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Research Article

The analysis of three level inverter circuit with regard to current harmonic distortion by using ANFIS

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Abstract: The inverters are frequently used in power electronics applications in the industrial area. Research on multi-level inverter circuit designs in power systems interfaces has intensified in recent years. The design type and quality of the inverter circuit topology is very important for the output voltage to be closer to the sinusoidal waveform. In addition, artificial intelligence techniques for the control algorithms of the power switches of the inverter circuit provide useful information in terms of monitoring the estimated the voltage conditions of the inverter output parameters. In this work, an Adaptive-Network Based Fuzzy Inference Systems (ANFIS) model is proposed to estimate the Total Harmonic Distortion (THD) value of the output current of a three-phase three-level inverter circuit. By changing the switching frequency in the control circuit of the inverter, a data set for the THD values of the inverter current is obtained by Fast Fourier Transform (FFT) analysis in MATLAB. This data set is used in a training and testing phase of ANFIS artificial intelligence algorithm, and the THD value of the current is estimated. At the end of the estimation, the mean absolute error (MAE) values for training and testing are obtained as 0.1894% and 0.4009%, respectively, thereby, an ANFIS estimation example for parametric data set analysis in a power electronics circuit run with Matlab-Simulink software, and a parametric simulation study is presented to the literature for power electronics circuit designers.

Keywords: *ANFIS, Inverter circuit, Parameter estimating, THD*

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1. INTRODUCTION

The inverter circuits are widely used for many industrial applications such as electric motor drivers, uninterrupted power supplies, electric vehicle power systems, renewable energy sources, in general in power electronics application areas. Designs can be made in different topologies such as single phase and multiphase designs. For this reason, studies on inverters are increasing gradually and accordingly, inverter technology is developing rapidly. The main goal in all studies is to keep the number of switches at a minimum and to obtain a better quality of output voltage and load current [1]. Inverters have applications in the literature as two-level with square wave inverter structure in classical designs or as multi-level circuit topologies with increasing the number of switching elements. In addition, designs can be made with diode or capacitor clamping circuits in neutral clamping inverters. On the other hand, with cascaded inverter circuits, circuit structures that have been frequently studied in recent years are also used, especially in renewable energy systems such as piecewise Fuel-Cell and solar energy. In this context, in a study on multi-level inverter circuits, a 5-level cascade connected inverter design for asynchronous motor drives has been implemented. From the experimental results and harmonic analysis obtained in such a setup, it has been determined that the system operates stable, is not affected by electrical noise, protection circuits work, and the inverter gives the desired response [2].

In a study on the optimization of switching signals in multi-level inverters, by using the selective harmonics elimination pulse width modulation technique (SHEPWM), certain harmonics in the output waveforms of inverters at different levels were eliminated. Thus, the nonlinear equation sets that are obtained by SHEPWM technique to find the switching angles to eliminate the dominant harmonics have been optimized by particle swarm optimization (PSO) and genetic algorithms (GA) methods. The total harmonic distortion amount of the output waveform has been reduced. According to the data obtained, it has been observed that it is better than the optimization results made with the genetic algorithm [3]. On the other hand, carrier phase-shifted PWM has been proposed in the past literature to reduce the Common Mode Voltage (CMV) for three-level T-type NPC inverters. Consequently, phase regulation can reduce the peak value of CMV by 50% compared to pulse width modulation (PWM) method. With this method, lower root mean square value can be obtained. It has been observed that the proposed carrier phase shifted PWM method is excellent output waveform performance [4].

In addition, selective harmonic reduction of inverter circuits using bio-inspired intelligent algorithms (BIA) for renewable energy sources was examined and the working principles of nine well-known BIAs were explained in detail. A few factors such as inverter control parameters of the best five BIAs were evaluated and it was found that PSO performance was superior to control algorithms in terms of performance parameters. It can be said that all BIAs are easy to realize and apply and show a good potential to solve the specific reason in inverter circuits, especially in voltage source inverters [5]. In a study in which multi-level T-type inverter circuits performance analysis based on modified hysteresis current controller was conducted, and this control system was operated and performed for a multi-level T-type inverter circuits. Thus, the feedback control system was tested according to the switching control signals for the operating frequency values (at kHz levels) according to different hysteresis bands. Compared with the traditional SPWM technique applied of the multi-level T type inverters, it can be said that the Total Harmonic Distortion (THD) of this type of controller usage is lower than the SPWM controlled inverters [6].

In another study where a three-level T-type inverter high efficiency drive system is examined, a variable speed drive was presented. The efficiency of the system, which consists of a proposed 3-level T-type converter topology and a standard induction machine, which is very efficient for low switching frequencies, is optimized in terms of fundamental and harmonic induction machine losses as well as converter losses [7]. Blaabjerg and Lee examined the quality performance of the three-level T-type inverter with the new control strategy and operated of the inverter circuit under the fault conditions.

Thus, it was performed a fault-tolerant control system with the sinusoidal waveforms and explained the fault by dividing it into two states. Generally, open circuit faults occur at half bridge switches or neutral point switches. The applicability and validity of the error-resistant control methods proposed from simulation and experimental results have been verified [8]. It covers gate control requirements, switching capability, inverter performance, cooling system volume, output filter, and dead time of the switching signals with compared to single-phase inverters using Si IGBTs, SiC (or GaN) MOSFETs. Considering the switching ability, GaN has the much more performance among these developments at 350 V, 16 A and provides much more efficiency at the higher operational frequency for the power electronics circuits [9].

Wang et al. [10] proposed a multi-scale fault diagnosis technique based on signal symmetry reconstruction pretreatment to perform diagnostics for any power switch of the inverter circuits under the load condition. This method consists of multi-scale features and Artificial Neural Network (ANN). Thus, the performance of this diagnostic method was confirmed with simulation and experimental studies. When the advantages of SiC switches for the grid interactive T-type inverters were investigated. Thus, SiC type switching devices significantly reduces semiconductor power losses and allows the much more power capacity level at the more switching frequency values for the same switching power losses. It can be said that the use of SiC type power switches for inverter circuits is a potentially useful alternative [11].

Nonlinear condition effects of three-level T-type inverters can be analyzed and the main reasons for nonlinearity are switching pulse conditions such as dead time estimation and voltage value on the switches. Thus, in the past literature, improvement methods with PWM of T-type inverter were suggested from the research results to alleviate the nonlinearity of the inverter [12]. Samadaei et al. [13] introduced a new module for asymmetric multi-level inverters with few components, and proposed a new combination module of two cascaded T-type inverters and a few other switch elements. THD value of the output voltage or current and the fewer semiconductor devices were the best advantages for this proposed module. Thus, this method was used as the new switching control system to improve the best quality output voltage with the lower THD value, and, it was shown to perform well in both simulation and experimental results. In a study for solar photovoltaic (PV) inverters, an intelligent-based fault tolerance system was examined. The control system based on ANN was used in solar PV panels, battery banks, power switches of the inverter circuits. Thus, the significant advantage of this inverter topology can be powered from input to output even under the fault conditions, and it was proven that the system can provide power despite faulty environments [14]. A comprehensive review of different T-type multi-level inverter topologies and the circuits performance were conducted by Salem and Abido. Thus, 3 Level, dual three-Level and five-Level T-type inverter topologies were presented and it was observed that the performance of T-type inverters was superior to conventional two-level and neutral point clamping (NPC) converters [15]. In a study, a multidimensional comparison of two common topologies for a 120 kW permanent magnet synchronous motor drive circuit to be used in electric vehicles was carried out. Especially, two-level topology and three-level neutral point clamp type voltage supply inverter output voltage and current quality, thermal performance, efficiency and switching frequency limitation, and, compared in terms of semiconductor thermal reliability were explored in the application [16].

In Ref. [17], a selective harmonic elimination technique based on genetic algorithm is proposed for multilevel inverters. Traditional multi-level inverter structures are analyzed. It has been seen that the cascade H-bridge topology requires less device components. It has been observed that the proposed genetic algorithm-based selective harmonic elimination technique eliminates the desired harmonics. In Ref. [18], harmonic equations of cascade connected H-bridge inverter topology are solved by particle swarm optimization and genetic algorithm. The total harmonic distortion of the output voltage has been eliminated as desired. Particle swarm optimization and genetic algorithm equation solutions are compared. It has been seen that the genetic algorithm gives better THD results.

In the scientific study for a voltage source grid-connected system, an LCL filter was designed at the inverter output, the total harmonic distortion of the current at the output was 2% in the experimental environment and 0.56% in the simulation, and it was reduced below the desired standard limit value [19].

Since the nonlinear equations contain trigonometric terms exhibiting multiple and complex solutions, a fully proven solution is not available in the past literature. In this context, it is a useful method to obtain a data set of nonlinear equations, which are presented with certain mathematical expressions but do not have a completely correct solution set, by using simulation software, and to develop solutions based on estimations from this data set. Thus, the performances of power electronics circuits can be tested quickly and accurately based on the certain input variables [20-21]. In this study, an ANFIS model is used to estimate the THD value of the output current of a three-phase three-level inverter circuit. The simulation studies were performed to obtain the data with the inverter circuit MATLAB-Simulink software. Using the data set obtained here, the parameters were calculated with ANFIS with high accuracy. Thus, a lot of useful information is presented in the development of control algorithms of the inverter circuit.

In Section 2, a mathematical expression of the multilevel inverter circuit and the THD formulation are given. In the next section, a data set related to PWM switching variables and load variables have been obtained for current harmonic values at the inverter output with parametric simulation study. The estimation process of THD values of the parametric data set using ANFIS is also explained. The most important contribution of this study to the literature is an exemplary parametric simulation study run with Matlab-Simulink at the point of estimating power electronics circuit parameters in data set analysis based on parametric dataset.

2. THD CALCULATION OF THE MULTI-INVERTER OUTPUT LINE VOLTAGE

This section explains the traditional method of calculating the THD of the line voltage and then gives mathematical expressions based on integrating the waveform at the inverter output. The voltage and current THD minimization requirements at the inverter output are often a serious concern for power electronics designers under a large-scale, non-linear and a mixed integer combinatorial uncertainty. The multilevel-cascaded inverter topology is shown in Fig. 1 [20-21].

Since the output voltage waveform is not sinusoidal according to a generalized half-wave symmetry output waveform of a multilevel inverter circuit shown in Fig. 2, it can be expressed with a Fourier series expansion as given in Eq. 1 [20-21].

$$V_{(\omega t)} = \sum_{n=1}^{\infty} \left(A_n \sin(n\omega t) + B_n \cos(n\omega t) \right) \quad (1)$$

Because the inverter output waveform is symmetrical, even harmonics are not taken into account, and only odd harmonics sinusoidal terms are considered when expanding the formula. Thus, the inverter output voltage on the load can be reduced as in Eq. 2:

$$V_{(\omega t)} = \sum_{n=1}^{\infty} \left(A_n \sin(n\omega t) \right) \quad (2)$$

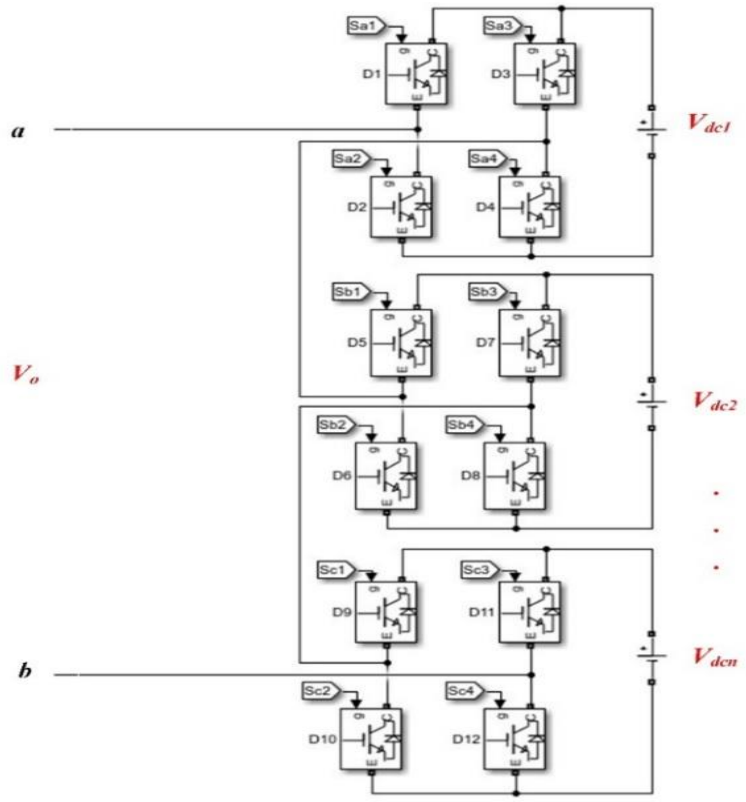

Figure 1. Multilevel-cascaded inverter circuit [21].

Therefore, the amplitude of the nth harmonic A_n is represented by Eq. 3:

$$A_n = \left(\frac{4V_{dc}}{n\pi}\right)\sum_{k=1}^{r}\cos\left(n\alpha_k\right) \tag{3}$$

where r is the number of switching angles in the symmetric half-period.

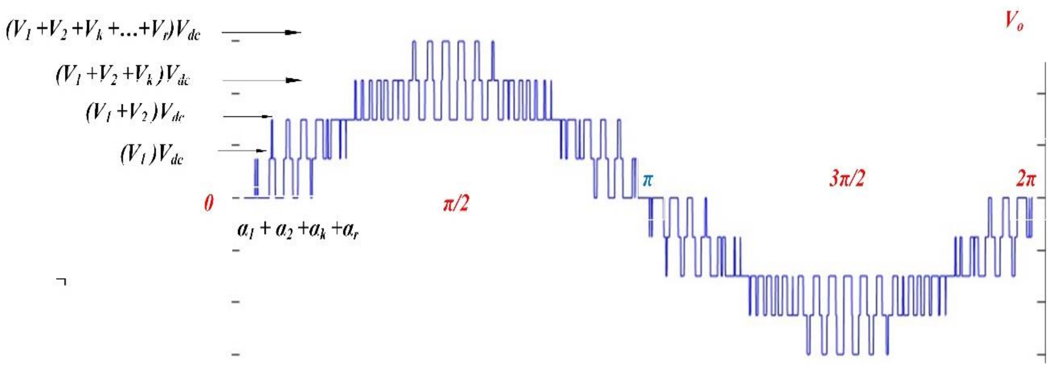

Figure 2. Half-period voltage waveform of the multi-level inverter [21].

The inverters are mainly used in three-phase medium/high voltages; all triple and triple harmonics are eliminated at three-phase symmetrical voltages with 120 degrees phase difference. Therefore, only low-order non-triple odd harmonics in the line-to-neutral voltage are considered eliminated. Consequently, optimal switching angles for PWM can be calculated by solving Eqs. 4-5 [21].

$$A_n = \left(\frac{4V_{dc}}{n\pi}\right)\sum_{k=1}^{r}V_k\ \cos\left(n\alpha_k\right) \tag{4}$$

where V_k and α_k, kth is the voltage amplitude and kth is the step of the PWM switching angle.

$$V_1 \cos(\alpha_1) + V_2 \cos(\alpha_2) + \ldots + V_r \cos(\alpha_r) = M\,r\left(\frac{\pi}{4V_{dc}}\right) \tag{5}$$

where M represents the modulation index in PWM switching. In this context, nonlinear equations contain trigonometric terms that exhibit multiple solutions. However, a solution set whose equations have been fully verified at certain points is also not available in the past literature [21].

The THD value of the symmetrical half-period waveform is calculated using the expression given by Eq. 6, considering the output stage voltage of a multilevel inverter [20].

$$THD = \frac{\sqrt{\sum_{n=5,7,11,....}^{\infty} V_n^2}}{V_1} \tag{6}$$

3. SIMULATION STUDIES WITH POWER ELECTRONICS CIRCUIT

Three-phase three-level inverter circuit modeling was performed in the power electronics program. The circuit modeling was simulated by changing the modulation index (M_a), switching frequency (f_s), R and L values of the RL series impedance load at the inverter output with the FFT analysis method in the Matlab-Simulink software. In the simulation study, the simulation circuit is used to determine the performance of the inverter circuit more realistically in Fig. 3,

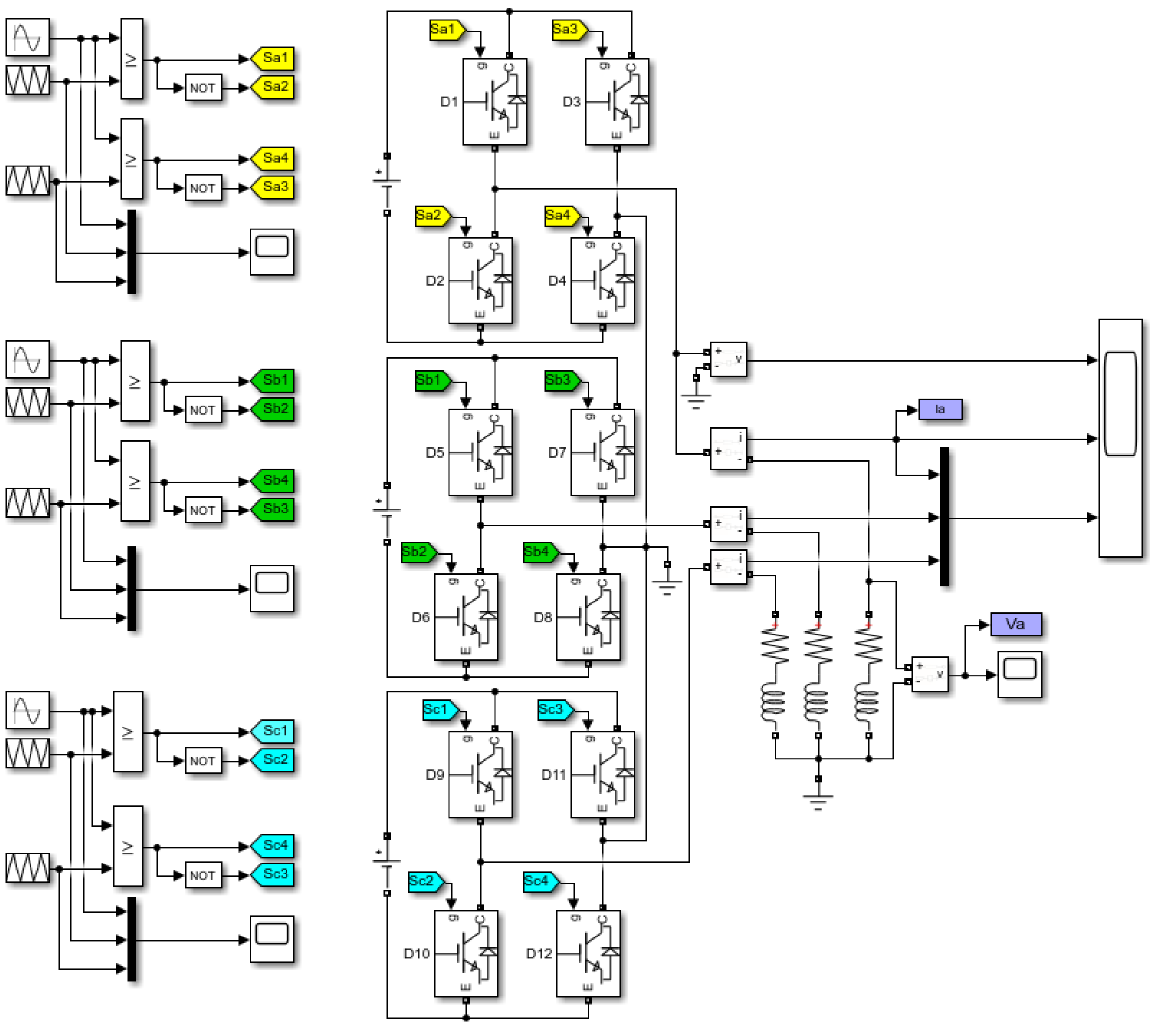

Figure 3. MATLAB/Simulink simulation model

3.1. Data Preparation

The inverter circuit is simulated according to the parameters given in Table 1 and analyzed with ANFIS using the obtained data. According to the results obtained from this simulation, a total of 340 data were obtained for the output current THD value depending on the switching frequency. These data are used in the classification of the ANFIS model, 272 of which were used in training and 68 of them in the classification of testing.

Table 1. Technical properties of the parametric simulation.

Parameters	Value
V_i	100-250V
f	50Hz
M_a	0.5-0.9
f_s	1-5kHz
L	5-15mH
R	5-30 Ω

In the simulation studies, the modulation index (M_a) is changed in the range of 0.5 - 0.9, and the switching frequency was changed in the range of 1-5 kHz. The *R* and *L* values of the *RL* series impedance load at the inverter output are also simulated at the values given in the table. Thus, a data set is created for the inverter output current THD values with different variables.

3.2. Adaptive Neural Network Based Fuzzy Inference System (ANFIS)

Adaptive Neuro-Fuzzy Inference System aims to reach a solution by using artificial intelligence in the prediction of nonlinear systems. It is a combination of the learning feature of artificial neural networks, which are especially used in prediction models, and the inference feature of fuzzy logic based on expertise in one system. While it needs data like in artificial neural networks, it also performs clustering in fuzzy logic. In cases where the input and output values are known, ANFIS determines all the rules itself, eliminating the need for experts. The multiplicity and homogeneity of the number of data is very important for the model to work. The cluster formats and numbers of the data may vary according to the type and complexity of the problem [22]. ANFIS architecture is given in Fig. 4.

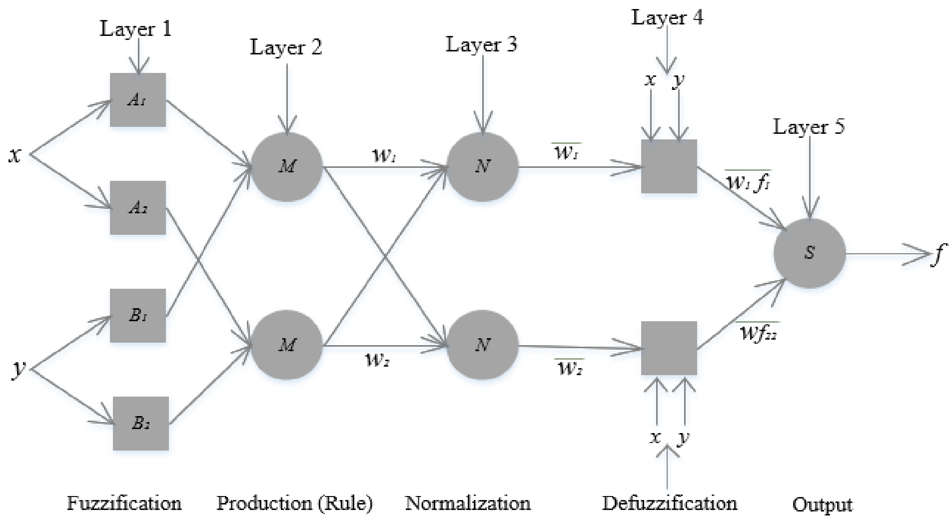

Figure 4. ANFIS architecture

All input parameter are introduced to the neural system. The number of clusters is determined for these introduced parameters. In the next step, weight values are assigned to all input parameters and multiplication operations are performed. The resulting outputs are sent to the sum function and errors are detected. A hybrid algorithm consisting of more than one method is used to minimize errors. These steps are repeated until the errors are optimized [22-23].

In general, the data set obtained from various simulation or experimental studies is randomly divided into two groups as 80% and 20%. In this study, ANFIS models are used to find the model that can best predict the THD value of the output current of a three-phase three-level inverter circuit obtained from parametric simulation studies. In this context, 340 data are obtained by using MATLAB software to create a data set, then 80% of this data set was used for training and the remaining 20% was used to test the performance of the trained model. In addition, Mean Absolute Error (MAE) is chosen as the performance determination criterion. The best membership function has been determined in the ANFIS interface. The actual and estimated values of the training data obtained because of the studies are given in Fig. 5, and the actual and estimated values of the test data are shown in Fig. 6.

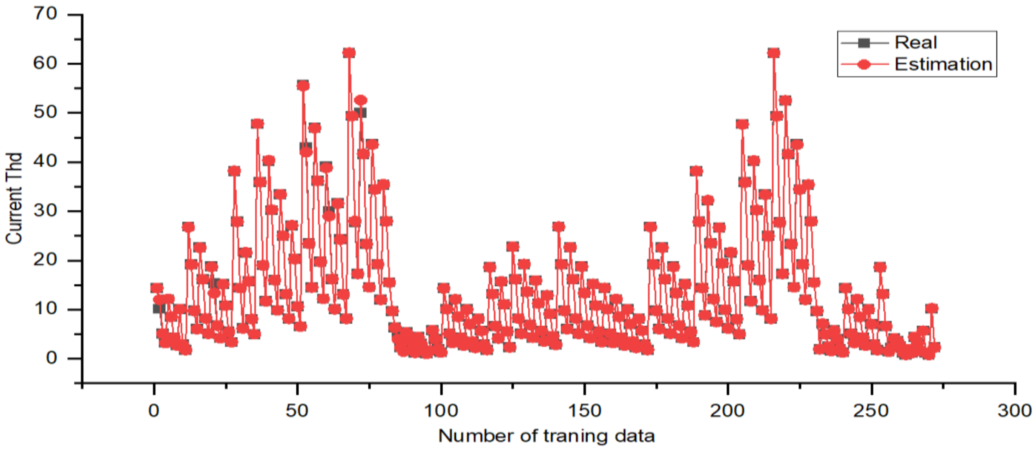

Figure 5. Real and estimated values of training data

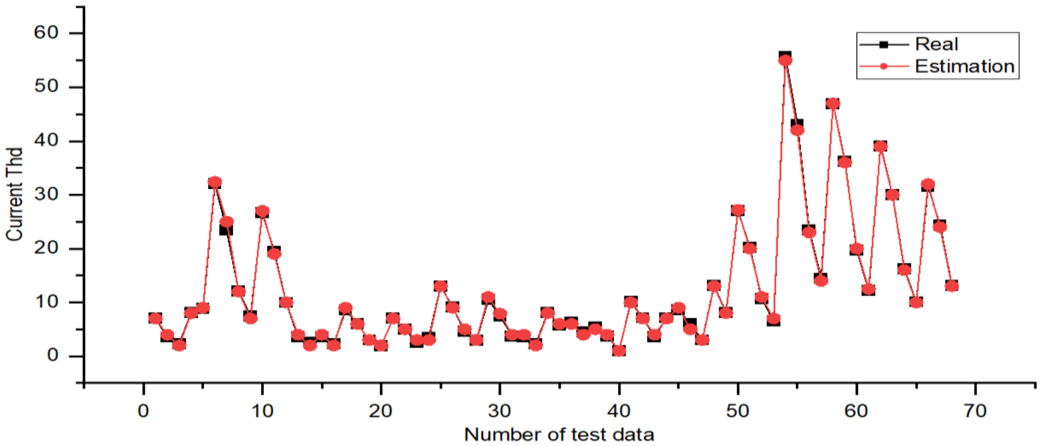

Figure 6. Real and estimated values of test data

3.3. Simulation Samples for Validation

In order to verify the proposed approach in this study, as can be seen in Fig. 7, the current waveform and THD values of the inductive load connected at the output of the three-level inverter are given in the Matlab-Simulink software. Thus, a sample of the variables determined in the estimation process of the THD value based on the data set was selected and the simulation was run.

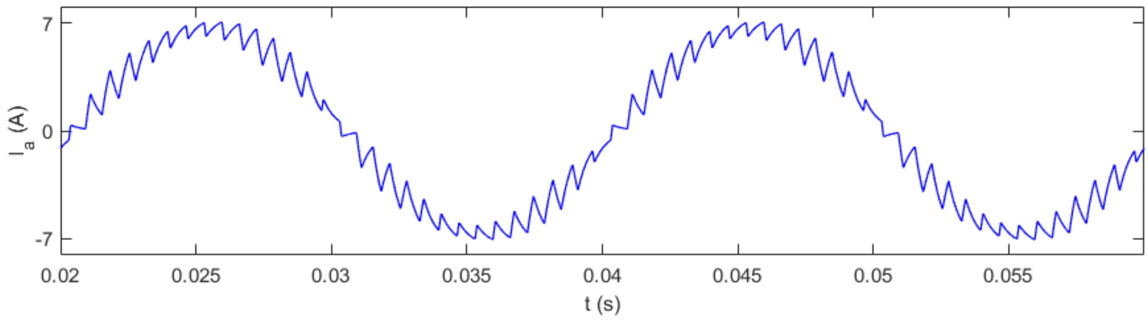

Figure 7. THD current waveform for validation check.

According to the validation simulation, it is seen that the current ripple values of the connected load at the inverter output decrease and also the THD value decreases to approximately 5.46% as given in Fig. 8. Thus, when there is a change in *R* and *L* parameters in the impedance values of the load at the inverter output, the PWM circuit parameters of the inverter switching control circuit depending on the load profile can be changed quickly by using this estimation method for adaptive control. In addition, the THD values can be kept at the desired levels under load changes in any case.

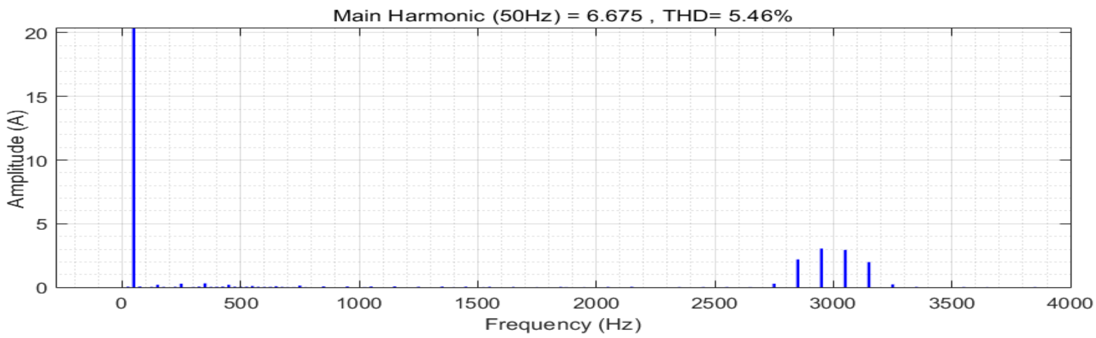

Figure 8. Harmonic spectrum of inverter output current.

4. CONCLUSION

The parameter estimation in power electronics circuits is an important step before the experimental realization of the circuit. For this purpose, the power electronics circuit interface is used in order to obtain a variation data set with certain input variables in linear steps [24]. In this study, ANFIS technique is proposed to estimate the THD value of the output current of a three-phase three-level inverter circuit. 340 pieces of data were obtained by using MATLAB - Simulink simulation software in power electronics circuit design. The obtained data set is divided into two groups at 80% and 20%. Then, 80% of the dataset is used for training and the rest for performance testing. At the end of the estimation phase, the mean absolute error (MAE) values for training and testing are calculated as 0.1894% and 0.4009%, respectively. By using the results of this study, it can be ensured that the harmonic distortion value of the current passing through the load does not exceed certain levels with smart techniques in the control circuit of the inverter. According to the verification simulation, the changes depending on the load profile at the inverter output can be determined very quickly in order to decrease the current ripple values of the connected load at the inverter output and also to keep the THD value at the desired levels. Thus, the PWM circuit parameters of the switching control circuit of the inverter can be adjusted. Such artificial intelligence-based switching are methods that can be used in the control circuit designs of network interfaces connected to renewable energy sources, which are exposed to load changes in control signals. In addition, it is thought that this study will guide researchers in creating data sets in parametric simulation studies.

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