmonics is proposed.

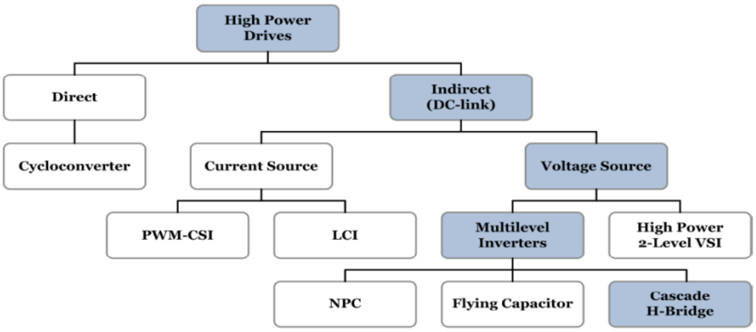

Fig. 1 Power converters classification

Multilevel configuration of CHB (Cascaded H-Bridge), including independent sources DC for each level which may each have been different. Figure 2 shows a seven-level CHB that its modulation is done at the base frequency. As we know, SHE is able to be provided better harmonic profile at a lower switching frequency than other methods. Modulation bandwidth is much simple to implement. If SHE is selected as a method for finding and storage the firing angles need to be provided.

For different voltage levels on the voltage fluctuations that are fixed input voltage, SHE can be used to determine the firing angles of switches at the base frequency based on pre-stored values in a look-up table according to the reference method [24].

Thus, stepped waveform of m-level can be realized by using a separate DC source. If DC voltage sources have a fixed value, we can find a relationship between voltage and modulation index, which is simple enough to be stored in a look-up table. If one of the voltage sources is changed, a new relationship must be found and stored in memory. This relationship will be very complicated if increase the number of DC sources which voltage can be changed.

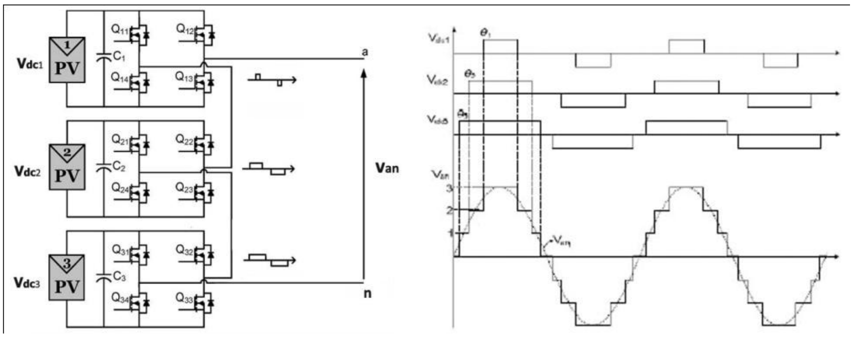

Fig. 2 A seven-level CHB (Cascaded H-Bridge)

Those DC sources might be capacitors, fuel cells, or solar panels and will consequently bring a voltage imbalance depending on the system dynamics. Therefore, fixed voltage DC sources for each level is not practical for some applications. In reference [25], a general genetic algorithm (GA) is applied to find the optimal firing angles if DC voltage sources are equal. A 7-level cascaded inverter with three identical DC voltages that its components voltage can keep in 120 volts and eliminate the 7^{th} and 5^{th} order harmonics, in this reference is investigated. An analytical solution to this problem by using the theory of symmetric polynomials for unipolar and bipolar designs is presented in references [26, 27]. However, if there are several DC sources, the degrees of the polynomials in these equations are large and number of the firing angles is increased. As a result, one reaches the limitations of the capability of contemporary computer algebra software tools (e.g., MATHEMATICA or MAPLE) to solve the system of polynomial equations using elimination theory (by computing the resultant polynomial of the system). This formulation resulted in a drastic reduction in the degrees of the polynomials that characterize the solution. Consequently, the computation of solutions of this final set of polynomial equations could be carried out using elimination theory (resultants) as the required symbolic computations were well within the capabilities of contemporary computer algebra software tools. This methodology resulted in the complete characterization of the solutions to the harmonic elimination problem [27].
In reference [28], analysis of responses is achieved for a five-level cascaded bridge inverter and a seven-level inverter, in situations where any level has the firing angle. Five-levels CHB considered in this reference include two full bridges and five firing angles for each cell and there are totally ten firing angles. Thus, by having ten equations, there are possible of keeping the fundamental harmonic of voltage at a desired level and eliminating the ten harmonic components. Thus, Five-levels CHB able to will be eliminate harmonics far lower than or equal to 31. This number for seven-levels CHB presented in this reference is 43. Since the listed articles are considered three phase applications, three order (3^{th}) harmonics cannot be seen in line-to-line voltage. The method presented in references [27] and [28] aren't able to find analytical answer for all range modulation index. Only when there is an analytical solution has been found in the references. In addition to the voltage inequality, they can also change over time. All previous references, DC voltage sources are considered with equal and unequal values, but voltage values are constant over time. If voltage levels are changed, the new responses is necessary to find for the firing angles of converters until higher order harmonics still remain eliminated. The other hand, increased the number of levels will add the complexity of the problem. The number and order equations are increased that must be solved. In this case, the voltage sources are varied, but they have the same value. Therefore, all voltage sources have equal (same) value at any time and although are changing, them relative to each other (equal) are maintained.
As previously shown, an alternative approach for determining optimal switching angles in real-time for variable DC sources is the calculation of switching angles answers as offline and storing them in a look-up table. Accurate representation of solutions to various DC sources, it needs to a large table. Such table requires a significant amount of memory and high processing speeds that there are beyond the capacity of the processor. Even assuming the existence such the ability to process, some points of the operation, there is no solution (switching angles) in the table and the resulting the interpolation will be required. For the case of three DC sources is presented in reference [29], possible to

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avoid difficulties related to finding solution using parallelism and generalize in artificial neural networks (ANN), quickly obtained the switching angle for any number of levels and the total switching angles.

The proposed method in this paper is carried out in two stages. Initially, particle swarm optimization (PSO) algorithm will be implemented to find switching angles (offline) for a predetermined set of voltage input to an 11-levels cascaded inverter and thereafter, with the previous data sets, artificial neural network (ANN) will be trained to determine angles for each voltage levels in real-time.

Important features of this method are to provide a space range which there is no analytical solution, particle swarm optimization (PSO) algorithm finds nearest solution and it provides a set of information to train artificial neural network (ANN) is desired. Moreover, such complex technique can be found one solution that may not found with analytical method according to acceptable the existing standards. For examples, particle swarm optimization (PSO) algorithm may be found a solution to generate the output voltage of 110 volts with an accuracy of ±5% while other analytical methods do not have any solution.

The proposed method can be summarized as follows:

-Extracting the system harmonic formulation based on the firing angles and system conditions.

-Test model of multilevel inverter.

-Creating different scenarios of system conditions (accidental or random manner).

-Classification of scenarios created to reduce the computational load (k-means method).

For each of system conditions, the firing angles are obtained by solving an optimization problem. Here is used swarm optimization (PSO) algorithm.

II.FORMULATING THE PROBLEM

2.1. Selective Harmonics Elimination (SHE) for Equal and Unequal DC Sources

The output voltage is composed of a fundamental component (n=1) and harmonics components (n>1). Each component of the output voltage can be expressed as follows:

$$V_{n-th}(\omega t) = \left[\frac{4}{n\pi}(V_{dc1}\cos(n\theta_1) + V_{dc2}\cos(n\theta_2) + V_{dc3}\cos(n\theta_3) + V_{dc4}\cos(n\theta_4) + V_{dc5}\cos(n\theta_5))\right]\sin(n\omega t) \quad (1)$$

Where n is n^{th} order harmonics, $V_{n\text{-}th}$ is n^{th} harmonic component, V_{dc1} is the voltage level of the first cell, θ_1 is the switching angle of the first cell, θ_2 is the switching angle for V_{dc2} and so continues.

Five free variables in the equation can be used to form a system of five equations, so that the zeros can be selected as desired to maintain value of the fundamental component in its nominal value and four harmonics bring zero.

2.2. The Objective Function

The objective function is considered in this program as follows:

$$objective = obj1 + obj2 + obj3 \quad (2)$$

Which it introduces multi-objective optimization problem.

The first objective is minimizing the difference between the effective value of the first harmonic of voltage and its desired level:

$$obj1 = \frac{\left| V_{Fund}^{rms} - V_{Fund,des}^{rms} \right|}{V_{Fund,des}^{rms}} \quad (3)$$

Where it V_{Fund}^{rms} is the effective value of the first harmonic of voltage and $V_{Fund,des}^{rms}$ is the desired effective value of the first harmonic of voltage.

The second objective is minimizing the amount of total harmonic distortion (THD) and is defined as follows:

$$obj2 = \begin{cases} \dfrac{\sqrt{\sum_{n=1}^{N_H}(V_n^{rms})^2}}{V_{Fund}^{rms}} - THD_{des} & \text{if } \dfrac{\sqrt{\sum_{n=1}^{N_H}(V_n^{rms})^2}}{V_{Fund}^{rms}} > THD_{des} \\ 0 & \text{Otherwise} \end{cases} \quad (4)$$

Where N_H is the total harmonics considered. Whatever this number is higher than the accuracy of the program increases. In written program, this value has been considered equal 29.

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The third objective is minimizing the amount of selective harmonics to SHE method and is defined as follows:

$$obj3 = \sum_{s\in\Psi_s} \left| V_s^{rms} - V_{s,des}^{rms} \right| + \left(V_s^{rms} - V_{s,des}^{rms} \right) \quad (5)$$

Where Ψ_s is set of selected harmonics in order to eliminate or reduce to the desired value. The purpose of writing this part of objective function in this form is only if the s[th] harmonic has greater effective value than desired value ($V_{s,des}^{rms}$), it is introduced in the objective function.

III.SIMULATION RESULTS

3.1. Using Particle Swarm Optimization (PSO) Algorithm

Particle Swarm Optimization (PSO) Algorithm parameters used in this study is listed in Table 1. Select these parameters based on the subjects cited is done in the previous chapter.

Table 1Characteristics of Solar Cells

Model	HIP-195BA15
Nominal Power (W)	195
The Maximum Voltage at Nominal Power (v)	35.3
The Maximum Open Circuit Voltage (V)	39.8
The Maximum Tolerable Current (A)	5.48
Short Circuit Current (A)	5.95
Temperature Coefficient of Voltage (volt per degree Celsius)	-0.18
Temperature Coefficient of Current (mA per degree Celsius)	0.83

The firing angles are listed in Table 2 and Table 3 for the remaining samples presented. These angles are in degrees and are optimized to achieve the above objectives. To have a clearer picture than optimization done in here, the first sample is studied more accurate.

Table 2 Particle swarm optimization (PSO) algorithm parameters

PSO Parameters					
Swarm Size	C1	C2	W1	W2	$Iter_{Max}$
200	1.75	1.75	0.90	0.40	500

Table 3 The related firing angles of inverters in the remaining samples after classified

Sample	s=1	2	3	4	5	6	7	8	9	10	11	12	13
Firs Cell	28.0	25.80	37.90	25.20	25.10	25.60	54.10	37.30	13.60	4.40	29.80	53.40	4.60
Second Cell	16.90	16.10	15.60	15.80	15.70	15.50	16.90	0.0	4.50	53.0	39.90	16.10	53.20
Third Cell	5.60	5.30	5.20	5.30	5.50	5.20	43.90	26.90	23.30	41.30	51.60	40.80	39.40
Fourth Cell	61.80	52.30	26.50	34.90	34.70	36.30	6.10	15.60	34.20	14.0	19.50	5.60	14.20
Fifth Cell	40.20	36.90	51.60	51.10	51.30	52.20	28.0	50.40	51.50	25.60	6.70	27.50	25.50
Rate of the objective function	0.05	0.06	0.09	0.14	0.11	0.10	0.16	0.16	0.15	0.21	0.20	0.18	0.21
Sample	14	15	16	17	18	19	20	21	22	23	24	25	-
Firs Cell	43.70	53.70	18.02	26.60	27.20	41.80	39.30	31.50	32.10	16.0	16.10	0.0	-
Second Cell	54.40	28.30	41.08	16.70	16.70	52.90	28.60	41.50	41.90	52.0	51.70	38.90	-
Third Cell	32.60	18.10	52.60	36.90	38.00	31.10	17.90	52.50	52.90	39.60	39.10	28.50	-
Fourth Cell	20.40	6.80	29.22	50.40	51.00	20.30	51.30	20.90	21.60	5.50	5.50	50.70	-
Fifth Cell	8.70	40.80	6.80	5.80	5.70	8.60	6.30	8.50	9.10	27.20	26.90	16.60	-
Rate of the objective function	0.24	0.23	0.21	0.28	0.25	0.25	0.32	0.31	0.29	0.40	0.33	0.33	-

Figure 3 shows the objective function value of the optimization problem during the repetitions of particle swarm optimization (PSO) algorithm for the first sample. As can be seen, the algorithm is well in the early repetitions is close

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to the optimal solution. As a result, the objective function has reached the same value reported in Table 3. In continuation, each of components of the objective function has been studied to be specified the efficiency of the optimization algorithm and the matching its results be more specified with the objectives listed.

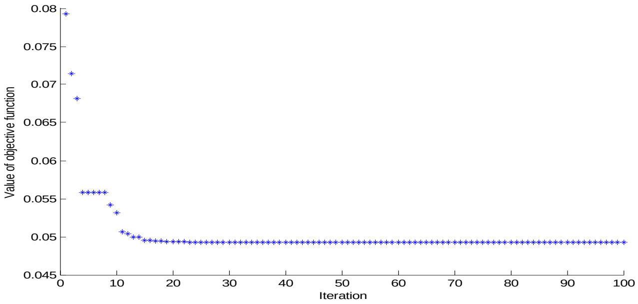

Fig. 3 The objective function value of the optimization problem during the repetitions of PSO algorithm

In figure 4, the output voltage waveform is shown for the first sample which is obtained with the aid of the calculated firing angles using particle swarm optimization (PSO) algorithm. In this figure, the desired first component also is drawn.

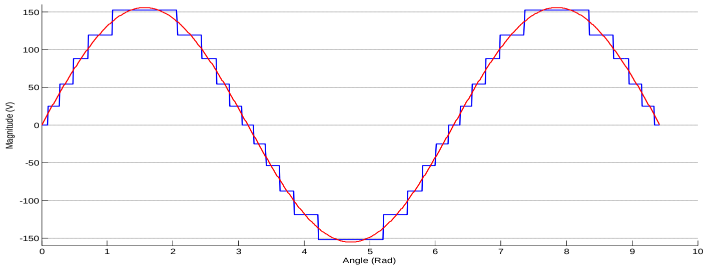

Fig. 4 The output voltage waveform for the first sample along with waveform of the desired first component

Fig. 5 shows the effective values of the various components in the output voltage waveform. Because these values can be interpreted, they are expressed as a percentage of the effective value of the first component in fig. 6. According to the results shown, the total harmonic distortion (THD) value is 0.05.

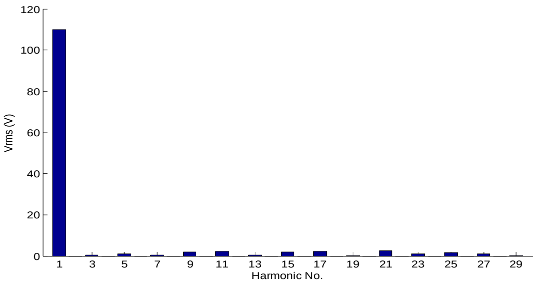

Fig. 5 The effective values of the various components in the output voltage waveform

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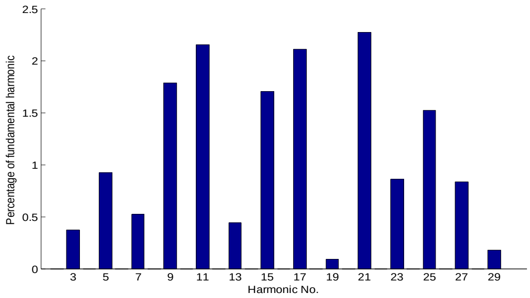

Fig. 6 Percentage of the effective values of the various components in the output voltage waveform

The analysis results of particle swarm optimization (PSO) algorithm show for the first sample that:
1-The first component of the effective voltage level is set on 110 volts.
2-The third component of the effective voltage level is 0.4 percent of the first component of the voltage which is less than 3% of the first component of the voltage.
3-The fifth component of the effective voltage level is 0.95 percent of the first component of the voltage which is less than 2% of the first component of the voltage.
4-The seventh component of the effective voltage level is 0.55 percent of the first component of the voltage which is less than 1% of the first component of the voltage.
5-The total harmonic distortion (THD) value is 0.05 which is less than 0.15.
So with the aid of particle swarm optimization (PSO) algorithm have been accomplished all optimization purposes. Also, the algorithm has been greatly reduced the total harmonic distortion (THD) level successfully.

3.2. ANN training

Here's a feedforward multilayer Perceptron neural network has been trained with one hidden layer of 20 neurons and second hidden layer of 10 neurons that are interconnected through weighting functions. The input and output vectors respectively included in any of the obtained scenarios and switching angles. For this training, it is used newcf function in MATLAB software.
The purpose training is to achieve the mean-square error (MSE) less than 10^{-14}. In this program, the mean-square error (MSE) is 7.55 x 10^{-15}. Fig.7. shows the trend achieving program to this error rate during each epoch. Due to the high number of hidden layout algorithm, with a small number of repetitions has been reached the desired response.

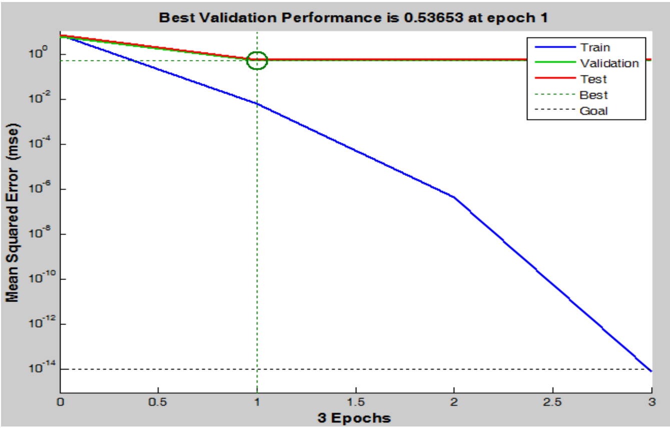

Fig. 7 The mean-square error (MSE) during ANN training

Now is the time to be testing the trained neural network. With the aid of the samples generation algorithm, five new conditions of system have been produced which is shown in Table 4. Trained neural network in the previous step has been handled to obtain optimal values of the firing angles for these conditions. Output results obtained in this way are listed in Table 5. Also for these samples, optimal values of the firing angles have been obtained using particle swarm optimization (PSO) algorithm. The results of this optimization are given in Table 6. By comparing the results shown in Tables 5 and 6 to be determined that firing angles can be calculated using the proposed algorithm in an appropriate manner. The mean error rate is 0.02 radian (equivalent to 1.14^o) caused by approximation using trained neural network for the firing angles in inverters. This error rate is only about 3.5 percent of the average value of firing angles for 5 inverters which is very small.

Table 4 Voltage generated of each cell in samples generation to test the ANN

Sample	s=1	2	3	4	5
Firs Cell	16	17	17	18	23
Second Cell	18	20	20	25	26
Third Cell	20	23	26	30	28
Fourth Cell	23	26	30	32	30
Fifth Cell	28	31	33	34	33

Table 5 The firing angles obtained (in radian) with neural network for samples generation to test the ANN

Sample	s=1	2	3	4	5
Firs Cell	0.98	1.02	0.98	0.78	0.72
Second Cell	0.49	0.50	0.50	0.95	1.05
Third Cell	0.11	0.08	0.07	0.10	0.48
Fourth Cell	0.25	0.26	0.28	0.30	0.11
Fifth Cell	0.67	0.68	0.72	0.54	0.32

Table 6 The firing angles obtained (in radian) with PSO algorithm for samples generation to test the ANN

Sample	s=1	2	3	4	5
Firs Cell	0.98	1.02	0.98	0.79	0.71
Second Cell	0.45	0.47	0.55	0.97	1.03
Third Cell	0.09	0.09	0.07	0.08	0.51
Fourth Cell	0.27	0.28	0.28	0.33	0.10
Fifth Cell	0.67	0.70	0.65	0.51	0.30

IV.CONCLUSION

According to the error rate obtained in calculating firing angles of each inverter in the structure of cascaded H-Bridge multilevel converter using ANN for samples trained compared to responses generated by particle swarm optimization (PSO) algorithm can be concluded that the purposed structure is well handled optimal control of multilevel converters.

According to the few time to get firing angles by ANN for samples trained, it can be concluded that the proposed structure has been introduced in this paper is very appropriate for real-time control of cascaded H-Bridge multilevel converters.

The results obtained of studies conducted show that particle swarm optimization (PSO) algorithm to get a good handle on the proper firing angles. However, the classical optimization methods are unable to obtain the optimal firing angles because it has extraordinary nature of nonlinear objective function in the problem-solving.

By increasing the number of solar cell units can be controlled more domain components and simultaneously the total harmonic distortion (THD) level can be a much lesser extent reduced. The reason for this problem is the increased degrees of freedom in the optimization problem. By increasing the degrees of freedom also is allowed to reach other objectives such as reducing switching losses and increased efficiency of multilevel converters.

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