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An Adaptive Neuro-Fuzzy based Methodology for Harmonic Analysis of a Power Transformer

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Abstract

The interfering nature of harmonics always causes various power quality issues that impacts on both efficiency, and expected transformer life. Optimal analysis of the three-phase core power transformers using harmonic spectrum can limit these power quality issues. This paper designs the Adaptive Neuro-Fuzzy Inference System (ANFIS) based model for the estimation of losses. Further optimal parameters selection of three-phase power transformer using iron and ferrite core materials. This paper demonstrates factors that deteriorate the power quality, responsible for harmonics distortions and inefficiency in power transformers. The proposed ANFIS based analysis provides an optimal solution to harmonic reduction and improves overall efficiency. Also, providing a comparative study of various core parameters that will be suitable for a three-phase core transformer. The proposed parameters are demonstrated for improving the overall transformer efficiency using iron and ferrite core material. ANSYS Maxwell simulation estimates the Total Harmonic Distortion (THD) and enhances THD in contributing to the optimal core material. The design of a three-phase power transformer and the performance evaluation of the proposed methodology performed in MATLAB simulation environment.

Keywords: ANFIS (Adaptive Neuro Fuzzy Inference System), AI (Artificial Intelligence), T/F (Transformer), THD (Total Harmonic Distortion), E/M (Electromagnetic), ANSYS Maxwell.

1 Introduction

Global population, industrial production, and consumption of power are growing relentlessly [1]. Load-demand requirements can be supported with more reliable power system components, like power transformers. We cannot afford the degradation or failure of power system equipment. Transformers are available in various designs, they can be shell or core type, or applications such as distribution transformers, etc. Transformers play a vital role in power system units that are available in compact form, whether for energy transformation at different frequency applications. To enhancement of power transformation, it is important to have a better working environment condition for transformer. Transformers have designed to deliver step-up or step-down voltages/currents for different types of loads [2]. The transformer's condition naturally wanes as it ages [3]. Aging progressively worsens due to overheating caused by overloading [4]. The design of a power transformer providing balancing act between maintaining compatibility with standards, minimizing overall costs, and maximize efficiency [5]. The power transformer is a critical piece of equipment in power transmission system, which needs reliable and fast fault clearance capability. Unresolved faults in the transformer may cause internal damage and lead to severe inefficiency [6]. Fault can occur in either internal or external structures of transformers and can pose a low or high risk of damage. Dangerous faults can lead to power failures and outages. To stop damage from fault occurring, it is advisable to detect and clear faults in a timely fashion. Therefore, the general protection of internal and external system plays a vital role in maintaining transformer protection [7]. The presence of harmonics and their distortions in the output waveform of a transformer may lead to power quality issues. They present hurdles in power transfer monitoring between the power systems components. Conventional power systems have fewer problems with harmonics identification because most of the loads are non-linear [8]. Harmonics mostly derive from nonlinear loads [9] and these nonlinear loads are responsible for power system inefficient [10].

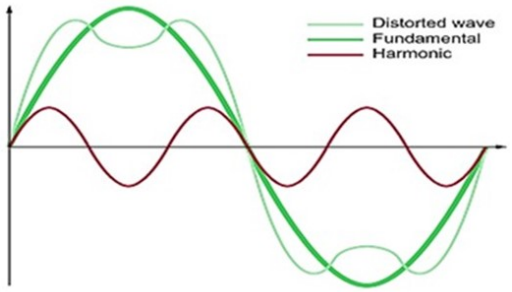

Figure 1: Harmonics and related spectrum of output waveform

Harmonics lead to power loss, which increases operating and maintenance costs. They cause severe heating in the transformer and insulation fatigue [11]. Fig. 1 shows representation of the harmonic spectrum. Harmonic distortions are also responsible for other problems such as noise in telecommunications, over-temperatures in electric equipment, electric stress, resonance, etc. [12]. Total Harmonic Distortion (THD) is a mathematical quantity of harmonics existing in an electrical waveform, termed as the ratio of the sum of powers for all harmonic components to the power of the fundamental frequencies [13]. Mathematically, THD is represented as:

$$\sqrt{[\left(\frac{1}{g^2}\right) - 1]}$$

Where g is distortion factor, which is defined to the measurement of intensity for nonlinearities [14]. The mathematical relationship of THD [15] and g as expressed below:

$$\frac{\sqrt{\sum_{h=2}^{[\infty]} V_{h,rms}^2}}{V_1}$$

Equation 2 showing the fundamental voltages in RMS (which represents the 'h' order harmonics voltage). Harmonics have the following undesirable effects on transformers [16]: increment in core and copper losses, increase in the electromagnetic (E/M) and electrostatic interference with communication circuits, increase in dielectric stress on insulation, and uneven resonance effect. Novel artificial intelligence-based computational techniques are emerging to assess these occurrences. These techniques included fuzzy logic controller-based techniques, artificial neural networks, genetic algorithms, and PSO-based monitoring systems. In this paper, the AI-based ANFIS technique is implementing. The adaptive neural-network-based fuzzy inference system is a hybridization of ANN and fuzzy logic. ANFIS is based on the Takagi–Sugeno-based fuzzy inference system [17]. These interference systems works correspond to IF-THEN rules, which are capable of handling non-linear operations. Therefore, the proposed ANFIS can work as a collective estimator. A typical Takagi-Sugeno fuzzy-based model has a basic system with the following form; When the first input represented as 'x' and the second input as 'y' then output 'z' is in the form of:

$$Output(z) = ax + by + c$$

For the zero-order model, when output 'z' is constant then other functions are:

$$a = b = 0$$

According to the desired output (z), Fig. 2 showing the design and operational framework of proposed ANFIS system or plant.

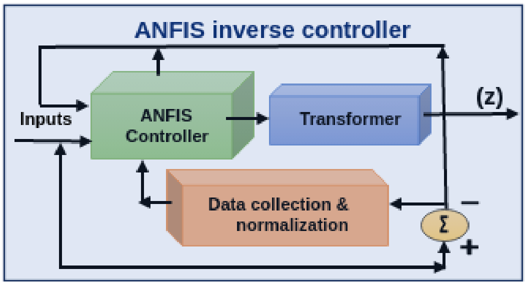

Figure 2: Framework showing ANFIS controller in a transformer plant

Several researchers proposed that DGA (Dissolved Gas Analysis) technique to diagnose internal faults in power transformers. It is associated with the hybrid-based technique, which used in the analysis of uncertain conditions. This technique may leads the better diagnosis of faults than traditional techniques [18]. Proposed ANFIS highlights the problem from observed data [19]. This research carried out experiments based on ANFIS technique using the hybrid RVM model to achieve the higher accuracy (in the range of 89-94%) [20]. Transformer life estimation of breakdown and their diagnostics are always a major issues for power utilities. Similarly, J. Fan [21] presented the research work using ANFIS designed model for the loss estimation as well as lifespan prediction of the power transformer. Here the research carried out based on standard physical parameters, such as ambient temperature, load level, and key components that are mainly responsible for degradation of power transformer life. Also, the estimation was based on hourly data. In 2018, S. Forouhari [22] presented a novel ANFIS based prototype to estimate the overall life of mineral-oil-filled power transformers. In this paper, the authors introduced an integrated asset prototype based on analytical pointers supervision. In early 2018, J. Kim [23] mathematically derived the relationship between source impedance and harmonic cancellation. This research is based on the performance of a shunt based phase shift transformer, in which the effect of line conductor observed for low level applications. In 2017 [24], this paper proposed the analysis of current harmonics for suppress harmonics in the SMES (Superconducting Magnetic Energy Storage) method. This research validated the simulation as well as analyzed the experimental with better accuracy.

This manuscript consists of six sections: Section I consists of an introduction to problem formulation and their possible solutions. Section II carried out the concepts and technical approach for selecting the optimal parameters to design of proposed system. Section III contains the optimization parameters and system description. Section IV deals with modelling and simulation. Section V presents calculations and results analysis using ANFIS controller. In the last section, the conclusions and future scope presented of proposed ANFIS based methodology.

2 Selection of Optimal Parameters for System Design

There are four stages in the design of the proposed ANFIS model:

2.1 Data collection and normalization stage

Transformer data is collected and accumulated so as to generate input values for the optimal design with alteration in model parameters as per specification. The best combination of collected data can be proceed for the inputs normalization, input data can be classified as follows:

a. Three phase input voltage to the transformer.

b. Induced (root mean square) RMS voltage.

c. Change in winding resistance.

d. Core losses.

2.2 Training stage of ANFIS based proposed model

The training data sets are implemented for designing the proposed ANFIS based model with a defined combination of the membership function. Firstly, the membership function is selected and the system is trained according to the training data set. Then the model is trained to find the best combinations of input parameters.

2.3 Calculate error (MSE) in the proposed model

The testing and training data sets are used to calculate error for the proposed model. The error evaluation based on the criteria of proposed ANFIS model from the rule base, that will be tested accordingly. Mean Squared Error (MSE) is defined as the average of all possible errors squared, (that means the average of squared difference between the actual values and the estimated values [24]. The average testing or training errors provides an idea for the average generated error during training and testing periods in the proposed model.

2.4 Harmonics analysis and validation

System validation of the proposed model provides the degree of precision using a estimated value based on the simulation results during training and testing. The following parameters are taken into account for the overall accuracy of the system:

2.4.1 RMS value of induced voltage

Here, the values of induced voltages have been taken into account for Root Mean Square (RMS) analysis [25] and further for the calculation of distortion factor (g) which is mathmatically termed as:

$$g = \frac{RMS\ value\ of\ induced\ voltage}{RMS\ (AC)\ value\ of\ induced\ voltage}$$

2.4.2 THD estimation

In this research paper, estimation of Total Harmonic Distortion (THD) to develop the optimal transformer designs using for proposed ANFIS model. In real time evaluation of THD values, the transformer model can be designed with specified parameters. From which, It is found that, THD values further compared with the ANFIS Controller based on simulation results [26].

Table 1: Specification of transformers for a different case study study

3 Phase input voltage	Core material	Linear B-H curve	Transformer designs
20KV	iron	yes	Trf-1
20KV	ferrite	yes	Trf-2
20KV	iron	nonlinear	Trf-3
11KV	iron	yes	Trf-4
11KV	ferrite	yes	Trf-5

3 Description of 3-Phase Transformer Model

The proposed system is a three-phase transformer with some defined parameters of three phase input voltage, core material, and B-H curve. This paper contains a modified transformer with system design using ANFIS. The modeling of the transformer using iron/ferrite core materials based on the proposed design parameters, referred in Fig. 3. The design analysis of proposed three-phase transformer is performed in the ANSYS (Analysis Systems Simulation) maxwell simulation environment.

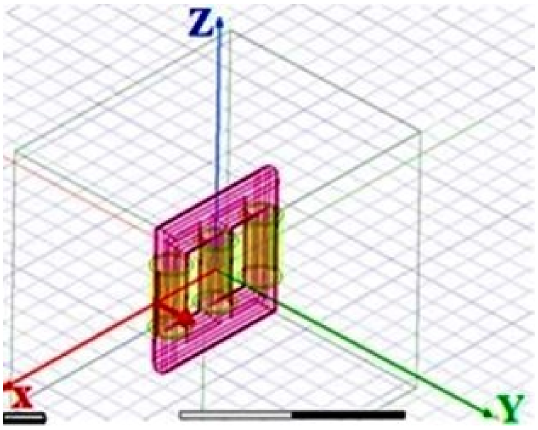

Figure 3: Transformer designed model in ANSYS toolbox

Table 1 showing the comparative analysis for different rating transformers, the description of base parameters and their specification will be testing the proposed model designs.

- **Transformers (Trf-):** There are different types of transformer (Trf-1 to Trf-6) design models that are implemented in ANSYS software based on specific ratings. These transformer have been particularly designed for the harmonic analysis, which are taken as Trf-1 for 20KV, Trf-3 for 20KV, and Trf-5 for 11KV etc.
- **Core material used:** Iron and ferrite materials used for the design of core transformer. That can be employed for the optimal specifications of materials, referred in Table 2.

Table 2: Description of proposed physical parameters

Core material	Relative permeability	Young's modulus (N/m2)	Poisson's ratio	Bulk conductivity (Siemens/m)
Iron	4000	1.95e11	0.28	1.03e11
Ferrite	1000	1.19e11	0.0	0.01

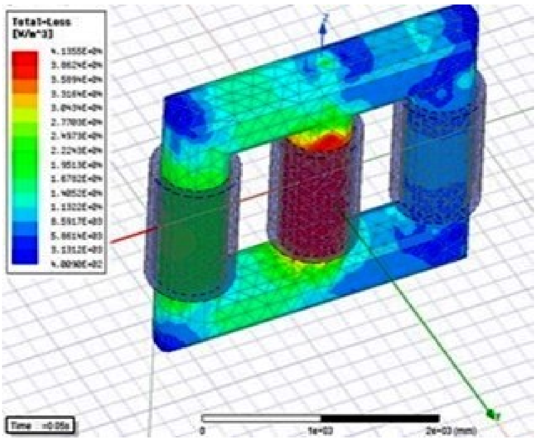

Figure 4: Total loss by iron material (see Table 2) using ANSYS toolbox

In proposed model, the mass density of iron material is taken as 7870 (w/kg) and the mass conductivity of ferrite is 1000 (w/kg). Total losses of different core materials directly affects the efficiency of transformer. The overall efficiency is estimated by the total loss prediction. Fig. 4 showing the total losses in iron core material, which is associated with relative permeability of 4000 using ANSYS toolbox. In this proposed model, iron core material used because of its appropriate distribution for convergence values with high magnetic field density.

4 ANFIS Modelling and Simulation

The proposed ANFIS system is a combination of ANN and fuzzy logic controller for computational as well as logical analysis. ANFIS learning sort of hybrid-based rule base. Before selecting the membership functions, firstly the functions will be train (70%) and test (15%) using normalized data sets. If the results are satisfactory then it accepts the selection of membership functions type; otherwise, it reselects the functions for again training and testing process. This process will be repeated again and again. The whole loop process continues until satisfactory values are obtained. Then they are compared with satisfactory ANFIS model parameters. The ANFIS structure consists of several nodes, in which some or all the nodes may be adaptive. The adaptive nature of proposed ANFIS systems contributes to the excellent controlling of the desired output parameters. The hidden layer of the ANFIS system is dependent on the degree of accuracy required. Based on specified constraints of different nodes, the output of these nodes depends on the weight functions of the corresponding layer. For each node, the values of the weight function are fixed. The directional links are used to link the nodes in various layers. The flow of signal via layer to provide a way for specific allocation with different weight functions based on desired degree of accuracy.

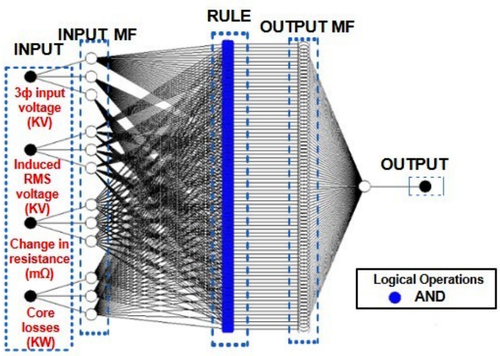

Figure 5: Simulation of proposed ANFIS based model

There are 5 layers in the proposed ANFIS model, these layers are represented as adaptive or fixed nodes. Each layer is interlinked through the directional links. As in Fig. 5, the first layer comprises four input parameters. where each node represents the fuzzy logic sets. The response of each nodes passing to the input of next layers, that is dependent of degree of the rule base given to the fuzzy set.

Fig. 6, layer 2 consists of weight functions w_{11}, w_{12}, and so on until w_{43}, which represents the extension in the degree of evaluation for membership functions. Layer 3 represents the rule-based layer in which the proposed input data set is given to a defined rule base. Layer 4 comprising the output membership functions and layer 5 comprising for the desired output.

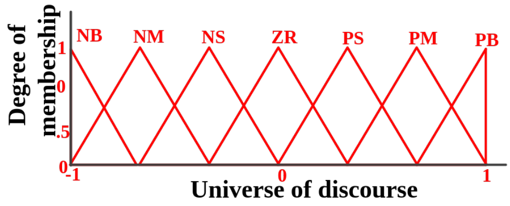

Figure 6: Membership functions of FLC system for inputs

put. In ‘Sugeno’ type ANFIS model, there are total 81 rules bases, while the number of 4 inputs and 1 output. On the other hand “And Method” takes ‘prod’, “Or Method” takes ‘probor’, and the defuzzification method takes ‘wtaver’. Proposed ANFIS techniques identify each harmonic related to the fundamental frequency. Certain physical parameters directly impact the harmonic spectrum such as; the type of core materials employed, permeabilities. etc. The implementation and description of the proposed ANFIS methodology are based on functional blocks in the form of a flowchart.

From Fig. 7 two criteria of inputs are taken into account when calculating THD for different designs of the transformers. these two criteria namely; evaluation of harmonics and factors depending on that harmonics rate. Based on the ANFIS analysis, following conclusions can be made for each criteria:

4.1 Evaluation of harmonic rate

It consists of various factors, which are used to calculate the harmonic rate in the power transformer, as referred to in Table 3 [27].

4.2 Factors depending on the harmonics

Several factors that are affected by the generation of harmonics in the transformer:

- Data interpretations can be analyzed by selecting and correlating input variable parameters.
- Normalization of raw data sets must be done through training and testing of the data sets.

The fuzzy surface view checks the degree of accuracy for the above criteria [28]. If it meets the desired requirements, then it goes further. Otherwise, it again normalizes the raw data sets and repeats the earlier step. At each instant, it calculates the percentage of error (MSE) within the specified limit and finally, the process will be completed.

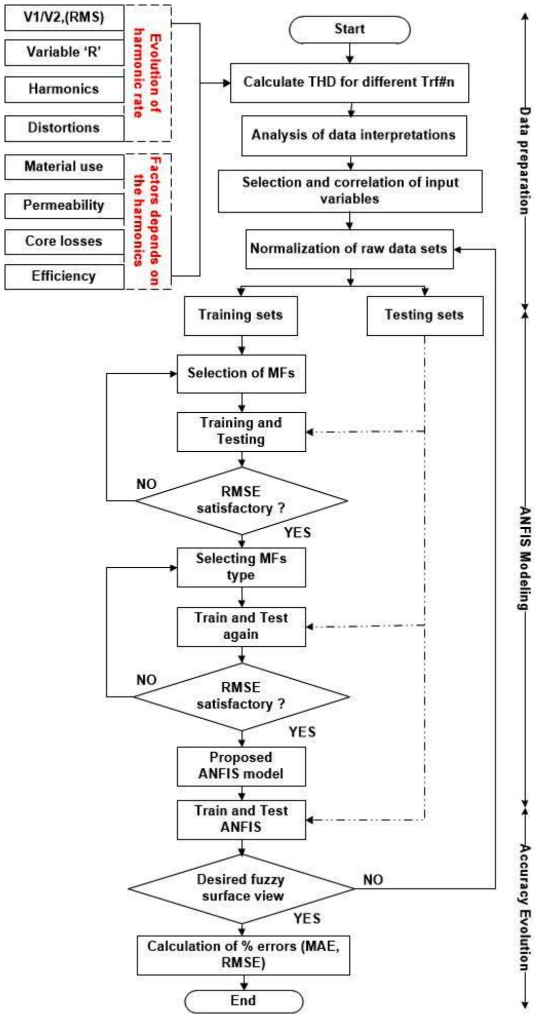

Figure 7: Flowchart of proposed hybrid neuro fuzzy based ANFIS model

5 Results and Discussion

The tabulated forms of induced voltage based on different instant are as follows in Fig. 8 (a) to (e). Fig. 9 contains the output waveforms of three-phase transformers. The x-axis shows time (*in ms*) and the y-axis showing the induced voltage (*in kV*) using the ANFYS simulation model.

From Fig. 9 THD mathematically calculated as depicted in Table 3, and the estimated THD range lies within 5%, which successfully fulfills the IEEE standard. In the real-time monitoring system, ANFIS based proposed approach successfully monitors the higher component of harmonics with a higher degree of accuracy. The proposed methodology efficiently measured the harmonics corresponding to induced voltages in the different winding of transformers (*20kV* and *11kV*) [29]. The IEC [TR-(61000-3-4:1998)] standard-based harmonic analysis [30] provides a novel intelligent power transformers protection scheme under various working conditions.

Curve Info	rms	crestfactor	avg	pk2pk	distortion(50)
InducedVoltage(Winding1) Setup1 : Transient	9.8667	1.6104 (SI)	-0.1799	31.7500	32.1587 (SI)
InducedVoltage(Winding2) Setup1 : Transient	9.8290	1.6327 (SI)	0.5134	32.0470	31.6953 (SI)
InducedVoltage(Winding3) Setup1 : Transient	9.9994	1.6058 (SI)	-0.3336	32.0745	26.8411 (SI)

Fig. 8 (a): Transformer (Tr#1) voltage parameters in ANFYS toolbox

Curve Info	rms	crestfactor	avg	pk2pk	distortion(50)
InducedVoltage(Winding1) Setup1 : Transient	9.8666	1.6104 (SI)	-0.1798	31.7499	32.1587 (SI)
InducedVoltage(Winding2) Setup1 : Transient	9.8290	1.6327 (SI)	0.5134	32.0470	31.6954 (SI)
InducedVoltage(Winding3) Setup1 : Transient	9.9994	1.6058 (SI)	-0.3336	32.0746	26.8412 (SI)

Fig. 8 (b): for Tr#2

Curve Info	rms	crestfactor	avg	pk2pk	distortion(50)
InducedVoltage(Winding1) Setup1 : Transient	9.8373	1.6153 (SI)	-0.2066	31.7493	32.2267 (SI)
InducedVoltage(Winding2) Setup1 : Transient	9.8286	1.6327 (SI)	0.5126	32.0462	31.6970 (SI)
InducedVoltage(Winding3) Setup1 : Transient	9.9992	1.6059 (SI)	-0.3352	32.0750	26.8385 (SI)

Fig. 8 (c): for Tr#3

Curve Info	rms	crestfactor	pk2pk	avg	distortion(50)
InducedVoltage(Winding1) Setup1 : Transient	5.4267	1.6104 (SI)	17.4625	-0.0989	32.1587 (SI)
InducedVoltage(Winding2) Setup1 : Transient	5.4059	1.6327 (SI)	17.6259	0.2824	31.6953 (SI)
InducedVoltage(Winding3) Setup1 : Transient	5.4997	1.6058 (SI)	17.6410	-0.1835	26.8411 (SI)

Fig. 8 (d): for Tr#4

Curve Info	rms	crestfactor	pk2pk	avg	distortion(50)
InducedVoltage(Winding1) Setup1 : Transient	5.4266	1.6104 (SI)	17.4625	-0.0989	32.1587 (SI)
InducedVoltage(Winding2) Setup1 : Transient	5.4059	1.6327 (SI)	17.6258	0.2824	31.6954 (SI)
InducedVoltage(Winding3) Setup1 : Transient	5.4997	1.6058 (SI)	17.6410	-0.1835	26.8412 (SI)

Fig. 8 (e): for Tr#5

Figure 8: Induced voltage of each winding and distortion level of the proposed transformer

Table 3 demonstrating the comparative analytical observations of transformers (Trf-1 to Trf-6), that verified the ANFIS based evaluation to provides effective power utilization. For optimal core material analysis the loss prediction has been an effective tool for harmonic spectrum estimation of the three-phase transformer at different instants.

Table 3: Comparative harmonic analysis of different transformers using Sugeno-type ANFIS model for different core materials

Transformers at different instants	Core material used	No load losses prediction (KW)	Permeability of material (iron/ferrite)	RMS value of induced voltage (KV)	Estimated no load efficiency	Distortion factor(g)	Minimum-Maximum THD (in
Trf-1	iron	46.3761	4000	9.8983	84.56	0.9993	3.74-3.88
Trf-2	ferrite	46.3427	1000	9.8983	84.89	0.9993	3.73-3.86
Trf-3	iron	-	nonlinear B-H curve	9.8883	87.11	0.9992	2.88-3.00
Trf-4	iron	5.4441	4000	6.4341	84.55	0.9993	3.74-3.88
Trf-5	ferrite	5.0423	1000	5.4440	83.97	0.9976	3.67-3.70

Table 4: Performance evaluation of proposed ANFIS based methodology

Performane parameters	Training	Testing
Mean Squared Error (MSE)	4.289	5.456
Average error at each instant	0.767	0.609
Accuracy of THD estimation based on simulation result (in percentage)	88.7	84.44

Fig. 10 showing the adaptive neuro-fuzzy designer tool using MATLAB simulation. The proposed ANFIS system successfully evaluated average training error (0.56708) as well as average testing error (0.079094) at each instant. From the ANFIS model, the prediction and evaluation of error have been an effective approach for harmonic distortion analysis. Therefore, various components of a power transformer can be tested accordingly and the ANFIS model can be designed for the desired rating of transformers.

For better efficiency the estimated THD range is 3-4%, which successfully lies within the IEEE standard. In Table 4, the highest efficiency of 87.11% was achieved at trf#3 instant with no loading conditions. On the other hand at that instants trf#3 of 11KV output voltage, THD is also reduced, as shown in Fig. 11. Therefore for non-linear load applications, the proposed model successfully employed using iron/ferrite core materials of the proposed power transformer.

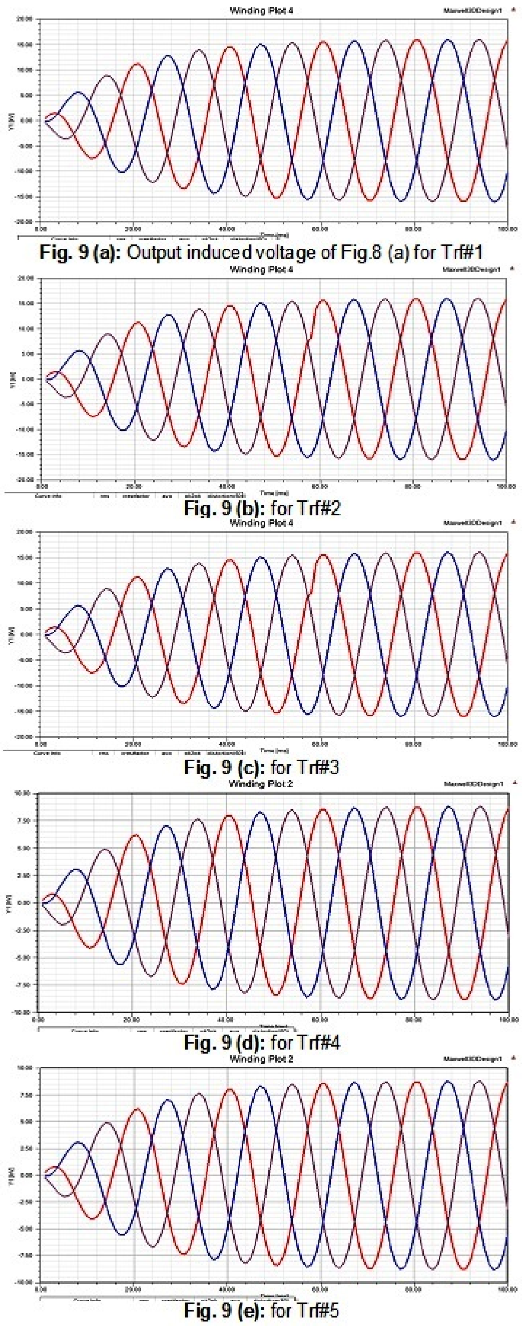

Figure 9: Induced output voltage corresponding to the Figure 8 (a)-(e)

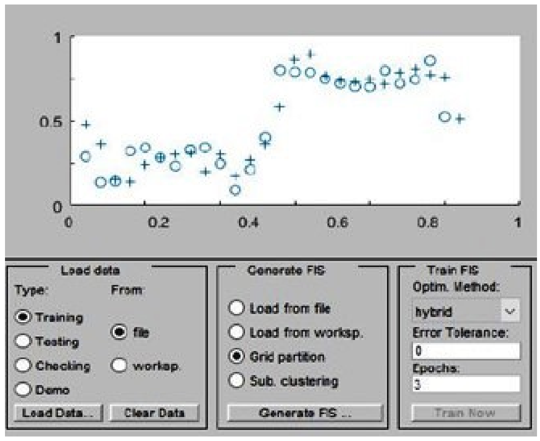

Figure 10: Function fit plot using neuro fuzzy designer tool in MATLAB simulation

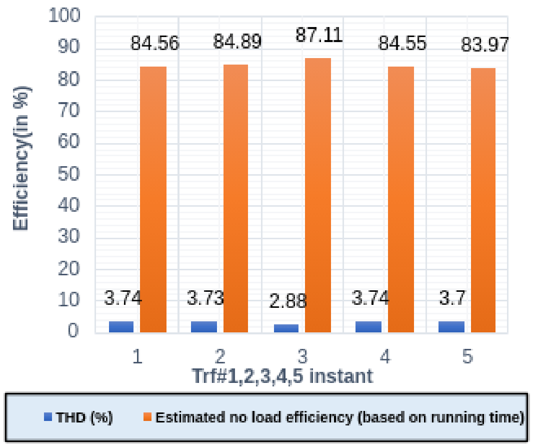

Figure 11: Efficiency vs. THD plot using iron core material [for Trf#(1,3,4) instant] and ferrite core material [for Trf#(2,5) instant]

6 Conclusions

This paper provided an effective approach for real-time harmonics monitoring of power transformers using ANFIS based model at different instants. Training of the proposed model employed for different core materials of the power transformer. The adaptive neuro-fuzzy system is employed for the design of different power transformer ratings (20KV and 11KV) at various instants. The error evolution of proposed methodology is shown in tabular form (Table 4), that providing better criteria for the selection of transformer core parameters. This research work has given insight into real-time utilization of the proposed MATLAB and ANSYS Maxwell simulation toolbox. The design and simulation provided an optimal approach for choosing the required input parameters. For real-time consideration, the selection criteria can predict better-expected life of a power transformer. In future research, novel techniques such as the implementation of neuro-genetic or finite element can be analysis to realize every small or micro-level effect on system parameters that directly affect overall transformer efficiency.

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