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ANFIS-based Parameter Estimation of a Single Phase Inverter Circuit with Isolation Transformer

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Abstract: This study aims to isolate the output interface of single-phase inverter circuits and the grid from each other. For this purpose, the electromagnetic modeling of the isolation transformer was carried out in three dimensions (3D) with the Ferrite N87 core material. In order to determine the leakage inductance behavior of the transformer, a data set was obtained as a specific parametric scenario by changing the geometric dimensions of the primary-secondary windings with parametric linear steps. Thus, the estimation process of the electromagnetic modelling of the transformer has been successfully carried out thanks to the training and testing processes of Adaptive Network Based Fuzzy Inference Systems (ANFIS) with the numerical information obtained from the finite element analysis (FEA) parametric data set. After the estimation processes, the percentage error is calculated as 0.3470% and 0.4448% for training and testing. Thus, the determination of the isolation transformer with the optimum values designed for the inverter circuit has become easier. Also, experimental analysis is performed on inverters to prove the robustness of the proposed method. In this context, first of all, RMS values that vary according to the different operating parameters of the inverters are created. The proposed ANFIS-based system estimates RMS values with 7,057 % error.

Keywords: Isolation transformer, Leakage inductance, Inverter, FEA, ANFIS

Öz: Bu çalışmada, tek fazlı evirici devrelerinin çıkış arayüzü ile şebekenin birbirinden izole edilmesi amaçlanmıştır. Bu amaçla, izolasyon transformatörünün elektromanyetik modellemesi Ferrite N87 çekirdek malzemesi ile üç boyutlu (3D) olarak gerçekleştirilmiştir. Transformatörün kaçak endüktans davranışını belirlemek için birincil-ikincil sargılarının geometrik ölçüleri parametrik lineer adımlar ile değiştirilerek spesifik bir parametrik senaryo halinde bir veri seti elde edilmiştir. Böylece sonlu elemanlar analizi (SEA) parametrik veri setinden elde edilen sayısal bilgilerle Bulanık Mantık Sistemine Dayalı Uyarlanır Ağlar (BMSDUA) eğitim ve test süreçleri sayesinde transformatörün elektromanyetik modellemesinin tahmin süreci başarıyla gerçekleştirilmiştir. Tahmin işlemlerinden sonra eğitim ve test için hata yüzdesi %0,3470 ve %0,4448 olarak hesaplanmıştır. Böylece evirici devresi için tasarlanan optimum değerlere sahip izolasyon trafosunun belirlenmesi kolaylaşmıştır. Ayrıca önerilen yöntemin sağlamlığını kanıtlamak için eviriciler üzerinde deneysel analizler yapılmıştır. Bu kapsamda öncelikle eviricilerin farklı çalışma parametrelerine göre değişen RMS değerleri oluşturulur. Önerilen BMSDUA tabanlı sistem, RMS değerlerini %7.057 hata ile tahmin etmektedir.

Anahtar Kelimeler: İzolasyon transformatörü, Kaçak endüktans, Evirici, SEA, BMSDUA

1. Introduction

The use of renewable energy sources has increased in recent years. There has been a need to isolate the inverter circuits, which are among the power electronic converters, and the grid interface from each other. For this reason, it is essential to design an isolation transformer that keeps costs and losses to a minimum. In recent years, it has become necessary to isolate the circuits used in power electronics grid integration with the increase in the installed power of renewable energy sources. In this context, it is extremely important to design an isolation transformer, which is included in DC-AC converter circuits, as large as possible with the lowest cost and the highest efficiency. In addition, the electromagnetic performance of an isolation transformer between the load and the inverter greatly changes the power electronics circuit performance in order to obtain a voltage close to a pure sinusoidal waveform. In this way, more efficient operation of the systems connected to the inverter output can be achieved.

The use of transformers in our daily life and in the industry is quite common. Although their use is usually to step-up or step-down of the voltage level to make it suitable at the desired level, it is also often used to isolate two or more electrical power systems from each other [1]. One of the reasons why transformers work efficiently is that they have no moving parts. As a general need, transformers have an important component in the transmission of electrical energy over long distances and distribution in the grid structure. For this reason, transformers are one of the most important power electronic components used in electrical energy transmission/distribution lines [2].

It has been determined that many analyzes have been made on the leakage inductance parameters of transformers. In fact, although leakage fluxes are undesirable because they affect the regulation in power distribution transformers, in medium/high-frequency transformers used in power electronics circuits, leakage flux inductance emerges as an important parameter in the resonance circuit as a circuit element.

Isolating transformers isolate the output voltage and the input voltage from each other, isolating the source and the load from each other. Especially based on this advantage, it ensures the safe operation of highly affected electrical devices such as computer-based information systems and grid integration circuits. On the other hand, electrical accidents that may occur due to wetness and humidity can be prevented in terms of the safety of living things [3]. Not much has been changed in the structure of transformers since they were invented. However, studies to reduce the size of the core materials and transformer used are still continuing [4]. In the design of the transformer, attention is paid to keeping the power losses as low as possible in terms of higher efficiency. In order to design low-power loss transformers, studies on the power losses of ideal wound transformers are frequently carried out [5]. Aghaei, et al. [6] discussed in detail the leakage inductance behavior of transformers whose primary and secondary windings are not regular, and thanks to FEA simulation studies, it is possible to have an idea about power losses and voltage regulation before the prototype production phase, and to prevent critical situations that may be encountered. The use of medium-frequency transformers is common in power converter circuits and power distribution grids. The correct adaptation to the increasing switching frequency depends on some parameters of the transformers. Therefore, many parameters of the electromagnetic behavior of transformers must be estimated before they are integrated into the power electronics circuit. In this context, Tian, et al. [7] developed an operating frequency-dependent method to estimate the leakage inductance value of an isolation transformer in the mid-frequency range. Thus, the relationship between the leakage inductance value and the magnetic field intensity distribution and electromagnetic behavior was investigated. In this way, the leakage inductance has been calculated successfully. In order to minimize the leakage inductance value, the advantages of interspersed winding structures and different winding structures and their effects on leakage inductance were compared with test the presented new method, such as 10kW, 500 / 5000V, and 5kHz specifications. Also, it was determined and reported that the results obtained at the end of the test phase were compatible with the results obtained using FEA. Similarly, Mogorovic and Dujic [8] designed a high-frequency transformer in power electronics grid integration circuits and made detailed analytical modeling of the leakage inductance behavior of this transformer providing galvanic isolation. Analyzes were made with the Finite Element Method (SEM). Prieto, et al. [9] aimed to estimate the leakage inductance and AC resistance of the transformer. Thus, Finite Element Analysis (FEA) based modeling techniques can be used to calculate different frequency and geometry effects. With the proposed method, it is ensured that the designer uses interleaving techniques effectively. Thus, a simple calculation is sufficient to determine the best winding shape of the designed transformer. It is presented that the leakage inductance value can be reduced up to nine times using the interleaving technique. Ramachandran and Deverajan [10] designed a fuzzy-based three-phase inverter circuit with a single DC source for a grid-connected photovoltaic (PV) system using a three-phase transformer. The aim of using fuzzy logic in this study is to meet high-quality output, minimum total harmonic distortion (THD) value and fast response. Rossmanith, et al. [11] used 3D finite element method (FEM) simulation to model common mode chokes leakage inductance. Artificial Neutral Network (ANN) was applied for the estimation of the obtained leakage inductance data. At the end of the study aimed at the relationship between leakage inductance and winding parameters, ANN successfully predicted leakage inductance values.

Spacecraft contain an inverter to obtain high voltage from a low-power source provided by solar panels. The power drawn from the low-voltage DC source is rectified and filtered using a pair of power transformers with an oscillator. Due to the natural inductive behavior of transformers, if the core is saturated and the voltage value exceeds the voltage value of the transistors connected to the inverters, the probability of the system tripping increases. In this context, a report detailing the results of a research program conducted to examine the magnetic properties of some materials for use in spacecraft transformers, static power converters and transformer rectifier power supplies is presented [12].

In this study, an electromagnetic FEA-based modeling method is presented for the inverter circuits to operate more efficiently. Ferrite N87 soft magnetic material, which is suitable for high frequency designs, was chosen as the core material of the isolation transformer modeled for the inverter circuit. This core material is defined in the designed E core form in the FEA software in terms of core geometry, specific core loss and saturation flux density values. First, parametric simulation studies were carried out with FEA software in order to obtain leakage inductance values according to variables such as the geometric properties of the primary-secondary windings of the isolation transformer, which can be found at the outputs of the inverter circuits, and the number of turns and a data set was obtained as leakage inductance values. This data set is assigned for the training and testing of Adaptive Networks Based on Fuzzy Logic System (ANFIS). In this way, the leakage inductance of the isolation transformers with different winding sizes that have not yet entered the production phase has been accurately estimated and the isolation transformer with the most efficient operating parameters has been determined. In the second step, the RMS values of the output voltage were obtained depending on the different leakage inductance values of the transformer integrated into the inverter and the PWM switching variables were determined.

2. Inverters

Today, with the rapidly developing technology, the increasing need for energy has increased the importance of environmentally friendly clean energy sources and their use has become widespread. However, in such application areas, the need to isolate the power electronic circuits of the grid and the renewable energy source from each other efficiently has arisen. In line with this need, performing the design of an isolation transformer is of great importance for the safe and efficient operation of the system.

Since almost all electrical devices work with alternating current electrical energy, it is necessary to have an AC power supply. Inverter circuits are also known as adjustable frequency AC voltage source, that is, inverters that convert the output from a DC voltage level to AC voltage at the desired voltage and desired frequency [13]. That is, the working principle of an inverter is to convert a certain level of DC input voltage to AC output voltage with a desired frequency and amplitude [14]. The input of the inverters can be fed from various sources such as batteries, solar cells or through the rectifier circuit. Depending on the type of source used in its input, inverters are divided into two parts voltage source inverter and current source inverter [15]. The frequency and amplitude of the AC output voltage can be changed or kept constant by keeping the DC input voltage and the inverter gain constant. In addition, if the DC input voltage has a fixed value and a variable output AC voltage is requested, a variable output voltage can be obtained with the changes made on the inverter gain. This is done with Pulse Width Modulation (PWM) control for the inverters. The gain of the inverters can be found by the ratio of DC input voltage to AC output voltage [16].

The waveform of the output voltage of ideal inverters is sinusoidal. However, the inverter output voltages obtained in practical applications do not have a sinusoidal form and have some harmonics. In high-power applications, waveforms with the sinusoidal form with little distortion are required. In low and medium power applications, square wave or partial square wave output voltages are requested. In response to this demand, the effect of harmonics on the output voltage can be greatly reduced by using semiconductor technology and switching techniques that have developed in recent years [16].

Mostly, any DC source (battery, fuel cell, solar cell, wind cell) can be at the input of inverters used in industrial applications such as variable speed AC motor drives, renewable energy sources, transportation services, induction heating, off-the-shelf power supplies and uninterruptible power supplies [16]. The desired number of output phases can be obtained with inverters. Although single-phase and three-phase inverters are preferred more frequently in industrial applications, the development of more than three-phase AC motors has recently gained importance in order to increase the reliability of some critical applications. Therefore, the production and design of inverters with the same phase number have been accelerated [15].

In the past, Silicon Controlled Rectifiers (SCRs) were used in high and medium-power inverters. SCR-based inverters needed commutation circuits to turn off the SCRs. While these commutation circuits increase the size and cost of the inverter, it also reduces their reliability and switching frequency. Due to these disadvantages, with the development of fully controlled semiconductor power switches, Insulated Gate Bipolar Transistors (IGBT) and Gate Turn Of (GTO) are used in medium power inverters, and Integrated Gate-Commutated Thyristors (IGCT) are used in high power inverters [15]. There is a reverse parallel connected diode next to each semiconductor power element (such as SCR, Bipolar Junction Transistor (BJT), MOSFET, IGBT) used in inverter circuits. The purpose of the use of this diode is to protect the circuit elements against the reverse current that may pass through it [17].

2.1. Single-Phase Two-Level Inverter

Regarding two-level inverters, the single-phase full-bridge inverter circuit given in Figure 1 has four active and four passive circuit elements. Square wave, partial square wave and PWM techniques can be used to control this type of inverter [17]

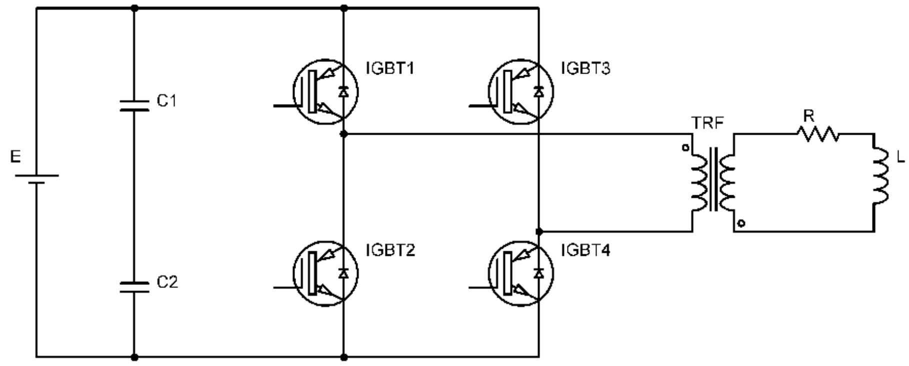


Figure 1. Single-Phase Two-Level inverter circuit

In a single-phase two-level inverter circuit consisting of four choppers, E input voltage is seen on the load when I_1 and I_2 IGBTs turn on at the same time. When I_3 and I_4 IGBTs turn on, the negative value of input voltage -E occurs on the load. In this circuit topology, Equation 1 can be given for the effective value of the AC voltage obtained at the inverter output [16].

$$V_o = \sqrt{\frac{2}{T_0}\int_0^{\frac{T_0}{2}} E^2 dt} = E \quad (1)$$

AC voltage induced at the output is obtained by the difference of the phase voltages a and b given in Equation 2, which has 180° phase difference [17].

$$V_{ab} = V_o = V_{ao} - V_{bo} \quad (2)$$

3. Isolation Transformers

Generally, isolation transformers are electrically separating the source and the load from each other by isolating the secondary output voltage from the primary voltage by means of magnetic coupling for the purpose of use. In this way, isolation transformers play an active role in the protection of sensitive electrical devices, especially from current and DC components with harmonic components [3, 18].

3.1. Leakage Inductance

In a transformer with two windings, not all of the magnetic flux induced by the windings connects the other winding. That is, there is magnetic flux induced by a winding in the gap between the core and the windings, in the gap between layers, inside the conductors, and inside the insulation between the windings. Since these flux components have no connection with the other winding, the coupling coefficient is less than one (k< 1). This leakage flux between the windings can be characterized as an inductance as it stores magnetic energy. These inductances, called leakage inductances, are modelled as L_{l1} and L_{l2} connected in series with the windings, as shown in Figure 2 [19].

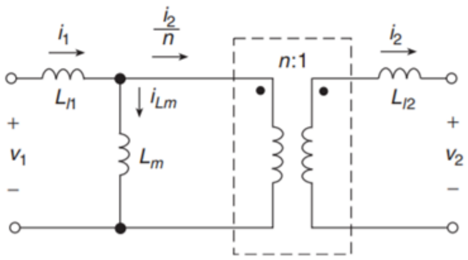


Figure 2. Transformer equivalent circuit.

The leakage inductance value varies depending on the winding arrangement of the transformer, the core geometry, and the core relative permittivity. Many studies have been done in the literature to reduce the leakage inductance value of the transformer. For this purpose, in some of these, the windings of the transformers are designed with wide and low thickness, the insulation between the windings is reduced, and the windings are placed in such a way that they overlap each other, double-strand windings are used and the number of turns is reduced. It has been determined that the leakage inductance is low in transformers with wide and flat windings with minimum insulation. In addition, making transformer windings from Litz wire or a twisted bundle of insulated wire also reduces leakage inductance. The use of wide and thin foil is required for the lowest leakage inductance value [19].

The equivalent circuit of a two-winding transformer includes a magnetizing inductor (Lm), leakage inductors L_{l1} and L_{l2}, as well as an ideal transformer with a conversion ratio n. Thus, the coupling coefficient (k) and conversion ratio (n) of the ideal transformer can be defined by Equations 3-5. In these equations, N_1 and N_2 are the turns of primary and secondary windings; L_{pr} and L_{sc} represent self inductance values of primary and secondary windings, respectively [20].

$$n = \frac{N_2}{N_1} = 1 \ (for\ isolation\ transformer) \quad (3)$$

$$k = \frac{L_m}{L_m + L_{lk}} \quad (4)$$

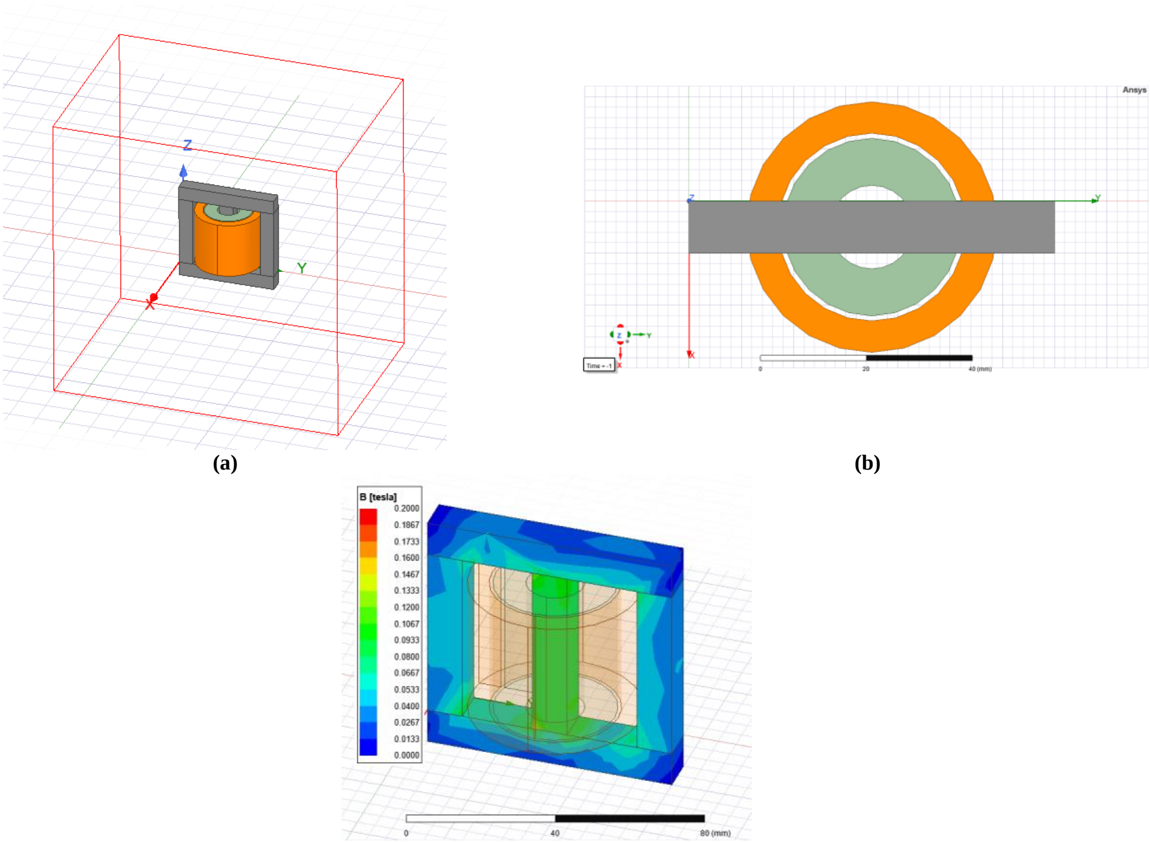
$$L_{l1} = L_{pr}(1 - k^2) \quad (5)$$

$$L_{l2} = L_{sc} - L_m(n)^2 \quad (6)$$

4. Parametric Simulation Studies

4.1. Design of the Isolation Transformer

The application developed in this article belongs to the thesis study in reference [21, 22]. The isolation transformer designed for inverters is given in Figure 3. The ferrite N87 is defined as the core material of the three-dimensionally modeled isolation transformer in order to verify of the leakage inductance data set.



(a) (b) (c)

Figure 3. Isolation transformer design with FEA software, (a) 3D image of the electromagnetic modeling, (b) the top view of the primary and secondary windings, (c) 3D flux density of the transformer core.

For parametric FEA simulation studies, the number of turns (N), primary winding radius (Lpr) and secondary winding radius (Lsc) variables of the windings of the isolation transformer are calculated according to different variations by defining the linear steps given in Table 1. Thus, in the transformer design parameters, the leakage inductance behavior of the three input variables is extracted and a parametric data set is obtained [22].

Table 1. The parameters of the FEA simulation issue.

Parameters	Value	Step
L_{pr}	10-17 mm	0.5
L_{sc}	18.5-24 mm	0.5
N	20-50	5

4.2. Design of the Two-Level Inverter

The values of the circuit elements to be used for the design of the single-phase two-level inverter were determined and designed as given in Figure 4.

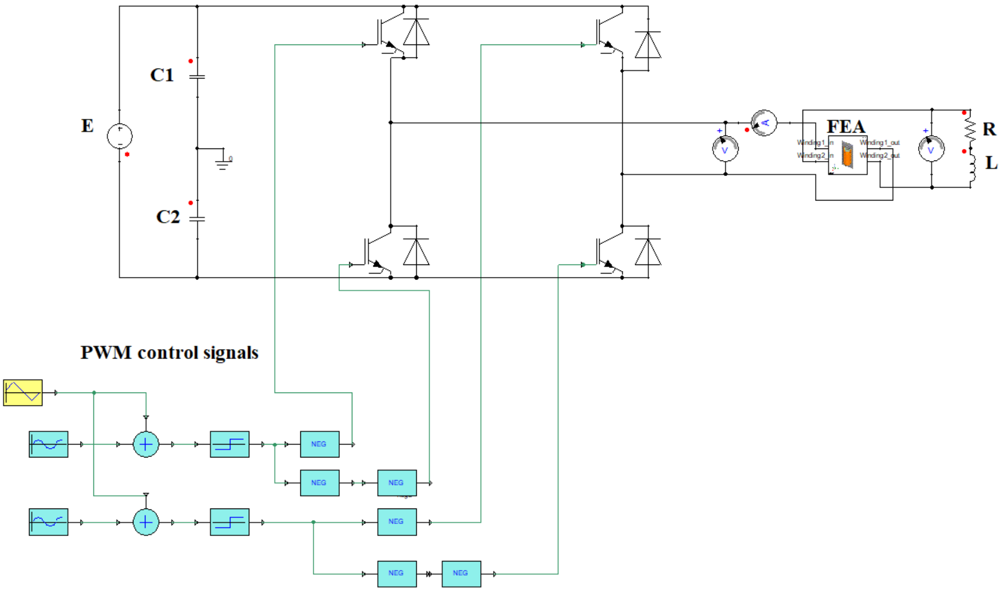


Figure 4. Single-phase two-level inverter circuit

Values of active and passive circuit elements used in circuit design are as given in Table 2. Parametric simulation studies are carried out with certain variational steps according to these data.

Table 2. Values of used circuit elements

Circuit Element	Value
E	400 V (DA)
C1, C2	6600 uF
R	10 ohm (load)
L	10 mH (load)

The parametric simulation method was used to determine the RMS value occurring at the output voltage of the inverter given in Figure 4. For parametric analysis, a data set was obtained by changing the leakage inductance (L_lk) of the transformer at the inverter output, the frequency of the PWM signal used in the control circuit of the inverter, and the frequency of the sine waves with linear steps given in Table 3.

Table 3. Parametric values of a single-phase two-level inverter circuit

Parameters	Value	Step
L_{lk}	0-10 μH	2 μH
PWM	15-30 kHz	5 kHz
f	1-10 kHz	1 kHz

5. The Estimation Studies with ANFIS

The unpredictability of possible future uncertainties and risks is a serious problem for many projects in general. The reason why risks and uncertainties cannot be determined is the adverse effects of inaccessible parameters on the systems. In other words, it is possible to predict future uncertainties and risks. However, it is not possible to accurately predict future events without an accurate analysis of past events. In this context, past events, whose data were previously recorded, should be recorded accurately and effectively, should be easily accessible when necessary, and the desired data should be easily produced [10]. Thus, ANFIS is one of the artificial intelligence techniques developed in recent years and Artificial Neural Networks are used to determine fuzzy logic parameters. Thus, it was established by taking advantage of the learning ability of artificial neural networks, considering the reasons such as the fuzzy logics inability to adapt easily to environmental conditions and its lack of learning ability. The uses of ANFIS can be listed as modeling nonlinear functions, linearly defining nonlinear components and estimating a chaotic time series [23, 24].

The leakage inductance values of the isolation transformer, which can be integrated into the outputs of the inverter circuits, were obtained using a parametric simulation technique. As input variables data to the ANFIS modeling, L_{pr}, L_{sc} and N parameters are defined for the parametric simulation setup. Leakage inductance values obtained by parametric simulations are presented as output parameters. With a total of 1260 data, the training and testing phase of the ANFIS system has been completed. 1008 of these data are used in the training phase of ANFIS and 252 in the testing phase. In order to divide the data into train and test, first the order of the data is randomly mixed. Then, random selection is made from these data.

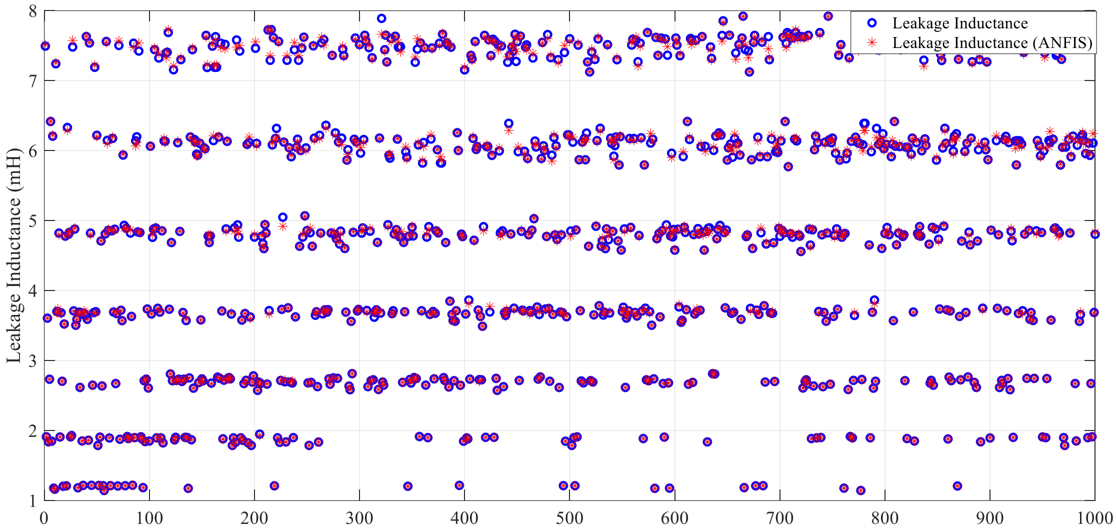


Figure 5. The training graph

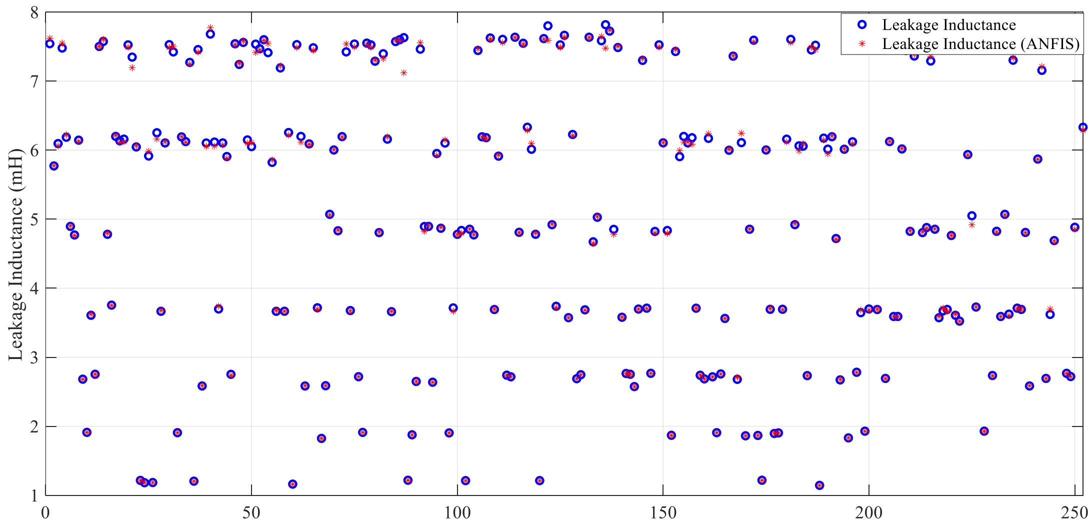


Figure 6. The testing graph

$$\boldsymbol{Error} = \frac{\sum\left(\frac{|\boldsymbol{Actual\ Value(i)} - \boldsymbol{Predicted\ Value(i)}|}{\boldsymbol{Actual\ Value(i)}}\right)}{\boldsymbol{i}} \boldsymbol{x100} \tag{3}$$

The most efficient membership function has been determined by making many preliminary studies in the ANFIS interface. The training and test graphics obtained as a result of the studies are given in Figure 5 and Figure 6. The differences between the actual and ANFIS-estimated values were analyzed with the formula given in Equation 3 and error values were calculated. According to the results obtained with the rule-based viewer given in Figure 7, the average percentage error is obtained as 0.3470% and 0.4448%, respectively, because of the training and testing phases.

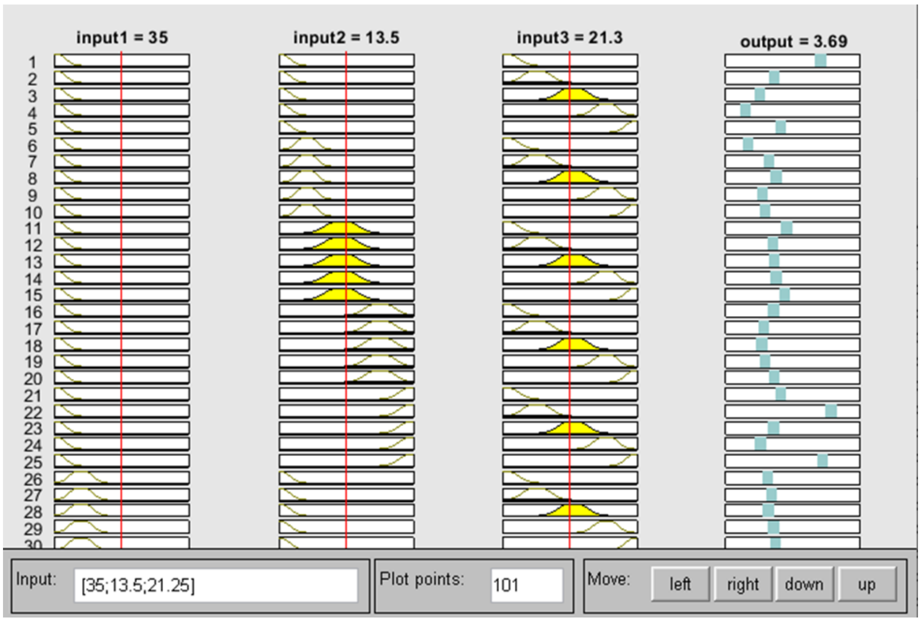


Figure 7. Testing ANFIS Model

As a result of the studies, the most efficient isolation transformer was easily determined. Then this transformer was used at the output of a single-phase two-level inverter. Simulation studies have been carried out to estimate the RMS value that changes depending on the various parameters of the designed inverter. The data set obtained as a result of the simulations was processed with ANFIS, one of the artificial intelligence methods, and a successful estimation was made.

The graph where the system's training estimated values and actual values are together is given in Figure 8.

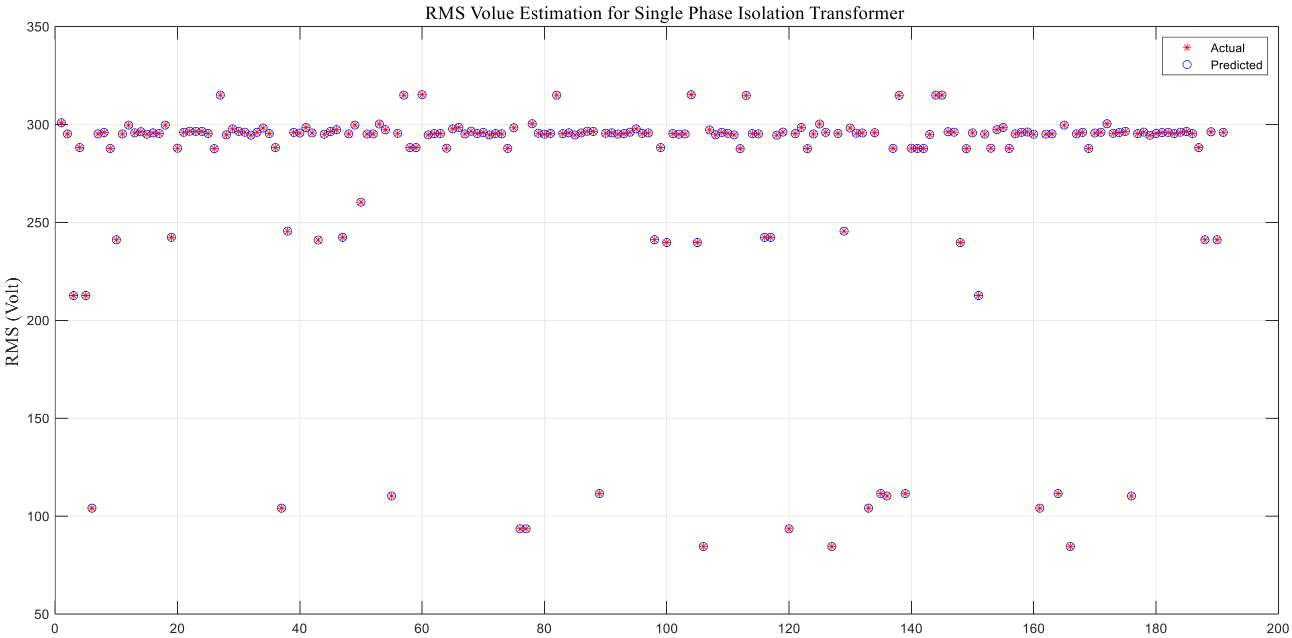


Figure 8. Trainig ANFIS Model

After the training process is completed and the test phase is started, the test prediction values and actual values obtained as a result of the system study are given in Fig. 9

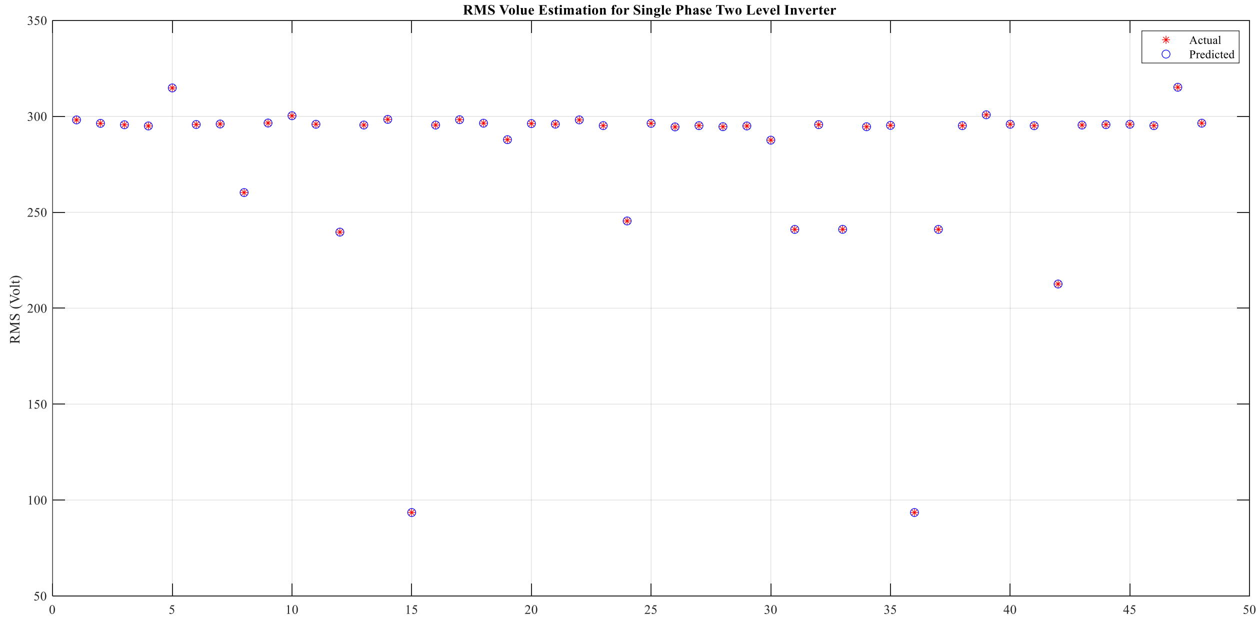


Figure 9. Testing ANFIS Model

The average percent error for the test was calculated as 6.7522%. Thus, by examining the given graphs and calculated error values, it was determined that the estimation phase was very successful.

6. Conclusion and Discussion

In this study, two different methods are presented for the analysis of the leakage flux effects of isolation transformers for the waveform of output voltages of two level inverter circuits to have a smooth sinusoidal form. In the first method, it is aimed that the output wave of single-phase two-level DC-AC inverter circuits, which can be adjusted at the desired level and frequency, is close to a smooth sinusoidal. In this direction, parametric simulation studies of an isolation transformer are carried out by using ANSYS-Maxwell software, which can be analyzed with SEM in an efficient and realistic way. Leakage inductance changes are observed by changing the radius and number of turns of the primary and secondary windings of the isolation transformer. Thus, because of parametric simulations, a data set is created for the estimation of the leakage inductance value of the isolation transformer, which varies depending on the radius of the primary and secondary windings and the number of turns. This data set is analyzed with ANFIS, one of the widely used artificial intelligence algorithms, and as a result, leakage inductance values were successfully estimated. In this context, the determination of the much more effective operating isolation transformer, which can be determined because of actually quite long-term and process-requiring studies, has been facilitated. In addition, the efficient isolation transformer designed according to the leakage inductance behavior is integrated into the output of two single-phase DC-AC inverter circuits and the output voltages of the inverters are observed. As a result of the study, the RMS value of single-phase two-level inverters with different operating parameters has been successfully estimated. As future studies, different high-frequency transformer designs can be made and their behavior in power electronics circuits can be deduced. In addition, designs can be made with nanocrystalline core material, which has been very popular in recent years, instead of ferrite core material for a certain power and frequency value. Thus, comparative performance studies can be made with ferrite core materials. The regression results obtained showed that the use of artificial intelligence in estimation of leakage inductance provided effective results. In this way, faster analysis can be done. However, more data are needed for more reliable results.

Competing Interest / Conflict of Interest

The authors declare that they no conflict of interest. The none of the authors have any competing interests in the manuscript.

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