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

**Abstract**

The interfering nature of harmonic always causes various power qualities issues, that deduct the expected transformer life as well as efficiency to an uncertain limit. The optimal analysis of the harmonic spectrum on three-phase core power transformers can limit these power quality issues. This paper designs the Adaptive Neuro-Fuzzy Inference System (ANFIS) based estimation of loses and design parameters selection using different core material in three-phase power transformers. This paper, validating different factors which deteriorating the power quality, harmonic distortion and efficiency in power transformer. The ANFIS based analysis provides an optimal solution to resolve the harmonic reduction and gives rise to the improvement of overall efficiency. Also, this paper focuses on the comparative study of various core parameters for three-phase core transformers, that are responsible for harmonics distortions. In this paper, the ANFIS model designed for iron and ferrite core material that suitable for improving the overall efficiency of the transformer in the ANSYS Maxwell simulation. The estimation of Total Harmonic Distortion (THD) and enhancement of THD contributing to the optimal core martial. The design of three-phase power transformer and the performance evaluation of 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

Since, the global population is increasing and every industry is growing, thus the global consumption of power is getting increase day by day [1]. Thus, there is a need of more power. More power means more energy generation with more reliable power system components like power transformer. So, 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 oriented such as distribution transformer etc. Its application is based on the frequent needs and implementation purpose. Transformer plays a vital role in other units, which are available in the compact form whether for rectifying or low frequency application purpose. For better power transformation, it is important to have a better working environment and good working condition of the transformer which combines to form efficient operation. Transformers have different types of loads, that they are designed to deliver step-up or step-down voltages and currents. The transformer’s condition naturally drops during its operation because of the process of ageing [2]-[3]. Ageing of the transformer increases due to overheating caused by overloading [4]. The design of a transformer is a very tough task in which several engineers focuses to accomplish compatibility with the standard while minimizing the overall costs and greater efficiency [5]. The power transformer is also perilous equipment of power transmission system, which needs the fault clearance tendency in them, attending to with topmost insistence [6]. Uncertainty a fault remains unnoticed then, it may cause internal damages in the transformer and will lead as severe inefficiency [6]. Fault development can occur on internal or external structures of transformers. It can be present in the system with a low damaging quality or can be the dangerous one. The dangerous ones can also lead to power failure, outage etc. To stop these occurrences of faults it is advised to clear the faults and detect it on time. Therefore, the overall protection of the internal system is a vital portion for maintaining the transformer protection [7]. The presence of harmonics and their distortions in the output of a transformer may lead to faults. They are the hurdles in the power transfer, which takes place between the systems. Conventional power system structure had very slightly less requirement to the transaction with harmonics because generally, loads are linear [8]. The main cause of harmonics is mainly nonlinear loads [9] further these nonlinear devices made the power system more complex [10].

|  |
| --- |
| Fig.1. Harmonics and related spectrum of output waveform |

The harmonics lead to power loss which increases the operational and maintenance costs. This further leads to severe heating in the transformer and fatigue of insulation [11]. Fig.1 showing the representation of harmonics. The harmonic distortions are also responsible for other problems like noise on telecommunication noise, over-temperature on electric equipment, electric stress, resonances, etc. [12].

1. Concepts and Technical Approach

Total Harmonic Distortion (THD) is a mathematical quantity of harmonics, that existing in an electrical signal that is termed as the ratio of the summation of powers for entire harmonic components to the power of the fundamental frequencies [13]. Mathematically THD is represented as:

(1)

Here, g is the distortion factor which is defined as the measure for the intensity of the nonlinear distortions [14]. Mathematical relationship of THD and g is express as [15].

(2)

In equation 2, representing voltage harmonics (in RMS and ‘h’ is the harmonic order) and is showing the fundamental voltages (in RMS). The effect of harmonics has the following disadvantages on the transformer [16] such as Core and copper losses increases, increase in the electromagnetic (E/M) and electrostatic interference with communication circuits, Increase in dielectric stress on insulation and Generation in resonance. Nowadays new intelligence-based computational techniques have given an idea for estimation of these occurrences.

These techniques may include; fuzzy logic, artificial neural network techniques, genetic algorithms, PSO based monitoring systems etc. ANFIS is also one of the vital intelligence-based techniques. Adaptive neural-network-based fuzzy inference system, which is a hybrid of ANN and fuzzy logic controller that is based on different interference systems such as Takagi–Sugeno fuzzy inference system [17]. These systems correspond to IF-THEN rules, which are capable of handling non-linear operations. Therefore, the ANFIS tool is measured as the collective estimator. A typical Takagi-Sugeno fuzzy-based model has a basic system with the following form; When input-1 is given as ‘x’ and input-2 as ‘y’ then output ‘z’ is in the form of:

*Output (z) = ax + by + c* (3)

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

*a = b = 0* (4)

The following fig.2 shows the working of ANFIS on a proposed system or a plant projected according to the desired environment.

**ANFIS**

**Controller**

**Transformer**



**ANSIS inverse controller**

**(Z)**

**ANFIS based learning algorithm**

**Inputs**

Fig.2. Framework showing ANFIS controller in a transformer plant

In 2017, J. Fan proposed an idea over DGA (Dissolved Gas Analysis) which is a widespread technique to diagnosis internally faults in the power transformers, that to form a hybrid-based technique, which associates the Relevance Vector Machine (RVM). The ANFIS to highlight the problem over some of the observed data for the study, with uncertain conditions, which leads to the undiagnosed of traditional techniques [18-19]. In this research, the author has done the experiments and find out the results for demonstrating that the hybrid RVM based ANFIS technique can accomplish the high accurateness percentage as high as up to 89-94% [20]. Transformer life estimation and their breakdown diagnostics are always significant problems for the various power utilities. Similarly, in the same year 2017, A. Majzoobi, presented research work on the ANFIS designed model of the power transformer for the loss of life, which is based on hourly based estimation. Here the author took the standard parameters like ambient temperature with their load level as the key components of degradation for power transformer. Here the transformer is a very important component which is to be well maintained. In 2018, S. Forouhari and A. Abu-Siada, presents a new ANFIS based decision prototype to estimation the overall life of mineral-oil-filled power transformers. Here, the authors introduced an integrated asset supervision prototype on the basis of some analytical pointers [22]. In early 2018, Jongwan Kim did a researched on the performance of shunt phase shift transformer in which effect of line conductor on the cancellation was observed. Jongwan Kim has mathematically derived the relationship between source impedance and harmonic cancellation [23].

In 2019, Jian Feng did research in which current analysis method was proposed to suppress harmonics in the SMES (superconducting magnetic energy storage) technology. The author has done verification of theoretical analysis to the simulation and experimental verification has been done [24].

1. Optimal Parameters for System Design

There are four stages involved in the designing of proposed ANFIS model, which are as following:

## *2.1. Data collection and normalization*

In this stage data is collected and accumulated so as for the generation of input values to the designed model with some specific parameters. The best combinations have been introduced for the inputs which are:

**a).** Three phase input voltage to the transformer.

**b).** Induced rms (root mean square) voltage.

**c).** Change in winding resistance.

**d).** Core losses.

## *2.2 Training of ANFIS based proposed model*

The training dataset is implemented for designing of the proposed ANFIS based model with a defined combination of the membership function. The selection of a membership function is done, and the model has trained accordingly to the set of training data. Then the model is trained for finding best satisfying combinations of the inputs.

## *2.3 Modelling of ANFIS based proposed model*

With the use of testing data sets the model went through some training and testing for the requirement of calculation of the error generated in the model. There are some parameters based on the criteria from which ANFIS proposed model is tested accordingly which are as follows: Mean squared error (MSE) is defined as the Mean squared error which finds out the average of all the defined error’s square means the average of the squared difference between the estimated values and what is estimated that is error [25]. Average testing or training error gives an idea of the average of the generated error gone through training and testing of the error in the proposed model.

## **3. Validating of ANFIS Accuracy**

It provides an idea of degree of preciseness to the measured value that is based on the practical results of training and testing of the proposed model. Following parameters are taken accounts for the overall accuracy of the system:

*3.1 RMS value of induced voltage:* Here root mean square values of induced voltages have been taken in account of calculation of the distortion factor (g). The distortion factor is given as:

*g =* (5)

*3.2 THD predicted:* It is estimated as the total harmonic distortion in the proposed ANFIS model of the transformer designs.

In this research paper, the transformer model is designed with specified parameters from which Total Harmonic Distortion (THD) have been found mathematically and then compared with the results of the ANFIS Controller [25]-[26].

This manuscript consists of four sections: Section I consists of an introduction to the idea and objective of the paper, Section II; this section consists of the concepts and technical approach. Section III; it consists of the optimization parameters and further calculations and results based on the models with mathematical formulas and ANFIS controller. The last section consists of the conclusion and future scope of the ANFIS based proposed methodology.

**4. Description of 3-Phase Transformer Model**

The system presented in this paper contains the proposed mode of a three-phase transformer with some defined parameters and then the ANFIS technique has been used. Here is the modeling of proposed transformer based on the design parameters referred in fig.3. Design analysis of proposed three-phase transformer done in the ANSYS (Analysis sy**s**tems simulation) environment.

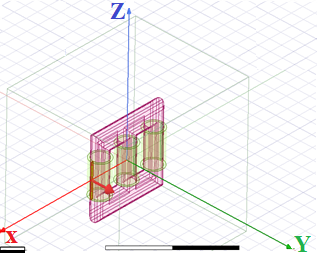


Fig.3. Transformer designed model in ANSYS toolbox

Table 1. Specification of transformer design at different case study

| S. No | Comparative analysis on different configuration of transformers | | | | |
| --- | --- | --- | --- | --- | --- |
| ***3 Phase input voltage*** | ***Core***  ***material*** | ***Linear B-H curve*** | ***Transformer***  ***designs*** | |
| 1  2  3  4  5 | 20KV  20KV  20KV  11KV  11KV | iron  ferrite  iron  iron  ferrite | yes  yes  nonlinear  yes  yes | | Trf#1  Trf#2  Trf#3  Trf#4  Trf#5 |

In the above Table.1 showing comparative analysis and the description of design base and their specification for proposed model designs.

* **Transformers (Trf#):** These are the different types of designed transformer models based on some parameters in the ANSYS Software. They have been particularly designed for the ANFIS model.
* **Core material used:** The material used for the core of transformer is iron and ferrite having following specifications as referred in table.2:

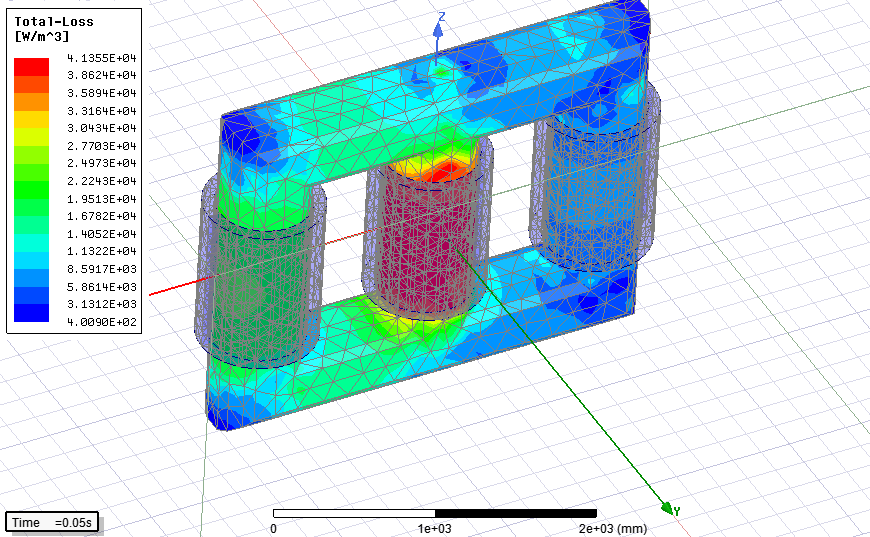


Fig.4. Iron material total loss (refer in table2) using ANSYS design toolbox

Table 2. Different parameters that depends on the overall performance

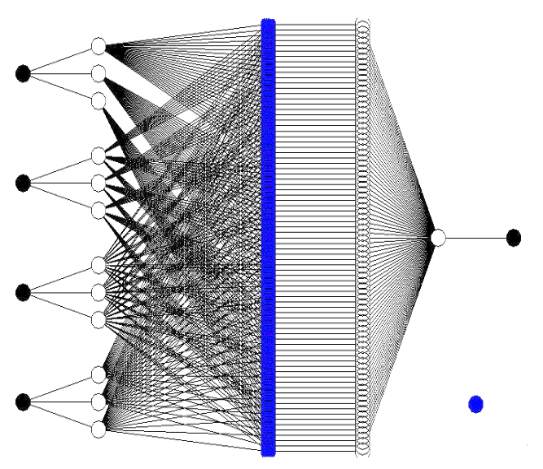
|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *Core*  *Material* | | *Relative*  *Permeability* | *Young’s Modulus*  *(N/m2)* | *Poisson’s*  *Ratio* | *Bulk Conductivity*  *(Siemens/m)* | *Mass Density*  *(w/kg)* |
| Iron  Ferrite | 4000  1000 | 1.95×  1.19× | 0.28  0.0 | 1.03×  0.01 | 7870  4600 |

Total losses of different core materials directly affect the efficiency of the transformer. Efficiency can be estimate based on the total loss predication. Fig.4 showing the total losses associated with iron material in ANSYS toolbox. In this model, Iron/ferrite core material employed because of its appropriate distribution for convergence values with high magnetic field density.

**5. ANFIS MODELLING**

The ANFIS system is a category of hybrid-based learning rule having both combination of ANN and fuzzy logic controller for computational as well as logical analysis. After that selection of membership function training and testing of the functions will be perform. If the results are satisfactory then it goes for selection of membership functions type otherwise again it reselects the functions. Then again training and testing is done. This whole loop process goes on until the satisfactory values are obtain and after that, it compares with the satisfactory ANFIS model unavoidable. This structure of ANFIS consists of nodes that are the one in which some or all may be adaptive.

The adaptive quality contributes to the quality of output of the particular node, being dependent based on specified constraints of different nodes while for others may be the nodes are fixed which means that the output of these nodes are depends on the output of preceding layer. Directional links are used to link the nodes of various layers by providing a way for the flow of signal without any allocation of different weights based on desired output.



**INPUT**

**INPUT MF**

**RULE**

**OUTPUT MF**

**OUTPUT**

**3ф input**

**voltage**

**(KV)**

**Induced**

**RMS** **voltage**

**(KV)**

**Core losses**

**(KW)**

**Change in**

**resistance (mΩ)**



**Logical Operations**

**AND**

Fig.5. Simulation of proposed ANFIS based model

There are 5 layers in the ANFIS model of the proposed system. The layers are represented as adaptive or fixed nodes layers which are interlinked or linked through the directional links. Refer in fig.4 the first layer comprises with four inputs nodes: where each node is representation of fuzzy logic sets. The response of nodes for the input of next layers, which is the belongingness degree of the input given to the fuzzy set.



Fig.6. Membership functions of FLC system for inputs and output

The layer 2 consists of input membership functions as and so on until which represents the degree of membership as an extension of valuation referred in fig.6. Layer 3 represents the rule-based layer in which input is given in a rule-defined manner. Layer 4 contains the output membership functions and layer 5 consists of the single output. In this model. Sugeno type ANFIS model. The number of inputs is 4, and outputs are 1, while total rules base is 81, while “And Method” is taking as 'prod' and “Or Method” is taking as 'probor', and defuzzification method is taking as 'wtaver'. Our ANFIS techniques identifying each harmonic in per cent related to the fundamental frequency. There are certain physical parameters such as type of core materials employed, permeabilities. etc. The ANFIS implementation and description of a different functional block for the proposed methodology are as follows.



Fig.7. Flowchart of proposed hybrid neuro fuzzy based ANFIS model

From the figure.7 the following conclusions can be made. For calculation of THD in different designs of transformers two criteria of inputs have been taken in account that are:

*5.1. Evolution of harmonic rate:* It consists of the factors which effect the harmonic calculations in the transformer referred in table.3 [27].

*5.2. Factors depending on the harmonics:* There are several factors which gets affected by the harmonic generation in the transformer:

* Data interpretations are analyzed followed by the selection and correlating input variable parameters.
* Normalization of raw data sets are done through training and testing of the sets.
* In this criteria requirement of fuzzy surface view is checked [28]. If it meets the requirements, then it goes further otherwise it again normalize raw datasets again and repeat the steps. Then, it calculates percentage of error evolved and the process is completed.

# **6.** **Results and Discussion**

Here are the tabulated forms of induced voltage based on different instants which are as follows. For the following figures.9 contains the output results of the three phase transformers. Here, x axis: time (in ms); y axis: Induce voltage (in kV) using ANFYS model.

|  |
| --- |
| Fig.8 (a). Transformer parameters of Trf#1 in ANFYS toolbox |
| Fig.8 (b). for Trf#2 |
| Fig.8 (c). for Trf#3 |
| Fig.8 (d). for Trf#4 |
| Fig.8 (e). for Trf#5 |



Fig.9 (a). Output induced voltage of Fig.8 (a) for Trf#1

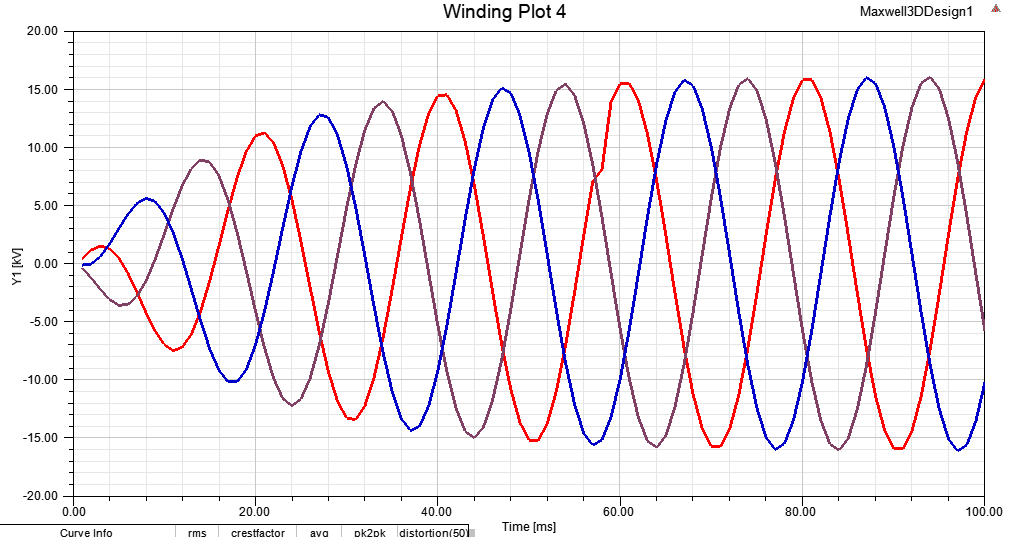


Fig.9 (b). for Trf#2

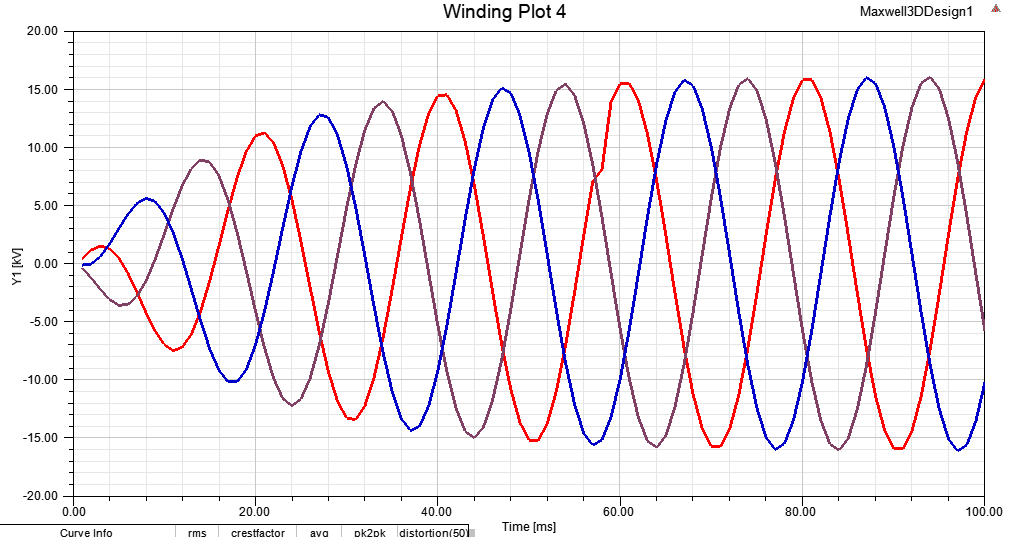


Fig.9 (c). for Trf#3

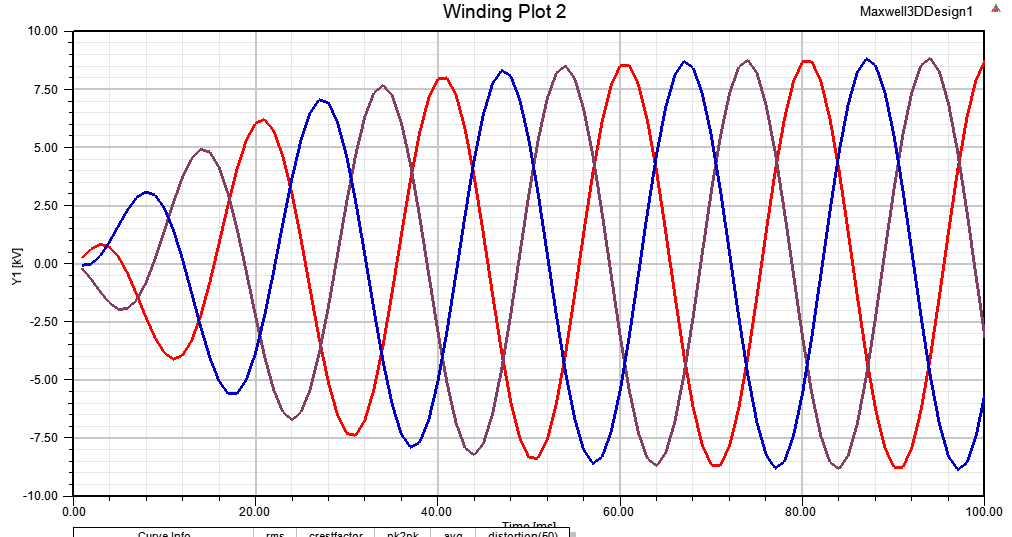


Fig.9 (d) for Trf#4

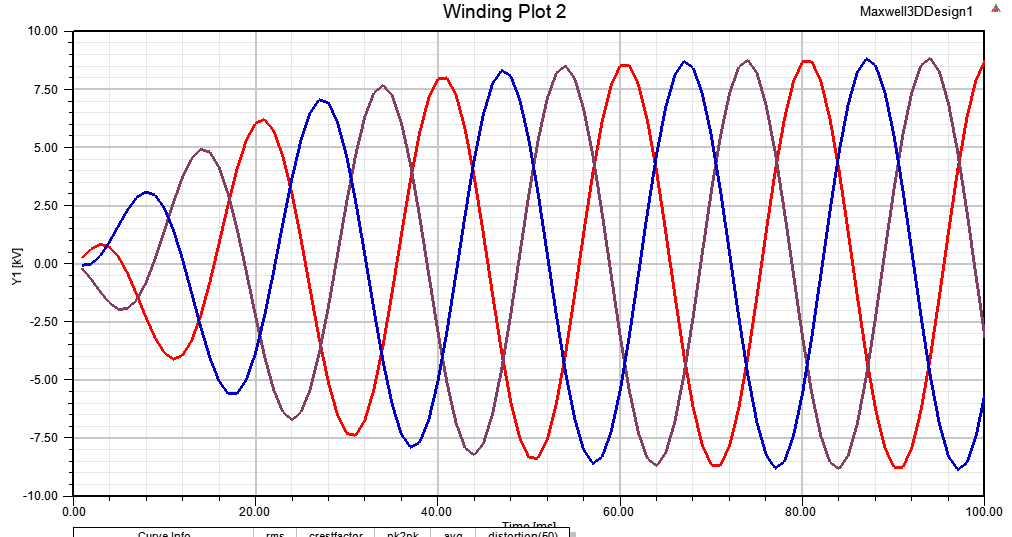


Fig.9 (e). for Trf#5

From the above-mentioned fig.9 THD has been calculated mathematically which is depicted in the following table.3. Estimated THD range within 5%, which is successfully lying in between the IEEE standard. ANFIS based approach monitoring the Higher component harmonics in real time. The proposed technique efficiently measured the harmonics corresponding to induced voltages in different windings of transformer. The IEC based harmonic standard TR-(61000-3-4:1998) [29] provides the protection scheme for transformer under various conditions.

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

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *Transformers at different instants* | *Material*  *used* | *No load losses prediction*  *(KW)* | *Permeability of material*  *(iron/ferrite)* | *RMS value of induced voltage (KV)* | *Estimated no load % efficiency (**based on running time)* | *Distortion factor*  *(g)* | *THD predicted*  *(%)* |
| 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 | 5.4441 | 84.55 | 0.9993 | 3.74-3.88 |
| Trf#5 | ferrite | 5.4423 | 1000 | 5.4440 | 83.97 | 0.9976 | 3.70-3.67 |

In Table.3, the comparable analytical observations verified the usage of ANFIS model in better way of understanding harmonic analysis of a three-phase transformer in changeable environment.

TABLE 4. Performance evolution of proposed ANFIS based methodology

|  |  |  |
| --- | --- | --- |
| Parameters | Training | Testing |
| Mean Squared Error (MSE) | 88.57 | 89.56 |
| Average Testing/Training Error (ATE) | 0.567 | 0.709 |
| Accuracy of prediction based on practical result (In %) | 88.7% | 76.44% |

The following fig.10 shows the neuro fuzzy designer model using MATLAB simulation. The proposed system for the evolution of testing error, which is 0.079094. From ANFIS model the prediction and evolution of error was better understood for the harmonic and distortions analysis. Therefore, any component of transformer can be tested accordingly and ANFIS Model can be designed for more and others required parameters.

![A picture containing graphical user interface, chart, scatter chart

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Fig.10. Neuro fuzzy designer results in MATLAB simulation

Estimated THD range within 3-4%, which is successfully lying in between the IEEE standard with better efficiency but highest efficiency at trf#3 instants which is 87.11% at loading conditions. On the other hand, at instants trf#3 THD is also reduced shown in fig.11. Therefore, for non-linear load applications proposed core materials can be practically employed based on the desired output voltage of power transformers.

Fig.11. Analysis of power transformer efficiency VS THD using iron core material for Trf#(1,3,4) instant and ferrite core material for Trf#(2,5) instant

# **7. Conclusions**

In this paper, the ANN-based error prediction system provides an idea of average testing. Training of the proposed model. While fuzzy system is employed for the design of different ratings power transformer at various instants. For ANFIS Model an error evolution of proposed methodology is shown in tabular form (table 4) that gives a criterion for selection of input parameters. The research work done gives an idea of proposed methodology for the real-time utilization of both the software’s MATLAB as well as ANSYS Maxwell design toolbox. Design and simulation provide an idea of choosing the required parameters used for the better selection criteria of three phase transformer. The prediction of the transformer’s expected life can also be taken into account for better results using AI techniques. Novel techniques such as finite element analysis can be implemented to realize every small or micro-level effect of any parameters, which directly affects transformer efficiency.

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