DISCRIMINATION TECHNIQUE BETWEEN TRANSFORMER INRUSH CURRENT AND INTERNAL FAULT CURRENT USING D1 WAVELET COEFFICIENT BASED ANFIS

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Abstract -This paper proposed a new classification method based on the discrete wavelet transform (DWT) combined with an automated classification mechanism based on adaptive network fuzzy inference system (ANFIS) for power transformer differential protection to discriminate between internal faults and no fault condition (inrush condition) in three phase power transformers.
For the evaluation of the developed algorithm, transformer modeling and simulation of fault and no fault condition are carried using Matlab/Simulink software Package. For each candidate internal fault or inrush current conditions current waveform suitable features are extracted by employing DWT. Then, a successfully trained adaptive network fuzzy inference system based classifier, developed utilizing inputs comprising the features extracted from a training set of waveforms is implemented for a testing set of sample waveforms. The simulation results obtained show that the method is faster, more reliable and accurate when compared with some of published research works in the area.

Keywords: power transformer, inrush current, differential protection, discrete wavelet transform, adaptive network fuzzy inference system.

I. INTRODUCTION

Power transformers are considered the main critical and the most expensive component in the power substations. The operation of the transformer under any abnormal condition such as faults or overloads compromises the life of the transformer, which means adequate protection should be provided for quicker isolation of the transformer under such conditions.

Transformers are protected mainly by differential relays , the differential protection may not operate correctly due to mismatch of current transformers provided at the two ends of the zone, differences in the relay circuitry and due to inrush currents or excessive currents caused by system over-voltages at the transformer terminals.
Over the years, various methods have been developed to ensure correct operation of differential relays.

Differentiation between transformer inrush current and internal faults currents is one of the major parameters that should be evaluated and clearly discriminated for proper operation of its protection schemes to avoid any power interruption. Mal-discrimination yields to cause unreliable power system. Nevertheless, developing the protection schemes still needs more and more attention especially with modern control systems/protection techniques recently developed [1, 2].

II. MAGNETIZING INRUSH CURRENT

When a transformer is de-energized, a permanent magnetization of the core remains due to hysteresis of the magnetic material. This “residual flux” is influenced by the transformer core material characteristics, core gap factor, winding capacitance, circuit breaker current chopping characteristics and other capacitances connected to the transformer. If the transformer were reenergized at the instant that the voltage waveform correspond to the residual magnetic flux density within the core, there would be a smooth continuation of the previous operation with no transients. However, in practice, the instant when switching takes place cannot be controlled, and a magnetizing transient occurs, almost inevitably. The transient generates a current known as inrush current. The magnitude of this inrush current can be several times the load current and flows only on one side of the differential relay, which tends to operate if some form of restraint is not provided. In Figure (1) a typical curve of inrush current due to the energization of a power transformer is shown [3].

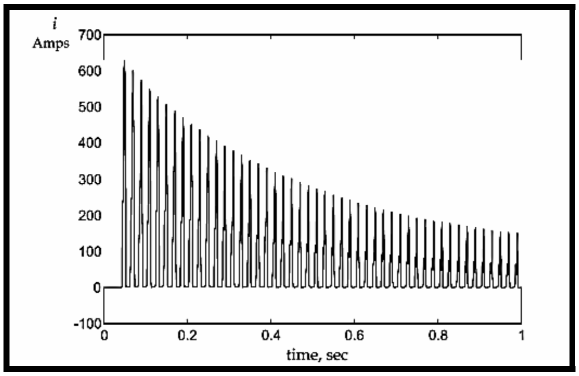

Figure 1: Typical magnetizing inrush current in a power transformer.

Typically, inrush currents are composed of unipolar or bipolar pulses, separated by intervals of very low values of current. The inrush current decays rapidly during the first few cycles, and then decays slowly The factors that determine the magnitude and duration of magnetizing inrush current include the following [2].

- Size of transformer.
- Instant of switching on.
- Size of power system.
- Type of magnetic core material of the transformer.
- Residual flux in the transformer before switching on.

III. DISCRIMINATION BETWEEN INRUSH CURRENT AND INTERNAL FAULT CURRENT

Most of the early methods of differential protection of transformers are based on harmonic content of differential current.

These methods are based on the ratio of the second harmonic to the fundamental component of the differential current in inrush current condition which is greater than the ratio in the fault conditions [4]. The second harmonic can also be generated during internal faults on the transformers or due to saturation of CTs or due to long transmission lines so this situation may cause greater ratio of the second harmonic than in inrush current condition.

The differential power method has been proposed to recognize the internal fault from inrush current [5]. This method is based on modal transform of voltage and current waveforms. The disadvantages of these methods include the need to use voltage transformers and increased protection algorithm calculation cost.

Some other methods detect faults, based on waveform fluctuations of differential current [6]. Other method is based on difference in the time interval between two respective peaks which in inrush current is smaller than the time intervals in the fault current. This method is based on the measuring of the time between the respective peaks of differential current [7].

Recently, neural network is used to recognize the internal fault current and inrush current. Trained neural network output shows either the fault or the normal condition of transformers by different samples of faulted and un-faulted conditions [8]. The disadvantage of this method is that the neural networks require a large amount of data to form numbers of training patterns .

Integration of A wavelet-based (WT) signal processing technique and adaptive neural fuzzy system (ANFIS) is tackled as most effective and fast technique to differentiate the faulted and un-faulted conditions. This technique has been proposed in [9].

The current paper proposes a new approach for discrimination between internal fault and inrush current for differential protection of power transformers using wavelet-based discrimination technique. Training data is extracted using these techniques and applied to the ANFIS as Fuzzy logic inputs which can identify faults with high reliability.

IV. WAVELET- TRANSFORM AND ANALYSIS

The waveforms associated with fast electromagnetic transients typically are non-periodic signals which contain both high-frequency oscillations and localized impulses superimposed on the power frequency and its harmonics. These characteristics present a problem for traditional discrete Fourier transform (DFT) because its use assumes a periodic signal and that the representation of a signal by the DFT is best reserved for periodic signals. In order to overcome these problems, the WT has been used as a powerful tool in the analysis of transient phenomena. The ability of WT to focus on short time intervals for high frequency components and long intervals for low-frequency components improves the analysis of signals with localized impulses and oscillations. For this reason, wavelet decomposition is ideal for studying transient signals and obtaining a much better current characterization and a more reliable discrimination [4, 7].

The continuous wavelet transform (CWT) is defined as the sum over all time of the signal multiplied by scaled and shifted versions of the wavelet function [18].

$$WT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) g\left(\frac{t-b}{a}\right) dt \qquad (1)$$

Where x (t) is the signal to be analyzed, a and b are respectively the scaling (dilation) and time shifting (translation) factors. g(t) is referred to as the "mother wavelet" and its dilates and translates are simply called as "wavelets". The results of CWT are many wavelet coefficients, which are a function of scale and position.

The CWT has a digitally implementable counterpart: the Discrete Wavelet Transform (DWT), which is defined as:

$$DWT(m,k) = \frac{1}{\sqrt{{a_0}^m}} \sum_n x(n) g\left(\frac{k - n{a_0}^m}{{a_o}^m}\right) \qquad (2)$$

Where, g(n) is the mother wavelet, and the scaling and translation parameters a and b of (1) are functions of an integer parameter m, $a = a_0^m$ and $b = n\, a_0^m$. The DWT can be implemented with the form of a filter bank, with the variable swap of k for n, (2) can be rewritten as:

$$DWT(m,k) = \frac{1}{\sqrt{a_0^{\,m}}} \sum_n x(k) g(a_0^{-m} n - k) \qquad (3)$$

This has the similar form of Finite Impulse Response (FIR) digital filters.

The DWT analyzes the signal at different frequency bands with different resolutions by decomposing the signal into a coarse approximation and detail information. The decomposition of the signal into different frequency bands is simply obtained by successive high pass and low pass filtering of the time domain signal. The original signal x[n] of frequency PI is first passed through a half band high pass filter g[n] and a low pass filter h[n]. After the filtering, half of the samples can be eliminated, since the signal now has a highest frequency of PI /2 radians instead of PI. The signal can therefore be subsampled by 2, simply by discarding every other sample. This constitutes one level of decomposition. This operation will continue to the required level of decomposition as shown in figure (2).

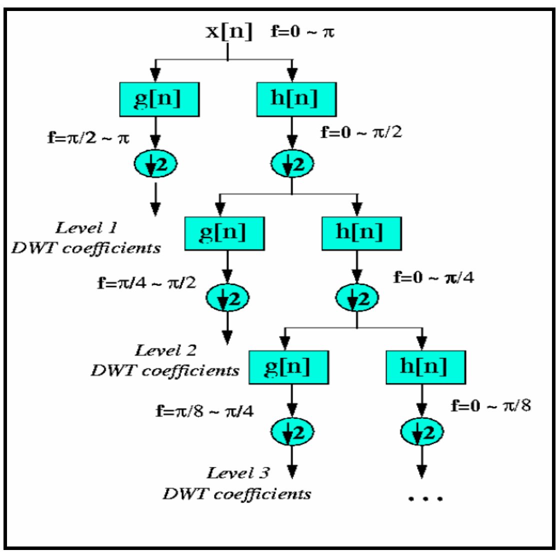

Figure 2: fuzzy inference system.

V. FUZZY INTERFACE SYSTEMS (FIS)

A typical transformer differential relay is that it should be able to block the trip introduced by transient magnetizing inrush current and rapidly operate the tripping during internal faults. The fuzzy method could be an alternative to fill the gap, when a clear discrimination detection boundary cannot be found in the multi-dimensional domain. A fuzzy solution indicates 'the most likelihood of an output' to a given input pattern. This makes sense in the engineering area [10].

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The fuzzy inference process contains the following steps as shown in figure (3) [11].

1. The inputs are crisp (non – fuzzy).
2. All rules evaluated in parallel using fuzzy reasoning.
3. The results of the rules are combined and distilled (defuzzified).
4. The result is crisp (non - fuzzy) number.

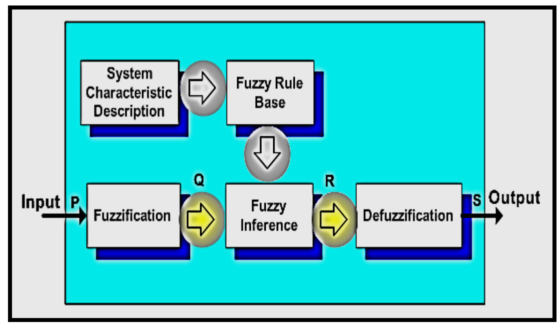

Figure 3: fuzzy inference system.

The basic structure of the type of fuzzy inference system seen thus far is a model that maps input characteristics to input membership functions, input membership function to rules, rules to a set of output characteristics, output characteristics to output membership functions, and the output membership function to a single-valued output or a decision associated with the output [11].

If we already have a collection of input/output data that would be used for modeling, the Fuzzy Logic Toolbox neuro-adaptive learning techniques incorporated in the ANFIS command can be used.

VI. DEVELOPED POWER SYSTEM MODEL AND DISCRIMINATION TECHNIQUES.

A software algorithm using the Matlab Simulink and Matlab M file is developed to analyze the current signals into their details using two different developed wavelet techniques, D1 wavelet coefficient and D5 wavelet coefficient based techniques, to make a decision about the state of the transformer. The power system is built to check the validity of the proposed relay; this system is assumed to be composed of:

- Three phase 3000 MVA power source (short circuit capacity), 120kv.
- Two - Three phase circuit breakers on the transformer sides.
- Three phase star / star 47 MVA, 120/25 KV power transformer.

- 3- 30 KM feeders.
- Three phase load.
- The required current transformers and the developed differential relay.

Figure (4) shows the developed Matlab / Simulink models of the considered power transformer connected with the electrical power system. Table (I) presents the main parameters for the simulated power transformer.

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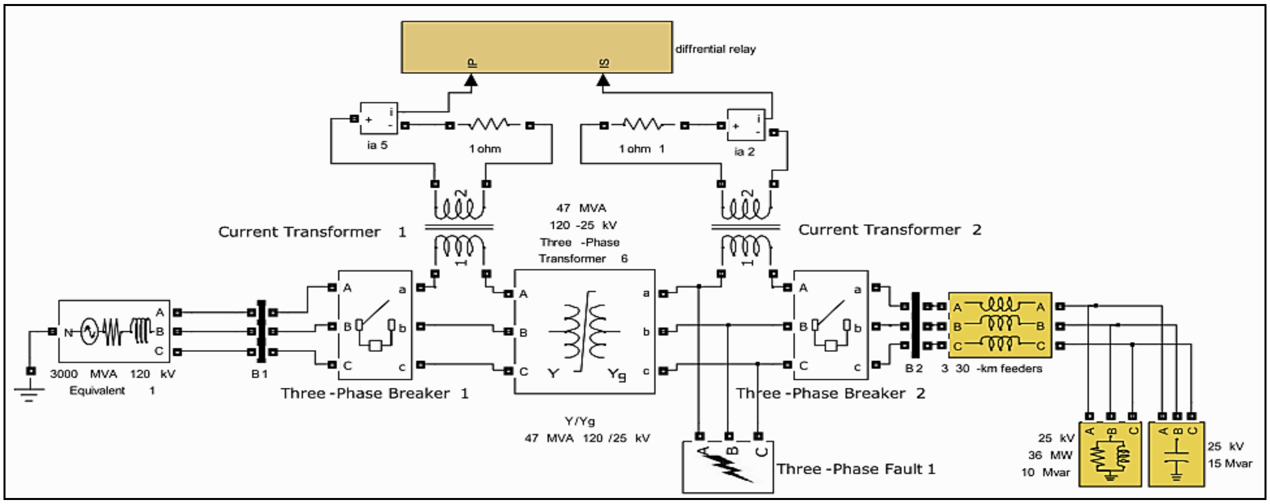

Figure (4): Developed Star/Star Transformer Matlab/Simulink of the power system model.

Table I: Simulated transformer main parameters.

Transformer connection	Y/Y g
Rated power	47 MVA
Voltage ratio	120/25 kV
Rated frequency	50 Hz
Primary winding resistance/phase	0.003 pu
Primary winding inductance/phase	0.09 pu
Secondary winding resistance/phase	0.003 pu
Secondary winding inductance/phase	0.09 pu
Core resistance	300 pu
Magnetizing reactance	300 pu

A Wavelet based discrimination techniques is developed to discriminate between the transformer inrush and internal fault currents using D1 wavelet coefficient.

VII. SIMULATION RESULTS

The differential relay operating current for Y-Y_g transformer energizing at no load for two cases with no internal fault condition (inrush current) and with three phase to ground fault (internal fault) are presented in Figure (5). In Figure (6) the point at which the relay operating current crosses the zero value during the first cycle after the relay sensing a fault is obtained. It is clear that the relay current in case of inrush condition will remain near zero for a period greater than that of internal fault condition.

The resultant frequencies (D1–D5) from WT are presented in figure (7) and figure (8) for the two cases respectively.

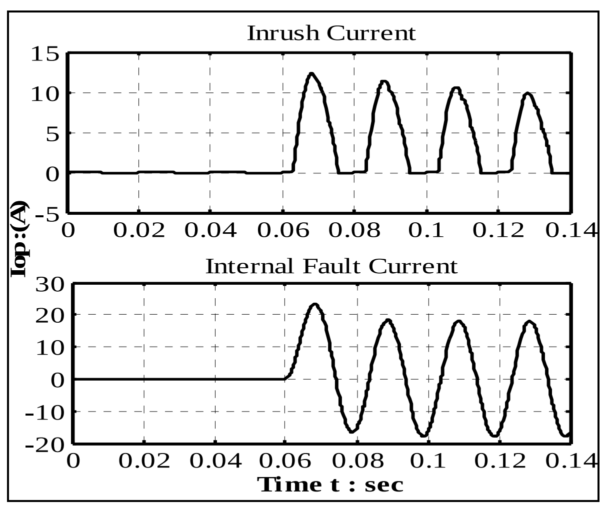

Figure 5: differential relay current "phase A incidence angle 0 degree, switching of the transformer on after 3 cycles".

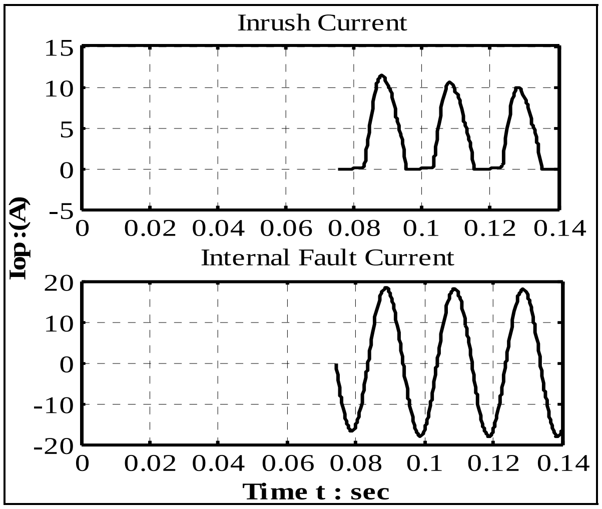

Figure 6: Differential relay current after the first zero crossing.

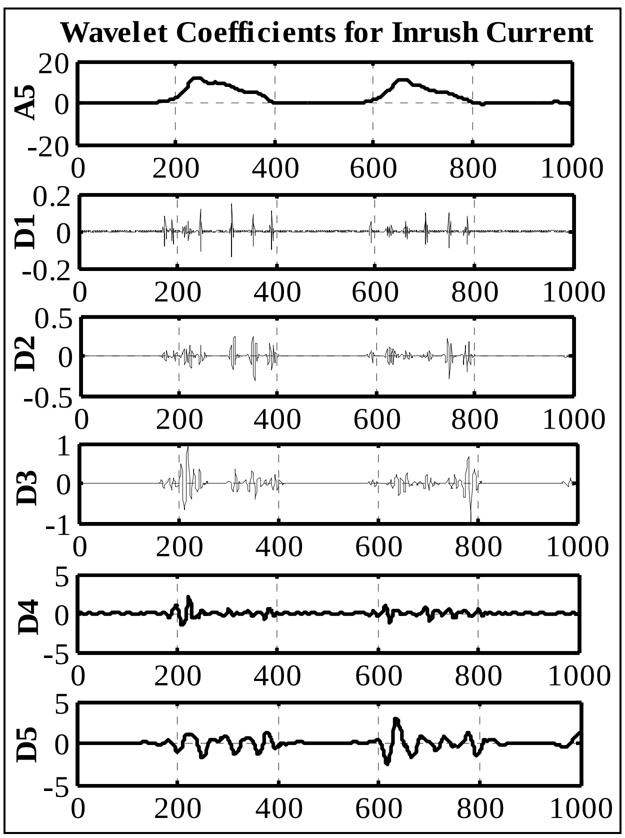

Figure 7: Wavelet coefficients for inrush current.

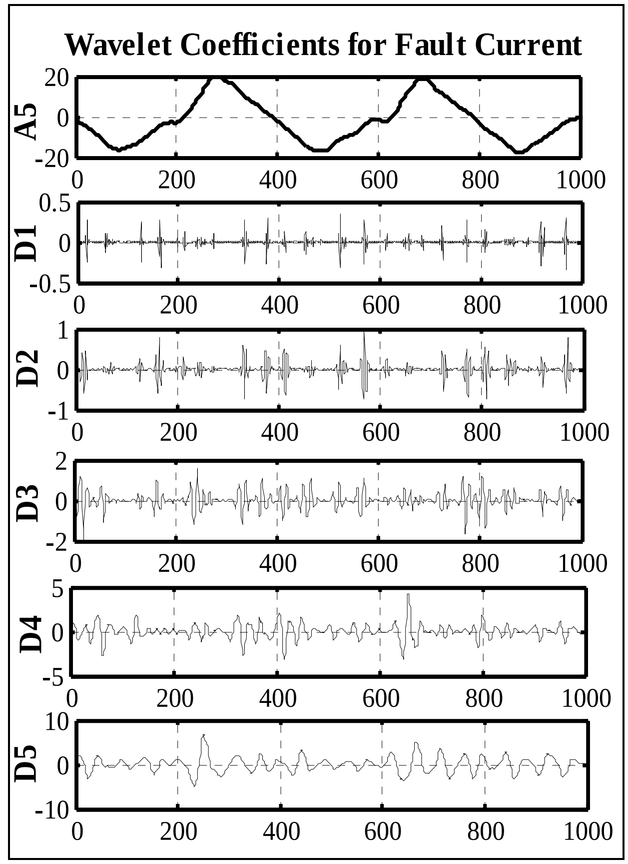

Figure 8: Wavelet coefficients for internal fault current.

Figure (9) shows the differential current waveform due to the inrush current and fault current at frequency levels D1.

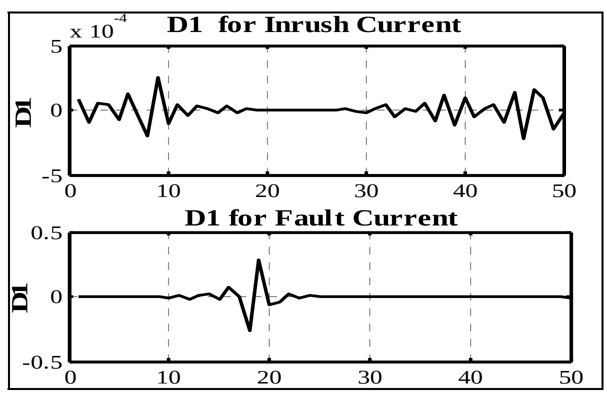

Figure 9: D1 wavelet coefficients for the two cases.

It is clear from figure (9) that values of the d1 wavelet coefficient vector for internal fault current is greater than the corresponding values for inrush current and this is clearly visible for the elements from 15 to 25 of the d1 wavelet coefficient vector as explained in figure 10.

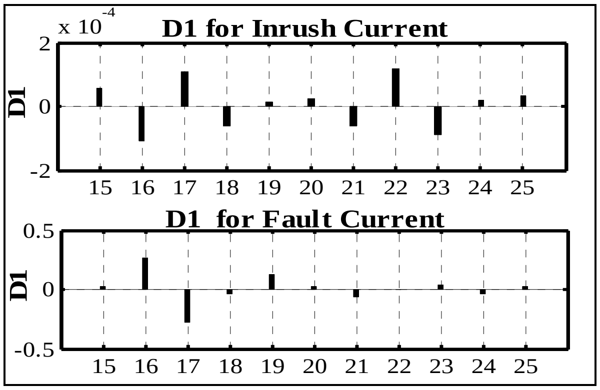

Figure 10: The elements of the D1wavelet coefficient vector for the two cases.

In figure (11) the highest three elements of the d1 wavelet coefficient vector are obtained for the two cases which are sufficient different to discriminate between the inrush current and the internal fault current and these values are used as inputs to the Anfis controller.

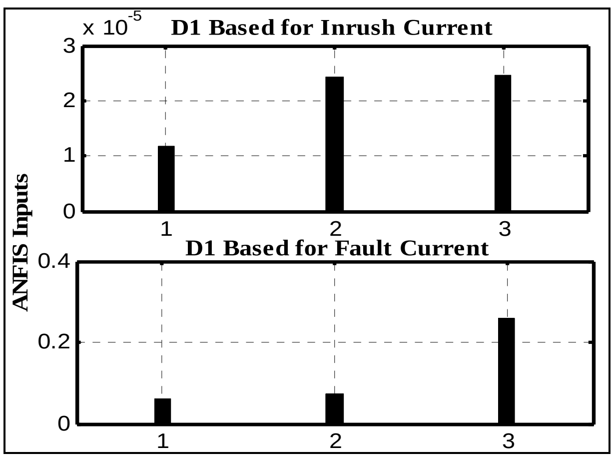

Figure 11: Fuzzy logic controller inputs based on D1 wavelet coefficients for the two cases.

VIII. FDAS RESULTS FOR THE TRANSFORMER MODEL

The proposed fuzzy system (FDAS) takes input data and classifies whether there were internal fault or inrush current. The fault discrimination patterns described above are translated into fuzzy IF-Then rules. The proposed fuzzy system was tested with data generated from the transformer model simulated in Matlab software.

The Matlab program graphical user interface (GUI) is used in this section, and the data collected for the YY transformer model are used to build the FDAS "fuzzy differential alarm system" using " ANFIS "system.

Table (II) shows the training data for the developed FDAS for D1 wavelet coefficient based discrimination technique for the developed power system, there are three inputs as described above, and one output of zero for inrush current and one for internal fault current .

Table II: Training Data for ANFIS for D1 Wavelet Coefficient Based Discrimination Technique

case	sw.angle	Input 1	Input 2	Input 3	Output
Inrush Current	0	1.18E-05	2.44E-05	2.47E-05	0
	10	5.5E-06	1.32E-05	2.33E-05	0
	20	1.67E-05	2.99E-05	4.63E-05	0
	30	1.17E-05	1.87E-05	2.03E-05	0
	40	7.68E-06	1.45E-05	2.12E-05	0
	50	6.8E-06	7.47E-06	1.51E-05	0
	60	6.87E-06	1.2E-05	2.69E-05	0
	70	7.27E-05	7.56E-05	8.67E-05	0
	80	9.12E-05	0.000108	0.000108	0
	90	3.76E-05	4.64E-05	6.04E-05	0
Internal Fault Current	0	0.059922	0.073038	0.260626	1
	10	0.038661	0.048457	0.129341	1
	20	0.129645	0.139657	0.171584	1
	30	0.05223	0.058177	0.124462	1
	40	0.100639	0.120186	0.174361	1
	50	0.061115	0.117684	0.16757	1
	60	0.053877	0.071958	0.231823	1
	70	0.027576	0.042927	0.118738	1
	80	0.065887	0.131019	0.271316	1
	90	0.036409	0.06718	0.13425	1

Table (III) shows the checking data for the developed FDAS for D1 wavelet coefficient based discrimination technique for the developed power system.

Figure (12) shows the structure of the developed Anfis system showing the three inputs and one output.

Figure (13) shows the developed Anfis system input and output member ship functions.

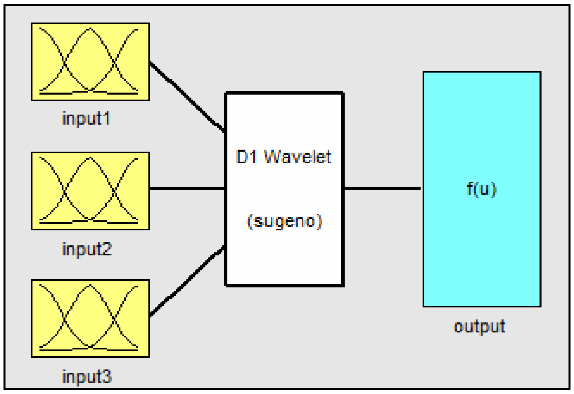

Figure 12: the developed Anfis system structure

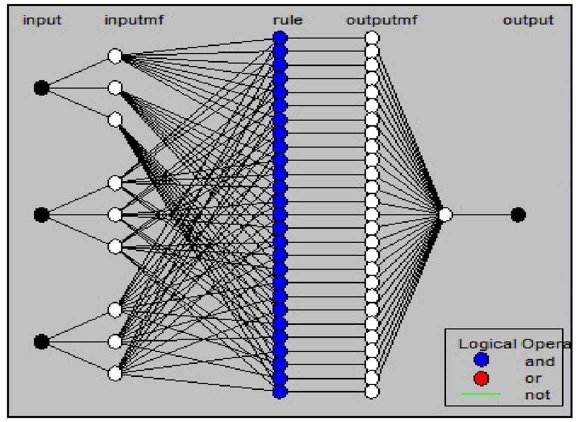

Figure 13: the developed Anfis system member ship functions.

Table III: Checking Data for ANFIS for D1 Wavelet Coefficient Based Discrimination Technique

case	sw.angle	Input 1	Input 2	Input 3	Output
Inrush Current	5	5.15E-06	6.7E-06	8.53E-06	0
	15	1.64E-05	2.54E-05	4.91E-05	0
	25	1.5E-05	1.51E-05	1.53E-05	0
	35	6.11E-06	1.05E-05	2.11E-05	0
	45	3.27E-05	3.33E-05	4.88E-05	0
	55	6.8E-06	1.34E-05	2E-05	0
	65	5.62E-05	6.75E-05	7.02E-05	0
	75	6.55E-05	6.95E-05	0.000127	0
	85	6.8E-05	7.57E-05	0.000102	0
Internal Fault Current	5	0.069019	0.093595	0.212497	1
	15	0.065079	0.112186	0.165299	1
	25	0.060748	0.070362	0.19635	1
	35	0.049289	0.055593	0.123805	1
	45	0.062968	0.129464	0.210996	1
	55	0.140274	0.147013	0.255804	1
	65	0.073734	0.101651	0.209245	1
	75	0.060023	0.12673	0.198868	1
	85	0.044119	0.103896	0.242796	1

Figure 14 presents the percentage training error of the developed algorithm. The average training error is about ($3.8 * 10^{-3}$). Figure 15 presents the fuzzy output with its testing data which shows closeness of the two profiles, the average testing error is about ($4 * 10^{-3}$). Table (IV) shows the Anfis system information and the number of rules.

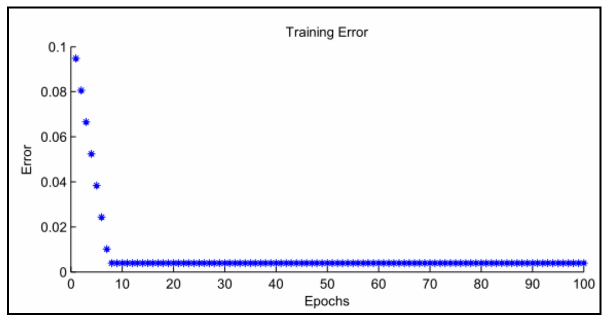

Figure 14: the percentage training error of the developed algorithm

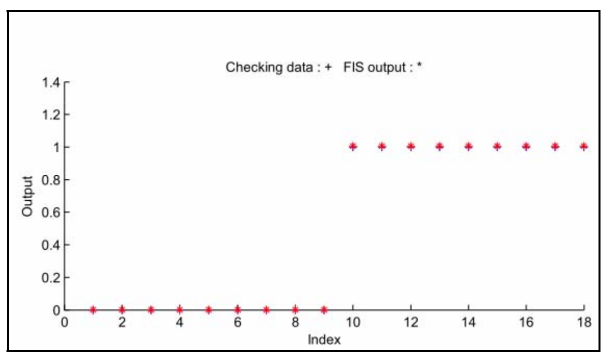

Figure 15: the fuzzy output with its testing data

TABLE IV: ANFIS info:

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Number of nodes: 78
Number of linear parameters: 27
Number of nonlinear parameters: 36
Total number of parameters: 63
Number of training data pairs: 20
Number of checking data pairs: 18

Number of fuzzy rules: 27
Error=3.8*10e-3

IX. CONCLUSION

An acceptable and precise power transformer with differential relay model is implemented, using the Matlab Simulink software package. The model is a very convenient way to test the transient behavior of the power transformer under both faulted and un-faulted conditions. This model is then used to analyze and investigate the inrush current during switching the transformer on and the fault current produced by internal faults.
A simulation method to analyze and test the optimized transformer protection schemes for differentiating between the internal fault currents and inrush currents is presented in the current study. The main analyzing technique used is the wave analyzer Wavelet technique.

A simple decision making logic scheme using fuzzy logic ANFIS is presented for the developed technique for distinguishing internal faults from inrush currents.

The extensive simulation results presented show that the proposed technique needs very simple input signals, but can accurately discriminate between an internal fault and an inrush current in different power transformer systems.

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