INTERNAL FAULT/ INRUSH CURRENTS DISCRIMINATION BASED ON FUZZY/ WAVELET TRANSFORM IN POWER TRANSFORMERS

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Abstract: Transformers are major elements of any power systems. Normally they must be properly protected by differential relays. This protection system should be precise and reliable via implementation of strong algorithms that able to differentiate between faulted and unfaulted condition to fully grantee of power continuity. This system should be able to detect the non-faulted condition, such as inrush currents which should not be activated in this condition meanwhile; it must be activated in internal fault conditions as fast as possible. This paper presents an approach for differential protection of power transformers this uses wavelet transform (WT) and adaptive network-based fuzzy inference system (ANFIS) to discriminate internal faults from inrush currents.

The proposed algorithm has been designed based on the differences between both amplitudes of wavelet transform coefficients in a specific frequency band and rising and decaying duration generated by faults and inrush currents. The performance of this simulated model is demonstrated by simulation of different faults and switching conditions on a power transformer using Matlab/Simulink software Package.

Keywords: Inrush/Fault currents differentiation, Transformer modeling, Neural fuzzy and wavelet.

I- INTRODUCTION

Transformers are considered one of the most important elements of electrical power systems and are normally protected by differential relays which should be reliable and precise as well. Therefore, the protective system should be able to differentiate between faulted such as internal fault and a non-faulted condition, such as inrush currents and consequently, it should operate in a faulted condition as fast as possible to avoid any damage. Differentiation between inrush current, internal faults is one of the major parameters should be evaluated and clearly discriminated for proper operation of its protection schemes to avoid any power interruption. Mal-discrimination yields to cause un-reliable power system [1, 2]. Nevertheless, developing the protection schemes still needs more and more attention especially with modern control systems/protection techniques recently developed. Proper protection schemes need precise modeling of the transformer and full knowledge of the transformer parameters to stand on a clear decision rather than to increase the system stabilities and transformer life time which is the gross costly effects in the electrical power distribution systems [3,4]. Mal operation of differential relays can affect both the reliability and stability of the whole power system. Most of the recent methods of digital 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 differential current in inrush current condition is greater than the ratio in the fault conditions [5-7]. 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 in inrush current.

The differential power method has been proposed to recognize fault from inrush current [8,9]. These methods are based on modeling transform for 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 [10-11]. Other method is based on difference in the time interval between two respective peaks, 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 [12]. Recently, neural network is used to recognize the fault current and inrush current. Neural network is by different samples of faulted and unfaulted conditions. Trained neural network output shows either the fault or the normal condition of transformers [13,14]. The disadvantage of this method is that the neural networks or fuzzy rules require a large amount of data to form numbers of training patterns. A wavelet-based (WT) signal processing technique is a powerful tool for power system transient analysis. Several new protective schemes have been proposed to deal with the foregoing simulation techniques. Integration of WT and artificial neural fuzzy system (ANFIS) is tackled as most effective and fast technique to differentiate the faulted and unfaulted conditions. This technique has been proposed in [15].

The current paper proposes this new approach for differential protection of power transformers using wavelet-based ANFIS. Training data is extracted using wavelet transform and applied to the ANFIS as inputs Fuzzy logic which can identify faults with high reliability.

2- 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 [16,17].

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 [nnnsa16].

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

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:

$$DWT(m,k) = \frac{1}{\sqrt{a_0^{\,m}}} \sum_n x(n) g\left(\frac{k - na_0^{\,m}}{a_o^{\,m}}\right) \qquad (2)$$

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:

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

which has the similar form of Finite Impulse Response (FIR) digital filters. The wavelet transforms acts as a group of band-pass filters with various central frequencies. It can be zoomed in by scaling and shifting the "mother wavelet". This implies that the wavelet transform can be used to obtain the wanted non stationary signals and to capture the transient components selectively and accurately. Hence the wavelet transform is an ideal means to extract the different components from the wideband transient signal generated by a fault.

3- FUZZY INTERFACE SYSTEMS (FIS)

A fuzzy set is a collection of objects with membership values between 0 (complete exclusion) and 1 (complete membership). The membership values express the degrees to which each object is compatible with the properties or features distinctive to the collection. A membership function is a curve that defines how each point on the input space is mapped to a membership value (or degree of membership) between 0 and 1. There are many types of membership functions such as triangular, trapezoidal and Gaussian membership functions. The fuzzy system without fuzzifier and defuzzifier is called pure fuzzy system [18].

The main problem with the pure fuzzy system is that its inputs and outputs are fuzzy sets, whereas in engineering systems the inputs and outputs are real-valued variables. In order to use pure fuzzy system in engineering systems, a simple method is to add a fuzzifier to the input, which transforms a real-valued variable into a fuzzy set, and to add a defuzzifier to the output, in order to transforms a fuzzy set into a real-valued variable. A sample fuzzy system with a fuzzifier and defuzzifier is shown in Figure. 1 Defuzzifiers are to convert the fuzzy outputs to their corresponding values in crisp number format. The required crisp output is denoted by. There are many methods of Defuzzification; such as the centroid method which is given by (4) and the weighted average method which is given by (5).

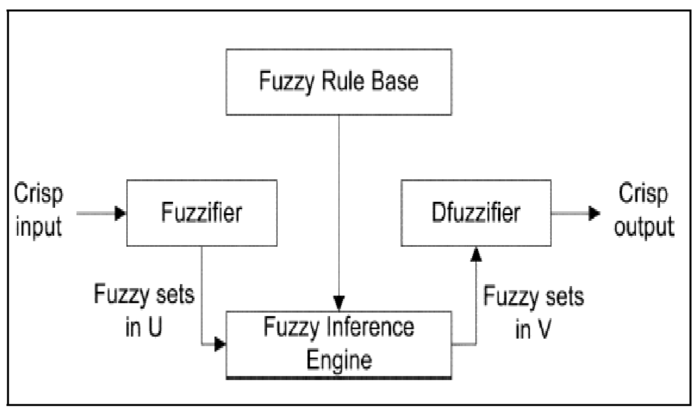

Fig.1: The main fuzzy system configuration with a fuzzifier and defuzzifier.

$$y^* = \frac{\int y . Mf_B(y) . dy}{\int Mf_B(y) . dy} \qquad (4)$$

$$y^* = \frac{\sum_{n=1}^{M} y_n z_n}{\sum_{n=1}^{M} z_n} \quad (5)$$

Where:
Mf_B : is the membership function for the set of input B
z_n : Peak value
y_n : value of the corresponding factor at the peak position

The Fuzzy Logic Toolbox can be used to create and edit fuzzy inference systems with the help of using graphical tools or command-line functions, by generating them automatically using either clustering or adaptive neuro-fuzzy techniques. Matlab/(Simulink - Fuzzy toolbox) can easily build and test the developed fuzzy system in a block diagram simulation environment.

4- SYSTEM MODELING AND SIMULATION TECHNIQUES

A- Power system Modeling

The system under study is composed of a 3-phase synchronous generator feeding a load through a 3-phase power transformer; the transformer is protected by a protection differential system. One circuit breaker is connected to the primary side of the transformer and takes its signal from the proposed differential relay so that it may trip the circuit in faulty condition. The inputs to the proposed relay are the difference between the current taken from the primary side of the transformer and the current taken from the secondary side. A software algorithm is used to analyze the current signals into their details using wavelet transform to make a decision about the state of the transformer. Two systems are used to check the validity of the proposed algorithm the first system is assumed to be composed of:

- Three phase 3000 MVA power source (short circuit capacity).
- Two - Three phase circuit breakers on the transformer sides.
- Three phase star / star 450 MVA, 500/220 KV power transformer.
- Three phase 300 KM transmission line.
- Three phase load of 200 MVA

The second system is similar to the first system but the transformer is delta/ star connected. Figure 2 shows the simple presentation for the two system configurations respectively. Table 1 presents the main parameters for the simulated power transformer. Simply, Figure 3 presents the main frame of the developed relaying algorithm using the Matlab/Simulink software package for the extraction purpose of the different current values during the different conditions assumed for simulation.

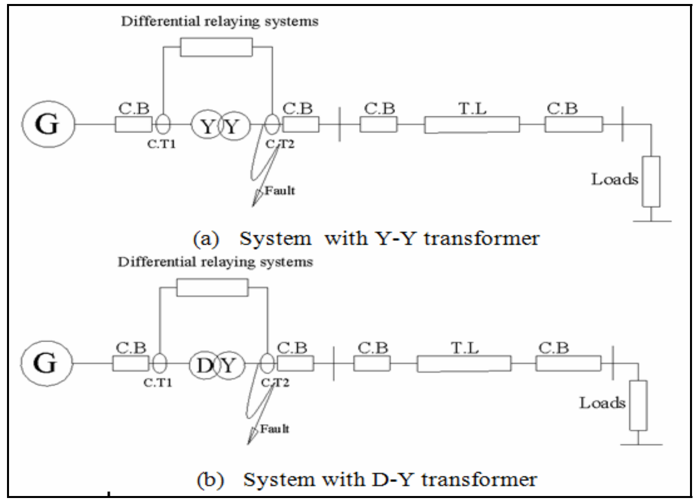

Fig.2: Developed Star/Star and Delta/Star Transformers

Table 1: Simulated transformer main parameters.

Transformer connection	Y/Y and Δ/Y (LV/HV)
Rated power	450 MVA
Voltage ratio	500/220 kV
Rated frequency	50 Hz
Primary winding resistance/phase	0.002 pu
Primary winding inductance/phase	0.08 pu
Secondary winding resistance/phase	0.002 pu
Secondary winding inductance/phase	0.08 pu
Core resistance	500 pu

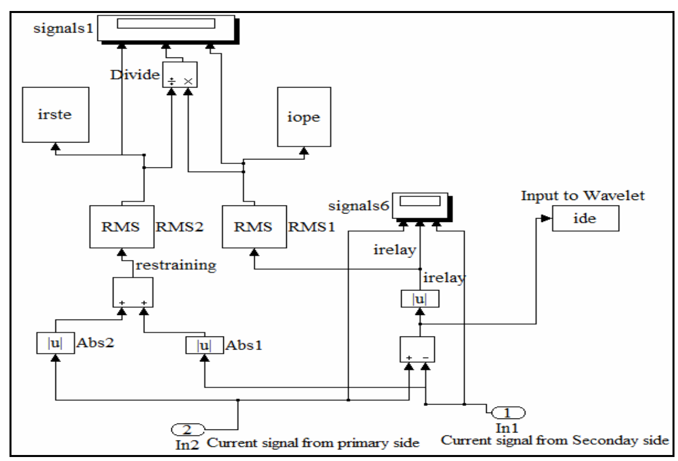

Fig. 3: Developed relay algorithm to help for differential protection schemes using Matlab/Simulink.

B- SIMULATION TECHNIQUES

The main concern of this section is imposed to discriminate between the transformer inrush/internal current using the different discrimination techniques. The first technique is the current wave shape based discrimination which depicts the current waves in different conditions then compares the cascaded peaks on the current profiles. The second technique is the time based discrimination technique which depends on the time taken for the variation of the relay current for a specific period after the first zero crossing which shows variation on current profiles for different conditions. The third technique is the Wavelet based discrimination technique using different components such as:

- D1, D2 wavelet coefficient based discrimination technique
- D3 wavelet coefficient based discrimination technique (fuzzy discrimination)

5- SIMULATION RESULTS

A- Current Wave Shape Based Discrimination Technique.

With switching on the power transform with no loads after three cycles of simulation, the two depicted current waveforms of the cases of inrush and internal fault currents are presented in Figure 4. 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 (internal fault) is depicted after three cycles to avoid any effects of the whole system starting contributions. These two different profiles will be extracted and depicted at different peaks to stand clearly how they perform differently.

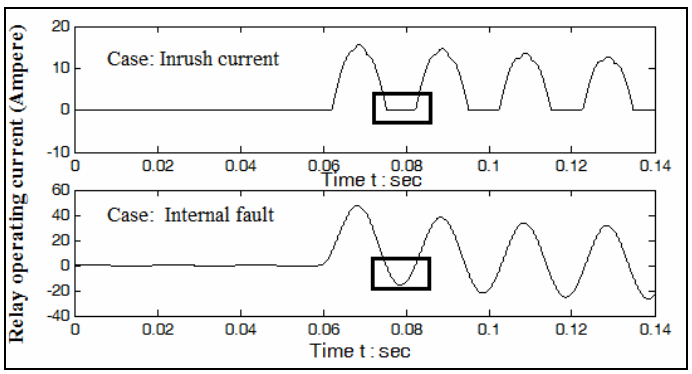

Fig. 4: The differential relay operating current for Y-Y_g transformer energizing at no load for two cases with inrush/internal currents

The small windows shown in Figure 4 will be focused to deeply depict the performance of the two profiles after the first zero crossing during the first cycle. Figure 5 shows the peak after first zero crossing point. It can be noted that the difference in profiles as the case of inrush current is very small compared with the case of internal fault current. Figure 6 presents the peaks of each profile at the cascaded zero crossing points during specific period of time of 0.8 ms. It can be noted that the for inrush current it gives a uniform pattern rather that the case of internal fault current due to the symmetry shapes.

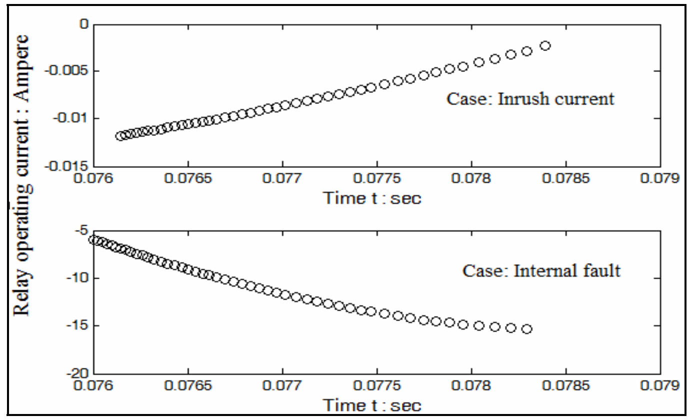

Fig.5: The current changes after the first zero crossing.

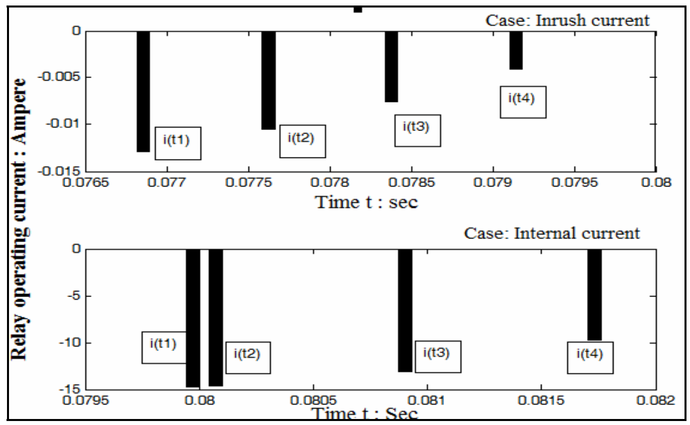

Fig.6: The current peaks at each zero crossing points.

From these different patterns for inrush and internal fault current, the different inputs to the developed Artificial Neural Fuzzy Interface Systems (ANFIS) can be extracted as shown in Figure 7. Figure 7 shows the absolute value of the difference between each two respective values of the relay current which will be high in case of fault condition and low in case of inrush current and use these three values as three input to the fuzzy (ANFIS) controller to give the proper decision if the relay current is due to fault or inrush condition.

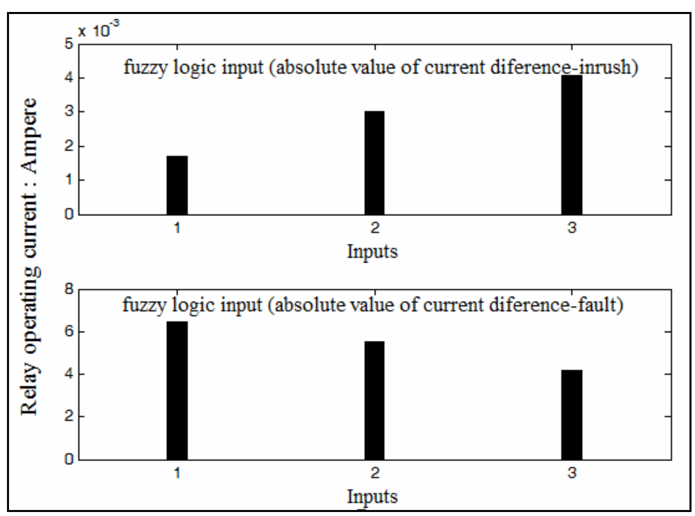

Fig. 7: Fuzzy logic inputs "Training data"

B- Wavelet Based Discrimination Technique

Differential currents have different behaviors under fault and inrush current conditions. Since the magnetizing inrush current corresponds to the transformer core saturation, the inrush current has a conical shape (non-sinusoidal); in other words inrush current at the switching time increases very slowly; as time passes, its slope increases. However, when a fault occurs, the differential current slope increases comparing to the starting of the inrush current. Therefore these features could be used as the basis of discriminating the faults from the inrush current. Actually two principles are used in practice:

1- The differential current originated from faults begins with higher slope and then its slope decreases. But differential current originated from inrush current begins with a low slope and then its slope increases.
2- A larger slope in the time domain shows that there are higher frequencies in the frequency domain.

Based on the above principles, it is expected that the amplitude of the high frequency components at the initial time has increasing trend in inrush current. It means that their amplitudes increase from a low value to a high value. The differential current due to the inrush current at t = 60 ms and the resultant frequency (D1–D5) from WT are presented in Figure 8. The above features at frequency (up to 4 kHz) level D3 are clearly visible. It is also expected that the amplitude of high frequencies (D1–D5) at the initial instants of time has a decreasing trend following internal faults. This trend has been shown in Figure 9 where the differential current due to the ABC–G internal fault at t = 60 ms and frequency levels from the WT are demonstrated.

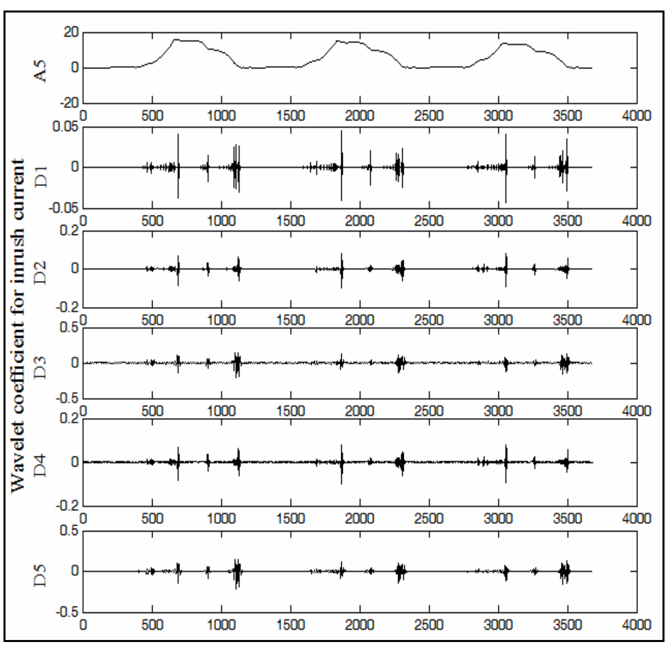

Fig.8: Wavelet coefficient for inrush current within frequency of 4kHz.

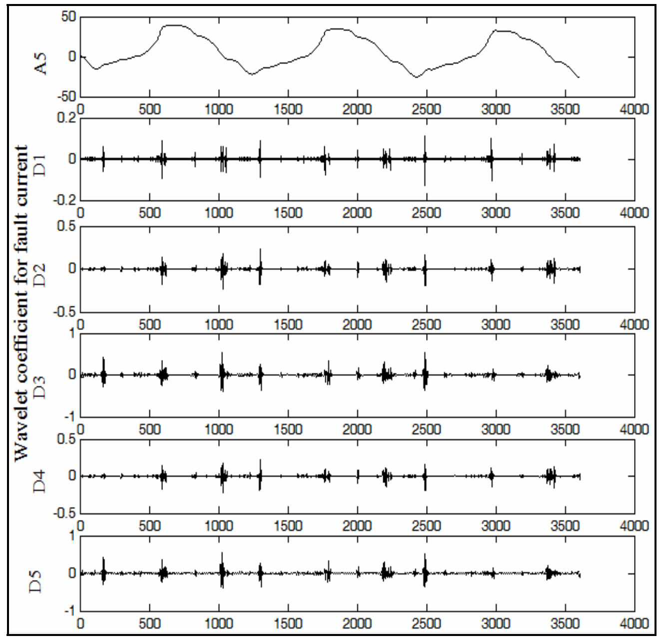

Fig.9: Wavelet coefficient for fault current within 4 kHz.

Analyzing deeply the first two coefficients D1and D2 yields a useful tool of discrimination between the two different cases of inrush and fault current. Figure 10 presents the profiles of D1 and D2 components (first 50 elements) for the different cases of inrush and internal fault conditions. Figure 11 presents the first four elements of the wavelet components D1 and D2 which shows minor deviation between the two considered cases. It is clear that it is difficult to discriminate between the inrush current and the internal fault based on the D1, D2 coefficients values only but if D1, D2 coefficients can be drawn versus the time as shown if Figure 12 which presents the first four elements of the wavelet components D1 and D2 versus time. With these profiles with time, it can be noted that there are different profiles between the two considered cases

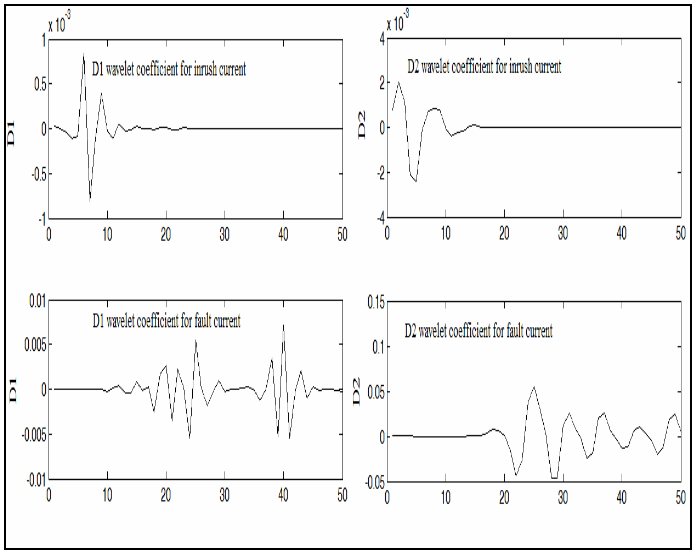

Fig.10: D1and D2 wavelet coefficients for the two cases within frequency of 50 Hz.

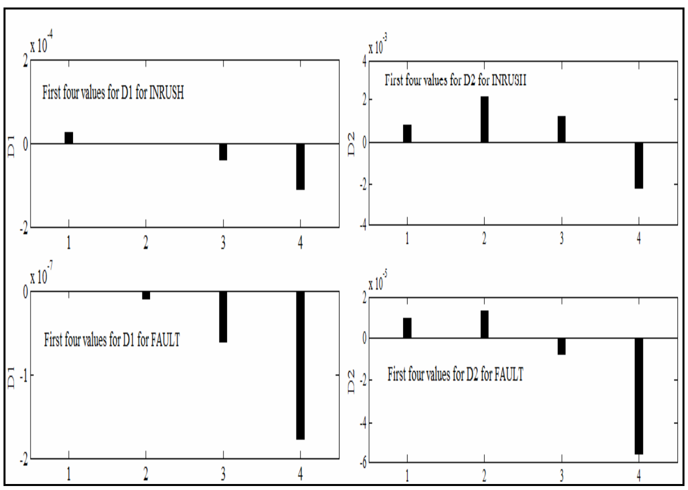

Fig.11: First four values for D1and D2 wavelet coefficients for the two cases within frequency of 50 Hz.

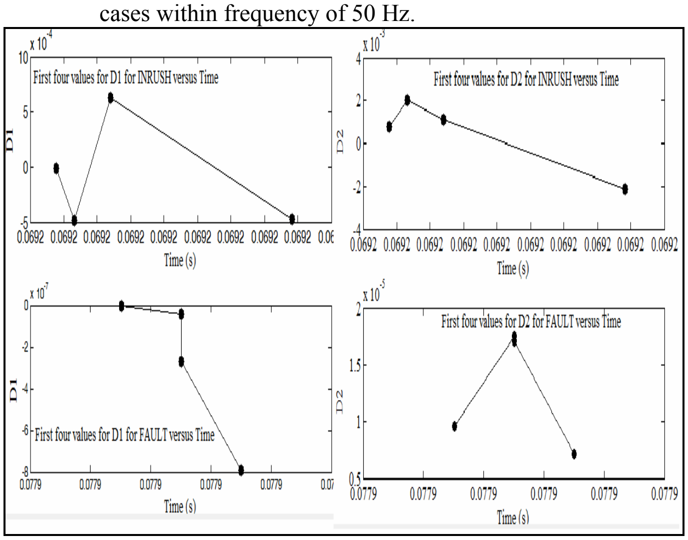

Fig.12: D1and D2 wavelet coefficients for the two cases versus time.

It is clear from the above Figures that the values of D1,D2 coefficients occur in a small time for internal fault condition compared to the its time in case of inrush current condition. So the difference between each two respective values and divide this value by the difference of two times of occurring these values to give three inputs to the fuzzy logic controller as shown in Figure 13 and these values are sufficient different to discriminate between the internal fault and the inrush current conditions.

For more accurate algorithms, more discrimination will be imposed based on D3 wavelet coefficient discrimination technique. Figure 14 presents the D3 components of the differential current due to the inrush/ internal fault current at frequency (up to 4.5 kHz).

Figure 15 presents the profiles of D3 components (first 50 elements) for the different cases of inrush and internal fault conditions.

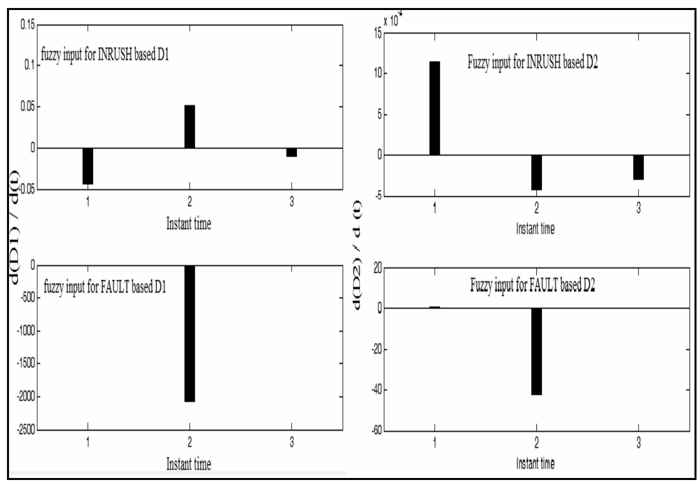

Fig. 13: Fuzzy logic controller inputs based on D1 and D2 wavelet coefficients

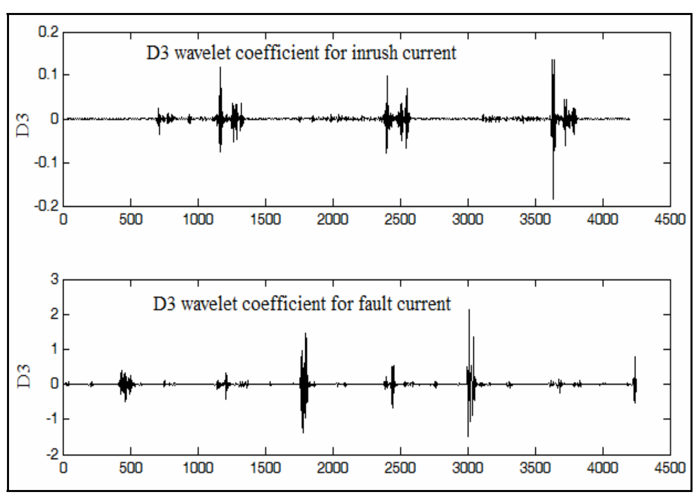

Fig.14: D3 Wavelet coefficient for inrush/internal fault current within frequency of 4.5 kHz.

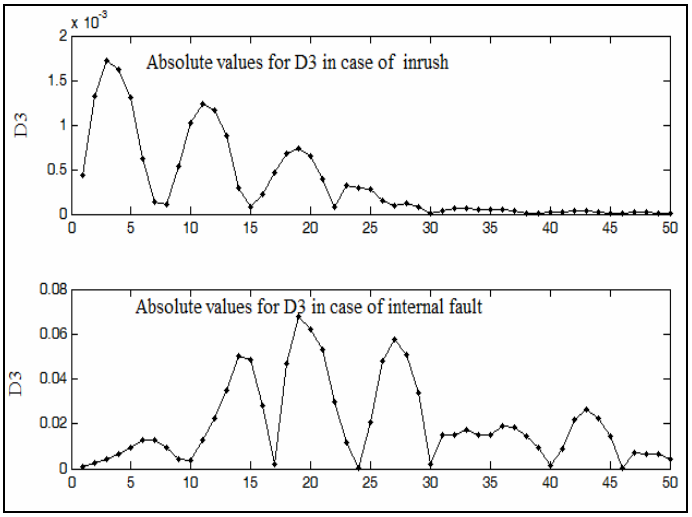

Fig.15: wavelet coefficients for the two cases within frequency of 50 Hz.

From the above Figures of D3 discrimination techniques, it is clear that for inrush current condition the first peak of the D3 wavelet coefficient vector is larger than the second peak and the second peak larger than the third peak meanwhile, in case of internal fault condition the first beak is less than the second peak and the second less than the third peak.

So if the difference between each two respective peaks is considered, it will be positive in case of internal fault condition and will be negative in case of inrush current condition and then use these differences as an input to the fuzzy logic controller to discriminate between the internal fault and the inrush current conditions as shown in Figure 16 and Figure 17.

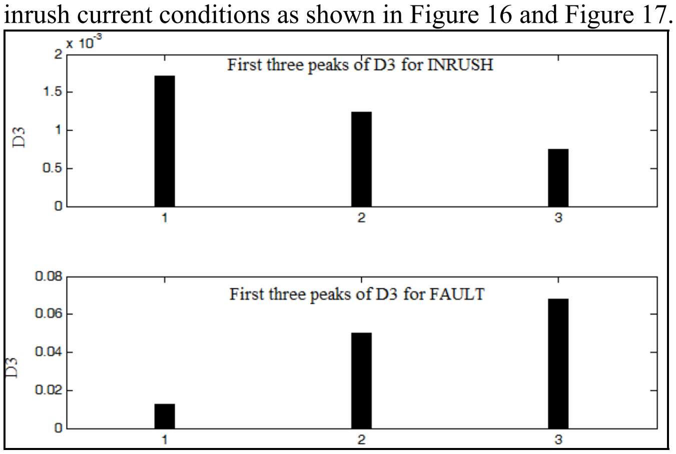

Fig.16: First current peaks of D3 wavelet component for the inrush and internal fault currents.

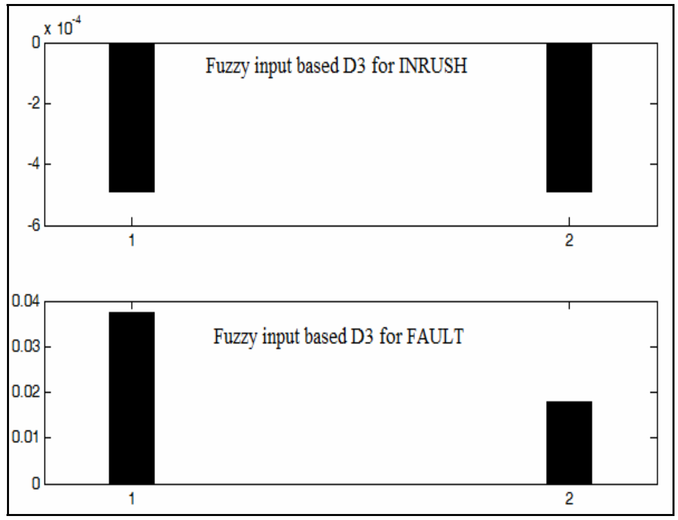

Fig.17: Fuzzy logic controller inputs based on D3 wavelet coefficients for the inrush and internal fault current.

For the second developed transformer model D-Y, as there is a phase shift between the primary current and secondary current of 30 degree for dyn11 type transformer. As the differential relay operating current is the phasor difference between the two currents hence the relay current will be large enough to make the relay to operate during normal operation condition to overcome this problem a time delay block will be added to the primary current signal to shift the primary current by 30. As per concluded from the results of the first developed model the most proper technique for discrimination is D3 wavelet component, therefore it will be tackled through the second model. As the switching instant will affect the amount of the differential relay current, hence different switching angles will be considered as:

Case (A) : switching angle = 20^0
Case (B) : switching angle = 40^0
Case (C) : switching angle = 60^0
Case (D) : switching angle = 80^0

Figure 18 presents the different cases of inrush current condition with different switching angles. It can be noted that the higher switching angle, the lower inrush current D3 component is obtained. Figure 19 presents the different cases of internal current condition with different switching angles. It can be noted that the higher switching angle, the higher internal current D3 component is obtained.

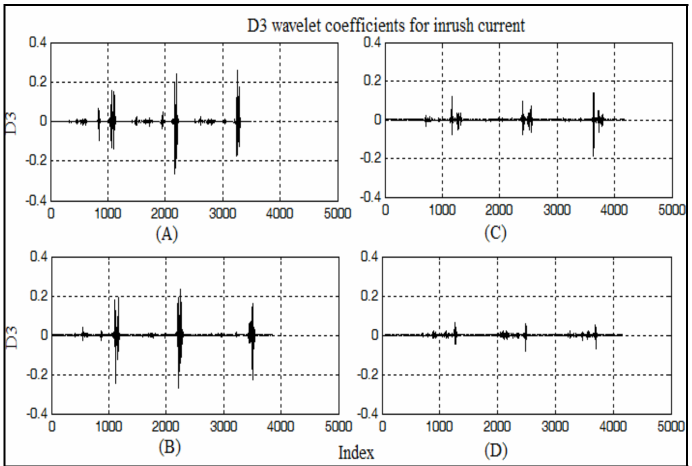

Fig.18 : The D3 wavelet coefficients for switching angles 20^0,40^0,60^0 and 80^0 degrees for inrush current D-Y Trans.

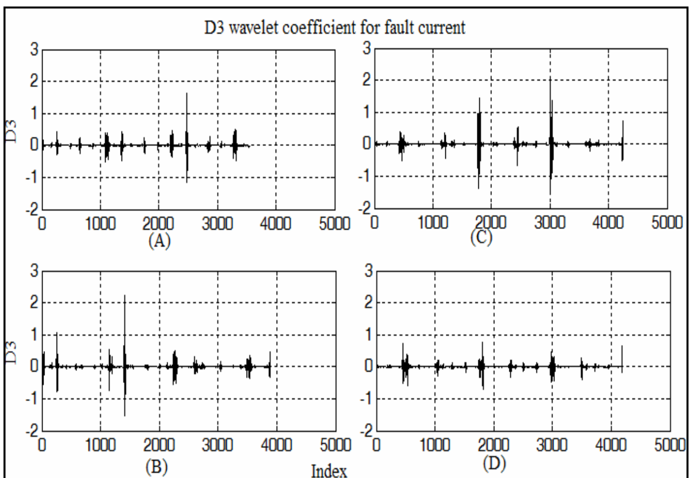

Fig. 19 : The D3 wavelet coefficients for switching angles 20^0,40^0,60^0 and 80^0 degrees for internal fault current D-Y Trans.

Figure 20 and Figure 21 present fuzzy logic controller inputs D3 based for inrush and internal fault. It can be noted that the D3 pattern in almost in (-ve) side while the D3 pattern in case of internal fault current is in (+ve) side for the considered different switching angles.

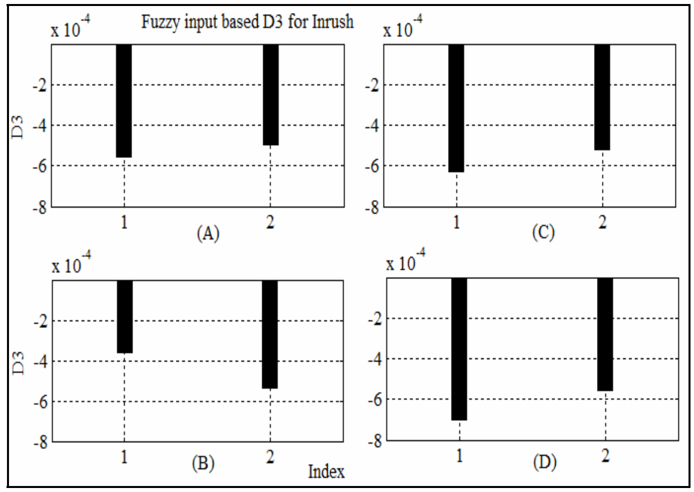

Fig.20: Fuzzy logic controller inputs based on D3 wavelet coefficients for the inrush current with different switching angles for D-Y Trans.

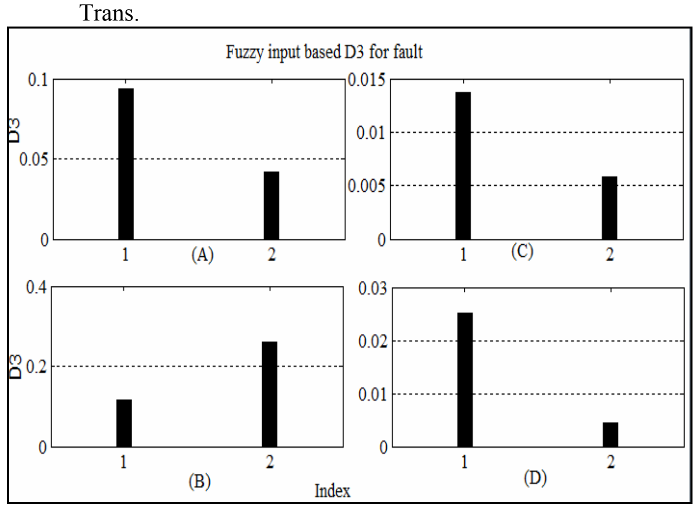

Fig.21: Fuzzy logic controller inputs based on D3 wavelet coefficients for the internal fault current with different switching angles for D-Y Trans.

Figure 22 present simple presentation for the developed fuzzy algorithm to discriminate between the inrush and fault conditions. There are five main inputs and one output to state of inrush and fault currents conditions.

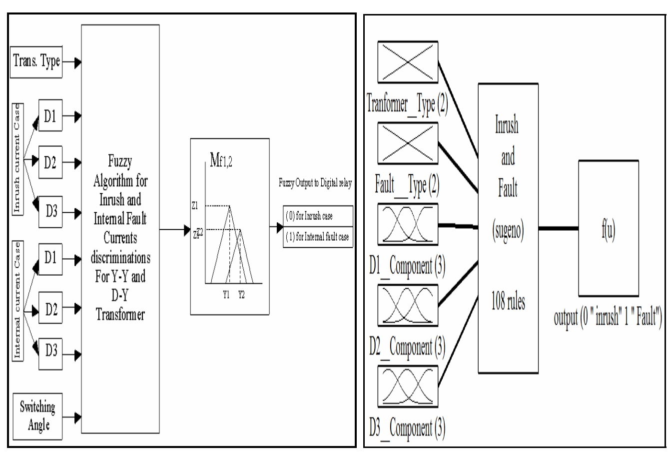

Fig.22: Simple presentation of the developed fuzzy algorithm.

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Figure 23 presents the percentage training error of the developed algorithms. The average error is about 0.15. Figure 24 presents the fuzzy output with its testing data which shows closeness of the two profiles specially the huge size of data extracted from the transformer models.

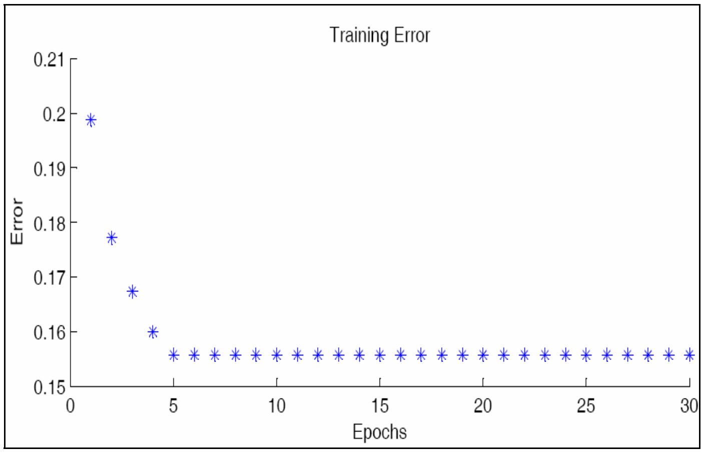

Fig. 23: Training error of the developed algorithms

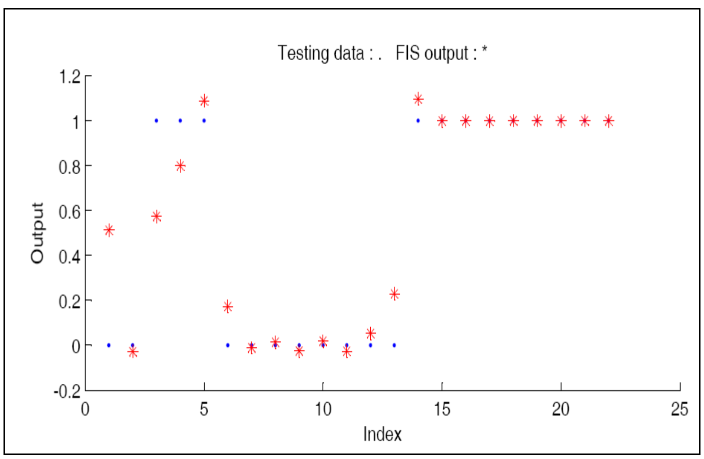

Fig. 24: The Fuzzy output with the testing data.

Finally, the number of input data will be reduced to develop 108 rules. After FIS training, final error of the training process becomes 0.002. As the output of the FIS is a real number and desirable output is 1 or 0, the output value of FIS must be rounded (1 means the fault condition and 0 means the safe condition).

6- CONCLUSIONS

A fuzzy algorithms based on wavelet analysis is developed to differentiate between the inrush and internal fault conditions for differential protection of power transformer. This technique is based on the differences between magnitudes of wavelet transform coefficients in the specific frequency band generated by internal fault and inrush currents. The output of FIS model shows internal fault or inrush current conditions of transformer as 1 to fault situation consequently switching has been occurred and 0 to inrush current without switching. The developed algorithm has advantages of high speed response and accuracy.

Hence, the developed algorithm can detect properly the fault current from inrush current in less than half-cycle. This algorithms is applied on the different transformer model of Y-Y and D-Yn11. The effects of different switching angles are fully demonstrated.

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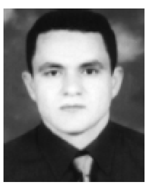

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