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Modeling and Analysis of Transformer Inrush current using ANFIS

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ABSTRACT
This paper presents a new technique for modeling of transformer inrush current using adaptive neuro-fuzzy inference system (ANFIS) as a type of soft computing (SC) techniques. AMATLAB/Simulink simulation of the three phase transformer is described. Inrush current at different switching instants, supply resistance and remnant flux are simulated. The proposed ANFIS network is trained off-line to identify the peak and 2nd harmonic of inrush current based on switching instants, supply resistance and remnant flux. The new approach indicates accuracy, robustness and effectiveness.

Index Terms**:** Transformer inrush current; Soft computing techniques; Adaptive neuro-fuzzy inference system.

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NOMENCLATURE

$i(t)$	Instantaneous Inrush current (λ)
V_m	Maximum applied voltage (V)
Z_t	System and transformer impedance (Ω)
t , t_o	Time and time at which core saturates (sec)
K_w	Winding factor
K_s	Constant of short circuit power of network
α	Function of time
φ	Energization angle
τ	Time constant of transformer winding
B_N	Nominal flux density of transformer core
B_R	Remnant flux density of transformer core
B_S	Saturation flux density of transformer core
θ	Switching instant (angle)
R_s	Source resistance
n	the rank of the harmonics
H_n	The magnitude of n^{th} harmonic component
T, f	The periodic time and frequency of system
a_n ,b_n	The Fourier coefficients

I. INTRODUCTION

Power transformers are critical components in power system networks and are the most expensive and vital equipment in substations of electric power systems. The high non-linearity of the iron core reflects into a current waveform that is rich in harmonics. The typical harmonic content of a transformer inrush current waveform includes 62 % of 2nd harmonic and 55% of DC component of fundamental power frequency [1]. In addition, inrush currents caused by transformer energization can reach magnitudes of 10 to 20 times the nominal Full-load current of a transformer [2-3]. As well, inrush currents can approach 70 to 90 % of the short circuit current level [4]. Moreover, the duration of inrush currents may last from tens of cycles up to few minutes for large power transformers. The nature of inrush currents leads to adverse effects on the transformer itself as well on to protection system's performance and power quality. Transformers are more subjected to switching operations, and, consequently, inrush currents. The compression of transformer windings during inrush conditions increases the risk of insulation failure [5]. One of the major problems with transformer inrush currents is the false operation of protection during inrush conditions. This subject has been of great interest to many researchers [6].

So the detection of the value of the second harmonic component and the peak value of the transformer inrush current wave form is very important [7 – 9].

Inrush current was calculated by numerical calculation [10], semi analytic solution [1], analytic formula, coupled electromagnetic model [11] and detection algorithm for digital computer [12]. ANN Model is used for modeling and simulation which gives relatively good performance [13-14].

This paper introduces a novel method for modeling and simulation of transformer inrush current at different operating conditions using Adaptive Neuro-Fuzzy Inference System (ANFIS) which is widely used in the industry. The main objective of this study is to estimate the peak inrush current and second harmonic current based on different operating conditions. Inrush current can be measured by instruments for small rating transformers but measurement issues arises in large rating of transformer due to large electromagnetic transient forces. Hence, there is a need of a system which can predict maximum inrush current and harmonics for large rating of transformer. The peak and 2nd harmonic of inrush current are quickly identified for a new operating point as a function of the switching instants, supply resistance and remnant flux. This function is a complex non-linear one; therefore ANFIS is trained to map this function accordingly.

II. ANALYTICAL MODEL OF TRANSFORMER INRUSH CURRENT.

Transformer Inrush current is classified into three types;

1- Initial Inrush Current:

This type of the inrush current occurs when the transformer is switched-on to the supply.

2- Recovery Inrush Current:

This type of the inrush current occurs after a fault external to the transformer is cleared. The recovery inrush current is always less than the initial inrush current.

3- Sympathetic Inrush Current:

This type of the inrush current is a somewhat unusual event, but occurs often enough, when a transformer is connected in parallel with a second energized transformer.

Generally inrush current contains DC offset, odd harmonics, and even harmonics Figure 1 shows the generation of inrush current in transformer. As seen from the figure, exceeding flux from the knee point of saturation or magnetization curve, results in large magnetizing current that in some circumstances can be ten times the rated current in a power transformer.

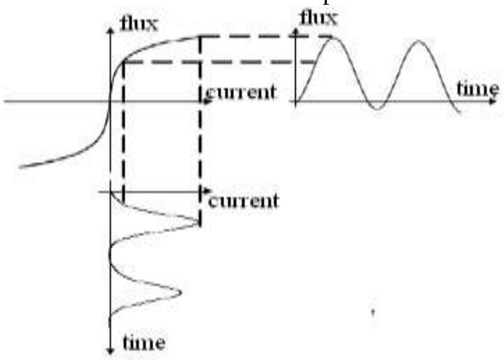

Fig.1. Generation of inrush current in transformer.

The general equation for the amplitude of inrush current as a function of time can be expressed as [13];

$$i(t) = \frac{\sqrt{2}V_m}{Z_t} * K_w * K_s * [\sin(\omega t - \varphi) - e^{-\frac{(t-t_o)}{\tau}} \sin\alpha] \quad (1)$$

For the use of designing a protective system for transformer, the maximum value of inrush current is an important factor. In these cases, a simplified equation can be used to calculate the peak value of the first cycle of the inrush current. This equation is as follow [13];

$$i_{peak} = \frac{\sqrt{2}V_m}{Z_t} * \left(\frac{2\,B_N + B_R - B_S}{B_N}\right) \quad (2)$$

Also second harmonic components of inrush current, can be calculated as follow at n=2, [15];

$$H_n = \sqrt{a_n^2 + b_n^2} \quad (3)$$

Where,

$$a_n = \frac{2}{T}\int_{t-T}^{t} i(t)\cos(n\,.\,2\pi f.\,t)\ dt \quad (4)$$

$$b_n = \frac{2}{T}\int_{t-T}^{t} i(t)\sin(n\,.\,2\pi f.\,t)\ dt \quad (5)$$

As seen from equations (1) to (5), the value of inrush current and its harmonic are dependent on the parameters of transformer and operating conditions. So a comprehensive analysis for finding the relations between the inrush current characteristics and these factors are needed.

Switching instants, supply resistance and remnant flux are the factors influencing the magnitude and duration of magnetizing inrush current.

III. SIMULATION AND ANALYSIS OF TRANSFORMER INRUSH CURRENT.

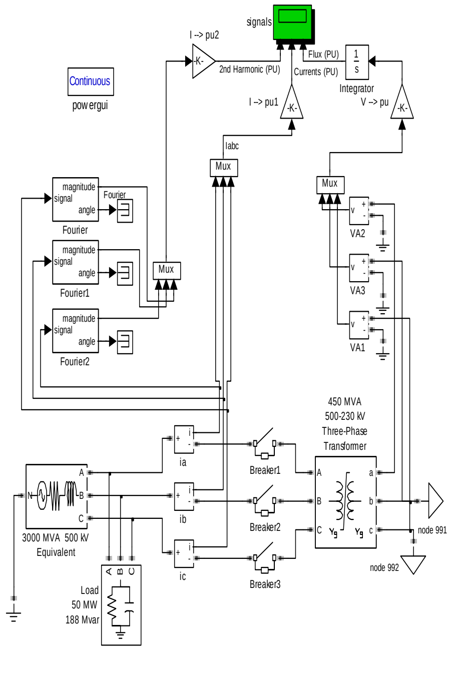

Fig.2. MATLAB Simulink Model for evaluating transformer inrush current.

Simulation was carried out for collecting various data sets using MATLAB/Simulink Model as shown in figure 2. This model considers data of first few cycles. These data sets include values of inrush current and harmonic content at different operating conditions but frequency remains constant i.e. 60 Hz.

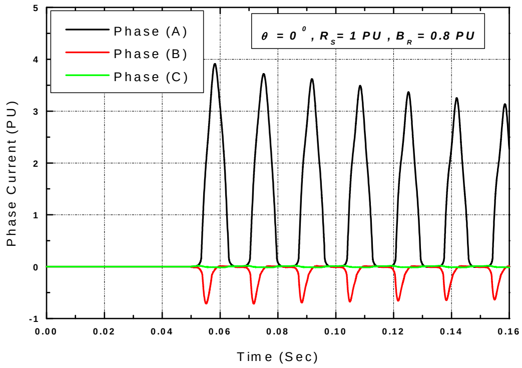

Fig.3.Variation of Inrush phase current with time.

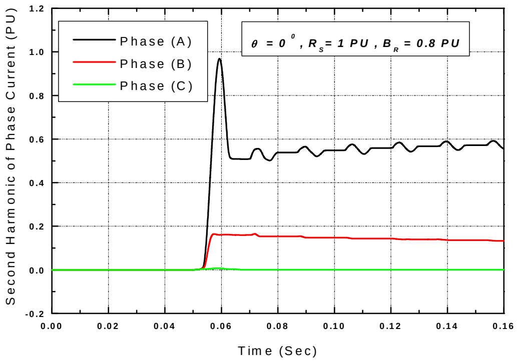

Fig.4. Variation of 2nd harmonic of phase current with time.

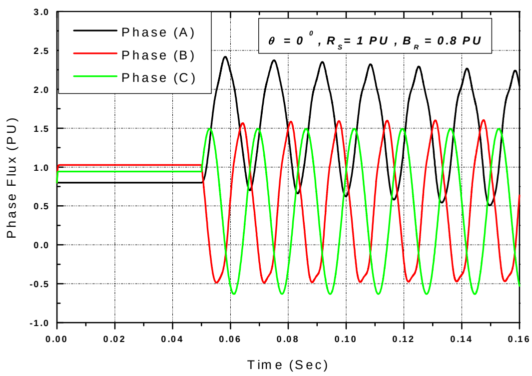

Fig.5. Variation of phase flux with time.

Inrush Currents, 2nd harmonics and phase flux for studied transformer have been shown in Figs 3, 4 and 5.
The peak value of inrush current is 3.9 PU and its second harmonic is 90 %. Phase A is the highest inrush current among all phases.

IV. INRUSH CURRENT WITH DIFFERENT SWITCHING ANGLE

In this section, the effect of switching angle variation on the characteristics of inrush current has been investigated. The remnant flux (Br) for all switching angles is 0.8 PU. Also the source resistance has been considered to 1 PU. Figs 6 and 7 show the effect of different switching angles (θ) on the amplitude of inrush current and its second harmonic for phase (A). As seen from the figure, the highest amplitude of inrush current is at 0°. Also, it can be seen, increasing the switching angle will decrease the amplitude of inrush current and its second harmonic.

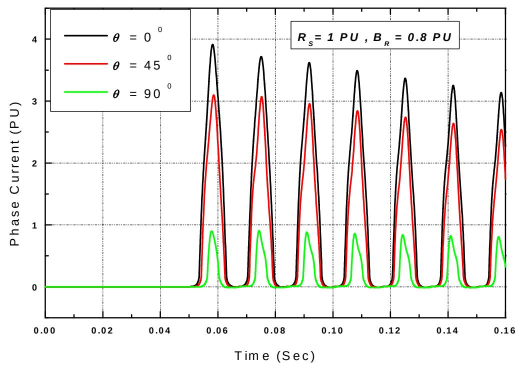

Fig.6. Variation of inrush current of phase (A) with time at different switching angle.

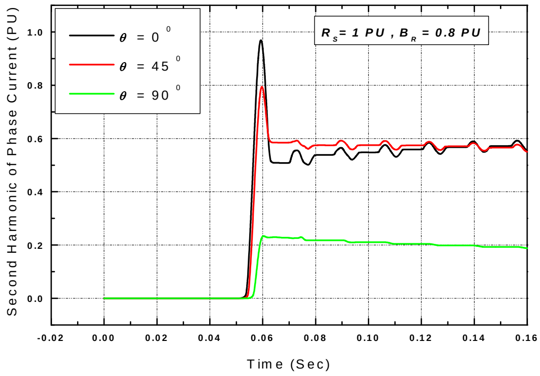

Fig.7. Variation of 2[nd] harmonic of phase (A) current with time at different switching angle.

Figs 8 and 9 show the variation of peak Inrush current for all phases with different switching angles (θ) and the second harmonics for all phases. As seen from the figure, the highest amplitude of inrush current is at 0°. Also, it can be seen, increasing of the switching angle will decrease the amplitude of inrush current and its second harmonic with certain ranges.

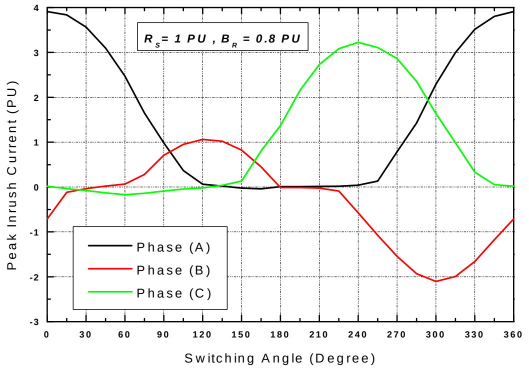

Fig.8.Variation of Peak inrush currents with switching angle.

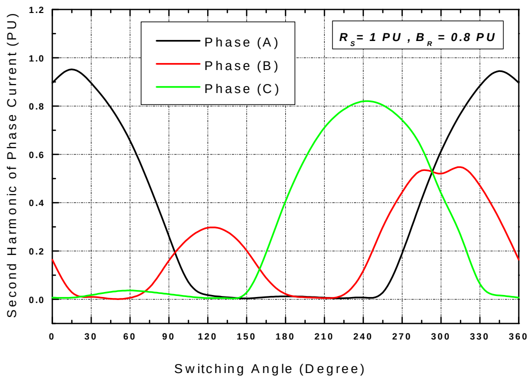

Fig.9.Variation of 2nd harmonic of inrush current with switching angle.

V. INRUSH CURRENT WITH DIFFERENT SOURCE RESISTANCE

In this case, the switching angle (θ) is 0°. Also, the remnant flux (Br) is the same as the previous kept equal to section. The effects of source resistance have been considered. Figs 10 and 11 show the effect of source resistance on the amplitude of inrush current and its second harmonics for phase (A).

As seen from figure, increasing source resistance will decrease the amplitude of inrush current and its second harmonic.

Figs 12 and 13 show the variation of peak Inrush current for all phases with different source resistance and its second harmonics for all phases. As seen from the figure, the highest amplitude of inrush current is at Rs= 1 PU. Also, it can be seen, increasing of the source resistance will decrease the amplitude of inrush current and its second harmonic

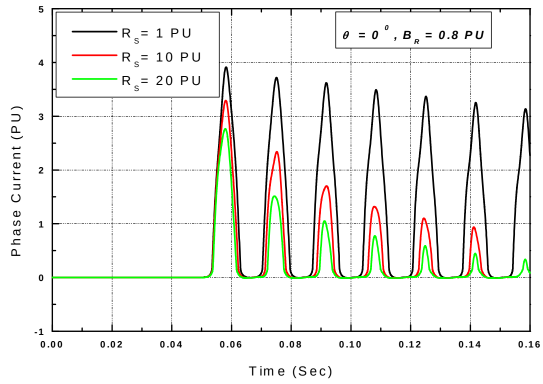

Fig.10. Variation of inrush current of phase (A) with time at different source resistance.

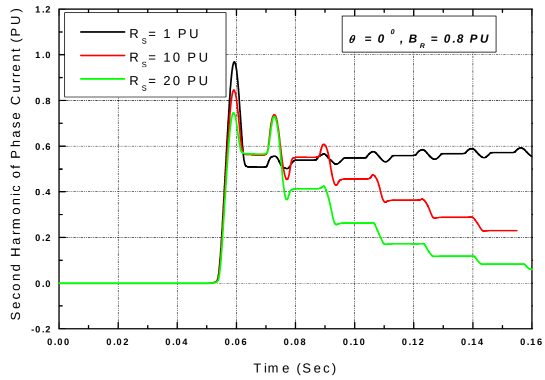

Fig.11. Variation of 2nd harmonic of phase (A) current with time at different source resistance.

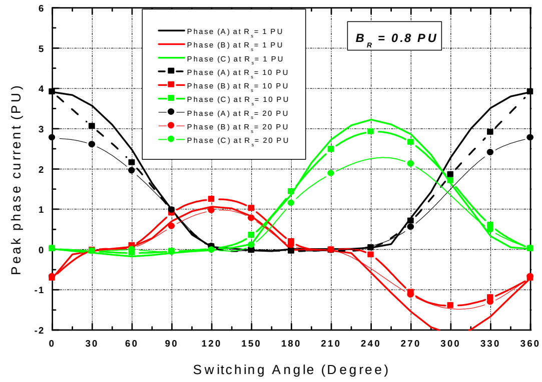

Fig.12.Variation of Peak inrush currents with switching angle at different source resistance.

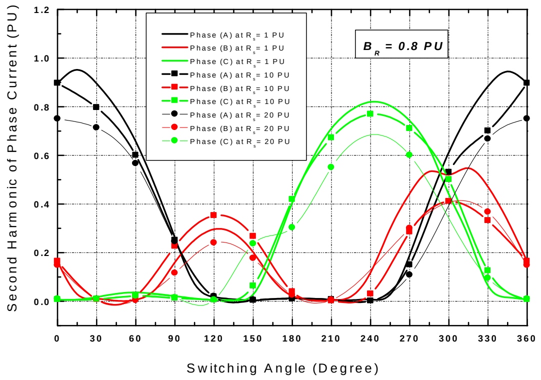

Fig.13.Variation of 2nd harmonic of inrush current with switching angle at different source resistance.

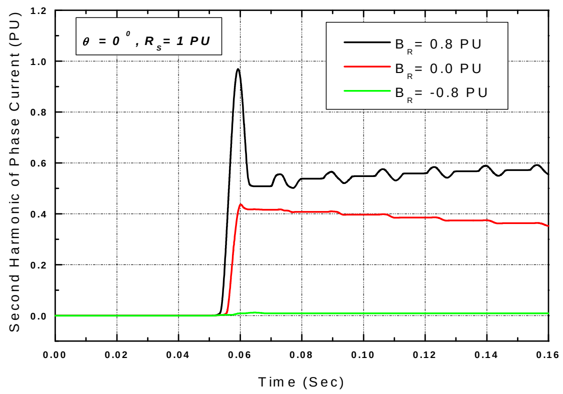

Fig.15. Variation of 2nd harmonic of phase (A) current with time at different remnant flux.

VI. INRUSH CURRENT WITH DIFFERENT REMNANT FLUX

In this case, the switching angle (θ) is kept equal to 0°. Also, the source resistance is 1 PU. The effects of the remnant flux have been considered. Figs 14 and 15 show the effect of remnant flux on the amplitude of inrush current and its second harmonic for phase (A).

As seen from figure, increasing remnant flux will decrease the amplitude of inrush current and its second harmonic.

Fig. 16 and 17 show the variation of peak Inrush current for all phases with different remnant flux and its second harmonics for all phases. As seen from the figure, the highest amplitude of inrush current is at BR= 0.8 PU. Also, the results indicate that switching at θ=90° or Br=0 may not necessarily reduce the magnitude of inrush current. So, for reducing inrush current, an appropriate switching angle by considering remnant flux must be selected.

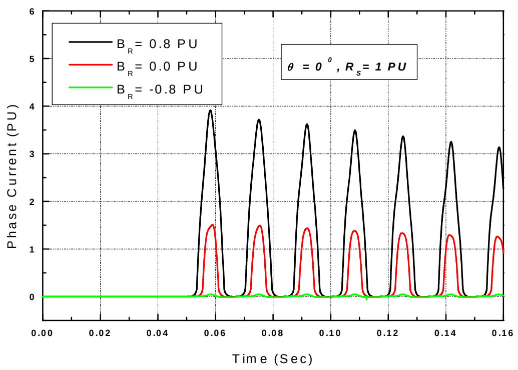

Fig.14. Variation of inrush current of phase (A) with time at different remnant flux.

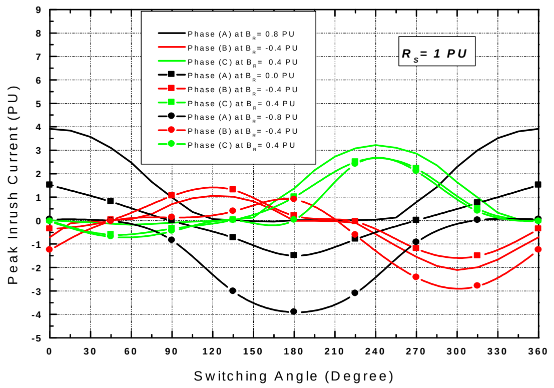

Fig.16.Variation of Peak inrush currents with switching angle at different remnant flux.

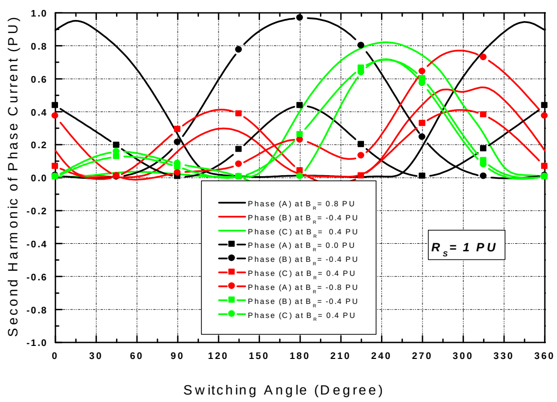

Fig.17.Variation of 2nd harmonic of inrush current with switching angle at different remnant flux

VII. ANFIS FOR INRUSH CURRENT IDENTIFICATION

It is noted that the equations of the transformer inrush current and its second harmonics are non-linear, resulting in a complex mathematical model. As it is desired to reach the amplitude of inrush current and its second harmonics accurately and fast due to change in the transformer operating conditions, it is better to use ANFIS technique.

This can be mathematically expressed as follows;

$$\%\, i_{peak} \text{ and } \%\, H_2 = f(\theta, R_s, B_R) \qquad (6)$$

Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid intelligent system which consists of a combination of fuzzy inference system with neural network. The deal with linguistic expressions understandable to human experts (if-then) rules and the ability of being trained by samples of input output data are the main advantages of ANFIS.

It uses a fuzzy system to represent knowledge in a linguistic way and has the learning ability of neural network that can adjust the membership functions parameters directly from data in order to improve the system Performance [16].

The ANFIS model is based upon a first order Takagi–Sugeno model five-layer architecture [17]. ANFIS is much more complex than the fuzzy inference systems, and is not available for all of the fuzzy inference system options. An error occurs if FIS structure does not comply with some constraints, one of these constraints is ANFIS has a single output, obtained using weighted average defuzzification [18]. So two ANFIS networks can be used for a two outputs(Peak inrush current and its second harmonic) system working in parallel with the same inputs patterns.

In the first layer of the two models, the Switching angle θ, supply resistanceR_s , and remnant flux B_R, multiplied by respective weights, are each mapped through three fuzzy logic membershipfunctions.

For ANFIS model has Peak inrush current as an output, membership functions are chosen to be Gbell membership function for all the inputs where it is given a good outputs compared the others membership functions as shown in Fig.18. With RMSE = 0.055231.

For ANFIS model has second harmonic as an output, membership functions are chosen to be Gbell membership function for all the inputs where it is given a good outputs compared the others membership functions as shown in Fig. 18 With RMSE = 0.018376.

In the second layer, the minimum error value of three input weights is calculated by rules firing strengths determination. In the third layer, normalize the rules firing strengths.

In the fourth layer, compute the contribution of each rule towards the overall output.

In the fifth layer, compute the overall output as the summation of contribution from each rule. A hybrid-learning algorithm that combines the gradient method and the least squares is estimated to learn parameters [19].

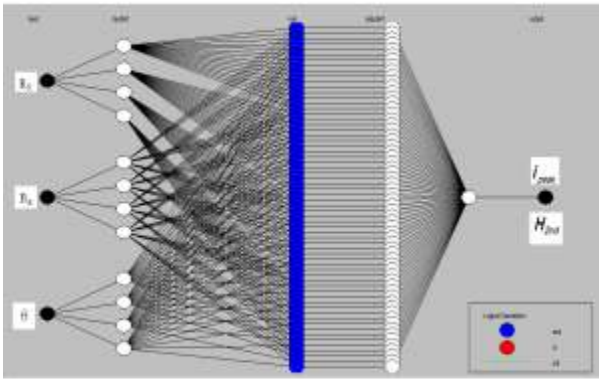

Figure18. Schematic diagram of the construction of the adopted ANFIS models

The testing of the ANFIS model performance at different operating conditions is shown in table (1)

Table (1) Sample testing data sets for calculated and predicted by ANFIS model.

Patterns	**Inputs**			**Simulation Results**		**ANFIS Results**	
	R_s	B_R	θ	i_{peak}	H_2	i_{peak}	H_2
1	1	0.8	0	3.91	0.89598	3.9595	0.915
2	1	0.8	45	3.09	0.79413	3.1217	0.7909
3	1	0.8	60	2.47	0.65634	2.4688	0.6443
4	1	0	0	1.51	0.4363	1.5119	0.4337
5	1	0	45	0.8	0.195	0.7945	0.2028
6	1	0	90	0.505	0.1001	0.4808	0.1118
7	1	-0.8	135	-3.02	0.774	-2.9541	0.7336
8	1	-0.8	180	-3.91	0.9683	-4.0124	0.9993
9	1	-0.8	225	-3.11	0.8	-2.9844	0.7806
10	10	0.8	210	-0.026	0.0066	-0.0065	1E-6
11	10	0.8	240	0.0375	0.00006	0.0746	1E-5
12	10	0.8	270	0.7	0.15	0.6712	0.1738
13	20	0.8	270	0.55	0.1075	0.5537	0.1076
14	20	0.8	330	2.4	0.6667	2.3965	0.6667
15	20	0.8	360	2.766	0.75	2.768	0.7041

It has been computed for each applied proposed technique. Table (1) depicts a comparison between the different computed data and estimated data by the ANFIS algorithms for transformer inrush current. It is clearly shown from the results obtained that the ANFIS presents good agreement with data obtained results obtained by Simulink for each signal tried before.

VIII. CONCLUSIONS

Results from this study evidently prove that developed ANFIS model is reliable to estimate maximum inrush current and second harmonic current content, with higher accuracy. The proposed system provides a faster and reliable response. Such a system could be very useful in predicting of maximum inrush current for large rating of transformer where large electromagnetic transient forces exist. ANFIS Model has beauty to train network with data of non-linearity which gives almost exact matching with target values. Therefore, ANFIS model is able to predict maximum inrush current value with an acceptable average of percentage error and second harmonic current content again with an acceptable average percentage error.

IX. APPENDIX

The transformer under study is 3-phase Yg/Yg,450MVA, 500/230KV, 60 Hz, with parameters as;
Primaryand secondary resistances, 0.002 PU
Primary and secondary inductances, 0.08 PU
Magnetizing resistance and inductance, 500 PU

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