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Discrimination Between Inrush and Internal Fault Currents in Protection Based Power Transformer using DWT

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Abstract: Inrush currents in electric power transformers are nonsinusoidal, high currents in magnitude that are generated due to saturation of flux in the transformer core during the energization. This paper proposes a decision technique for discrimination between inrush and internal faults currents in power transformers. The technique based on wave shapes recognition by criterion extracted of the instantaneous differential currents using the discrete wavelet transform based feature extraction technique. Adaptive Neuro-Fuzzy Inference System is used as a machine learning technique to classify inrush current and internal fault current of a power transformer. The criteria based on the calculation of energy contents in extracting coefficients D4 and D5 fed to ANFIS controller to give the decision. Simulation and lab tests have been implemented. The experimental results show the discrimination can be accurately made by quantifying the extracted features, also shows the technique is reliable, quite fast, and appropriate for different types of the power transformer.

Keywords: Inrush current; Internal faults; Differential protection; DWT; ANFIS

1. Introduction

The Power transformers are considering one of the extremely important equipment for the electric power operation. consequently, due to its high financial cost and importance, transformers need a reliable protection system, fast in response and insurance to avoid losses during faults conditions. It is a crucial part of transmission and distribution in power system. To guarantee the continuous provide source, efficient and reliable performance of equipment in power system, that wanted for protecting this equipment from any types of faults conditions. Protection relay is the main element (key) in protection system. Mainly the differential relay is utilized for protecting the power transformers. The differential protection systems are the main types that methodology utilized for high rating power transformers due to the sensitivity and reliability of operation. However, this type of protections is present a problem in distinguishing and identifying between the magnetizing inrush currents and internal faults types, that lead to maloperation protection system conditions. Which consider as the main challenge is to avoid the unwanted operation this happen due to magnetizing inrush currents [1]. Energization the faulty transformer (transformer that with a permanent internal fault) and inrush current case due to starting condition consider as a challenge for the power transformer differential protection relay, since the generation of harmonic restraint quantities during the inrush current process that can block the operation of the differential element, and also can causes an extra damage if backup protection takes a long duration time to trip. Also the energization can happen due to the rain water accumulation inside of transformer enclosure or due to insulation damage problems of the transformer windings. With high amplitudes of inrush currents leads to misguide the protection to operate falsely. There are many research works one in the field of discriminate the magnetizing inrush currents from internal fault currents [2]. The differential protection system scheme for high power transformer shown in Figure 1. The unwanted operation of protection imposed in the power grid is disturbance termed could be result to change in the states of power system, this unwanted categorized as a quick lasting,

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superimposed, oscillatory and containing high frequency harmonics components [3]. Differentiation between these two types of currents must be accurate and rapid in the decision. Many factors that the inrush current in transformer depends on, these factors are loading condition, the transformer residual of magnetism and the angle of switching. Recently, many techniques for tripping restrains are considered for correct the discrimination. Inrush current in transformer contains high order harmonics and also low order, in practice, 2^{nd} order harmonic often is utilized. The harmonic restraint type techniques utilize on the assumption that contains 2^{nd} - order harmonic with high level harmonics in inrush current [4]. While the internal faults not contain this type of harmonic. Furthermore, the internal fault was found in some certain cases, during internal faults the 2^{nd}- harmonic was generated in relatively large level and the inrush current produce second harmonic with low levels in the differential current protection, and this impairs second order type the ability of the criterion detection [5]. Consequently, the commonly utilized of second order harmonic restraint technique in conventional differential protection will have difficulty for distinguishing between both types of currents “internal fault currents and inrush currents”. The previous protection techniques of transformers have included many approaches, these are: Artificial Neural Networks (ANN) [6], restraints using voltage and flux based Fuzzy Logic [7] and Adaptive Neuro-Fuzzy ANFIS technique [8]. The Fuzzy control system cannot deal with distorted or noisy input signals. In addition, the Fuzzy control isn’t flexible and also not easy for adapting to change the new elements in the power grid. Also, Fuzzy controller response time is relatively slow response for action of protection purpose. In ANN based protection technique, the ANN-network will be difficult in training because of the circuit topology changes that are occur with in big realistic circuits which cannot be reflected in a huge ANN representing these topologies. The main restricted is “the generalization capability” of the ANN, where the designed network and also trained for a certain system protection and not be utilized to protect another type system. The use of Frequency analysis of input signal techniques was used for protection as a signal processing to find a certain discrimination criterion “certain band”. Fourier equipment utilized for frequency signal analysis like necessitate the signal that is periodic and stationary [9]. However, in disturbances case in power systems the signals are non-stationary, non-periodic, and with short duration time nature. The signal analysis like the Wavelet processing technique overcomes the Fourier analysis techniques limitations. The Wavelet transform technique application is a nascent development for transformer protection [10]. This technique is considered as a newly tools for applying the frequency analysis for signals processing that have complex characteristics. Recently this technique has emerged as a powerful-tool for processing the signals in applications of power system [11]. Wavelets transform can be employed to carry out the transient condition characteristics with effective and accurate also make analysis this duration with complex frequency-time structure. Also, accommodates nonuniform type bandwidths, also the technique Dealing with higher frequency signals, and it possible to implement the analysis in different levels of a filter band [12]. The proposes of this paper is design protection scheme using Discrete Wavelet Transform (DWT) based on ANFIS to discriminate inrush current from internal fault current in power transformer. The DWT is applied to the differential currents for obtaining the detail and approximation components. The proposed algorithm uses the last detail coefficients parameters (DS) from the first level. The use of Daubechies type of DWT decomposition, then the use of an adaptive neuro-fuzzy system controller (ANFS) to give the decision weather inrush current or internal faults. The proposed technique is examined by using simulated for various inrush and internal fault type signals in the power transformer. The differential current signals are developed by software in Matlab, then the developed DWT based ANFIS is applied to the extract signals for discriminating criterion.

2. Discrete Wavelet Transform

Wavelet signal analysis is a techniques of frequency analysis which is far better than conventional techniques over its complex characteristics. There are three types Wavelet transform. Continuous (CWT), discrete (DWT) and packet transform (PWT). The main concept idea is selecting mother wavelet to extract the detection signal at different range of

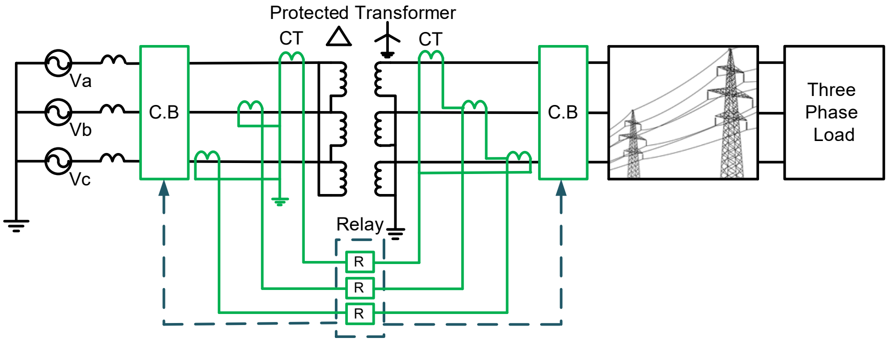


Figure 1. Basic differential protection scheme

frequencies in certain time. Wavelet (WT) is a technical tool for signal processing that is far better than the other conventional type techniques over its complex characteristics. The WT is an efficient frequency analysis tool utilized in power system analysis. This technique is of three forms. Discrete, continuous, and packet transform. The main concept of WT is selecting the mother-wavelet for signal analyzing at different bands of frequencies at a certain time. The key WT is in selecting the mother wavelet and the resolution levels. Transients condition have shorter time intervals and create high frequency components, also in contrast to low frequency components with high intervals in time. WT has the inherent advantage of focusing on the transient condition of shorter intervals time, thereby picking this condition for analysis. For this purpose, to analyze the transient current signal, for achieving reliable discrimination based on characteristics of current [13]. The discrete type of wavelet transform DWT is adequate for computer analysis applications that translation factors and the scale factor are in discrete form instead of continuous form. Calculating the coefficients in continuous WT at each scale factor is a fair quantity of data operation, and this generates an awful more processing data. DWT output is a finite of details coefficients. DWT by turns out that positions and scale factors based powers of two (dyadic scale factors and positions) are selection. The chosen process will be more efficient, smaller in execution time and accurate. The mother wavelet and scaling coefficients function are given that satisfying the two-scale equations following where n is an integer [14]:

$$\phi(t) = \sqrt{2}\sum_n h_n\,\phi(2t-n) \qquad (1)$$

$$\psi(t) = \sqrt{2}\sum_n g_n\,\psi(2t-n) \qquad (2)$$

where $\phi(t)$ in equation 1 is the scaling and $\psi(t)$ in equation 2 is the mother-wavelet for setting the coefficients of H= $\{h_n\}$ and G= $\{g_n\}$ so that $g_n = (-1)^n h_{1-n}$. mother wavelet and Each scaling function are represented by a set of G and H coefficients. These coefficients are representing as a high-pass and low-pass "finite impulse response (FIR)" filter coefficients respectively. They are used to construct the wavelet basis functions set $\phi_{j,k}(t)$ and $\psi_{j,k}(t)$ defined as :

$$\phi_{j,k}(t) = 2^{-j/2}\phi(2^{-j}t-k) \qquad (3)$$

$$\psi_{j,k}(t) = 2^{-j/2}\psi(2^{-j}t-k) \qquad (4)$$

where $\psi_{j,k}$ is the mother wavelet, j and k are the coefficient , $2^{-j/2}$ factor that define the filter type, t is the time variable and k is the period of time. If the coefficients are integers (j and k), this mean the basis functions are scaled by a 2^j factors, and translated by k of time. If the time in discrete sampled function is Δt, then $\phi_{j,k}(\Delta t)$ or $\psi_{j,k}(\Delta t)$ and in same as $\phi_{j0}(t-k)$ or $\psi_{j0}(t-k)$.

Figure 2 explains the implementation of wavelet (DWT), the original signal X, HPF and LPF, high-pass filters and low-pass filters group. The process is done by successive decomposition the signal which meaning the mother signal is bifurcated to the two components then passed through filters LPF and HPF [15]. The low pass filter output is bifurcated again and passed through the filters again HPF and LPF and the process of signal is repeated depending on the predetermined decomposition level [16]. The mother signal with frequency (Fs) sampled with 2Fs times to get the complete characteristics according to Nyquist's theorem while to reconstruction the signal, and as a corollary sampling Fs times that give a maximum frequency of Fs / 2. So that Fs /2, Fs /4, Fs /4, Fs /8 … are the frequencies in the first, second... details. In This paper the sampling frequency has considered of 50Hz.

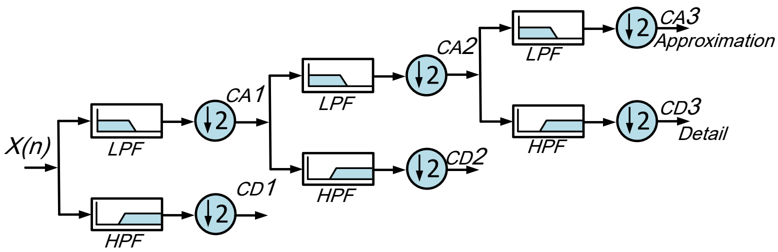


Figure 2. Diagram of multiresolution form approximation and details

By applying this analysis technique, any wavelet of signal can be implemented. The filters coefficients are associated with the selection of mother-wavelet. The signal is decomposed in to two signals approximation and details that which represent a smooth and detailed version of the original signal. This process is repeated with the approximation being decomposed further to generate the next components of approximation denote by A and detail denote by D, which are directly related to the original signal sampling rate this analysis called multi-resolution analysis denote by MRA [17]. This algorithm delivers a signals description for currents in differential protection as change with respect to time at different scales large or small depending on the components "large scales are associated with low-frequency components and small scales are associated with high-frequency signatures". Although wavelet analysis of signal is more complex than other types of signal processing, but it is ideally suited for dealing with non-stationary signals as are the magnetizing inrush current. There are many types of mother-wavelets, like Harr, Daubiches (db), Coiflet (coif) and Symmlet (sym) wavelets [18]. The choice of mother wavelet plays a significant role in detecting and localizing different types of fault transients [19]. Based on the conventional differential protection scheme, this paper proposes a differential protection algorithm for discriminate between inrush and internal fault in power transformers using the wavelet coefficient energy contain of the operating and restraining currents, this method based on the theorem of Parseval, the spectral energy (E) of the current i inside a sliding window with length _k is decomposed into energy of scaling and wavelet coefficients. The wavelet coefficient energy is given by [20]:

$$E = \sum i(n)^2 \tag{5}$$

Where E is the energy calculated by using a sliding window technique with covering a cycle, and n is sliding window length. In this work the chosen type was Daubechies (db), the current signal (operating restraining currents of differential protection) was decomposed up to five levels for better resolution and Detail coefficients four (cD4) and five (cD5) were used for feature extraction. The energy content is calculated for the extract coefficients cD4 and cD5, then these two signals fed to Adaptive Neuro-Fuzzy System ANFIS. The output of ANFIS gives the decision for discrimination between the inrush and internal fault conditions. Figure 3 shows the proposed method. This feature of differential current was extracted using discrete wavelet detail coefficients for one dimension using MATLAB.

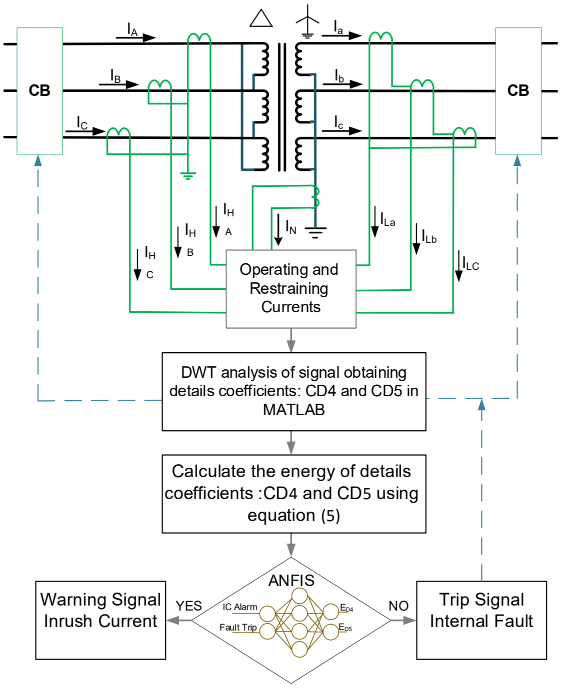


Figure 3. Proposed wavelet-ANFIS based differential protection algorithm

3. Modeling and Control Design

Neuro-Fuzzy systems are appropriate for approximate or reasoning uncertain especially for that systems with a difficult derive mathematical model. For these systems Fuzzy logic controllers play an important role in many applications especially the practical [21]. Many types of inference mechanisms in the Fuzzy logic control system, in this study "Takagi-Sugeno" is selection. It maps inputs through input membership function (MF) and related parameters, then through output membership function MF to outputs [22]. The Neuro-Fuzzy system uses "back-propagation" or a combination of "back-propagation and least square estimation" for membership estimation the parameters [23]. The objective of the learning Neuro-Fuzzy algorithm is to adjust the parameters of the input and output membership functions so that the ANFIS output best matching the training data. A hybrid learning strategy (Gradient Descent-GD and Least Squares Estimate-LSE) is applied to identify the network parameters. The GD method updates the antecedent membership function parameters while LSE identifies the consequent parameters [24]. To tune the TS rules using ANFIS, two sets of data are to be generated. The main idea in the data classification is designing rules of Fuzzy logic. The Neuro-Fuzzy controller technique contributed to many electrical protection applications like distance relay, differential relay and overcurrent relay [25]. The input Fuzzy Logic was split into 7 membership function triangular type MFs with overlapping of 50%. Thus, for two inputs, 49 control rules, the resulting linear functions required to be determined. This procedure is performed by using the Neuro-Fuzzy in Fuzzy Logic Toolbox in Matlab. The discrete wavelet transforms and Neuro-Fuzzy control system designed using MATLAB\Simulink. The input data extracted D4 and D5 and the Neuro-Fuzzy control controller output described in Table I, where this data is used to start the training procedure and the extract wave coefficients relation. The Neuro-Fuzzy control design structure and the surface are shown in Figures 4 and 5 respectively.

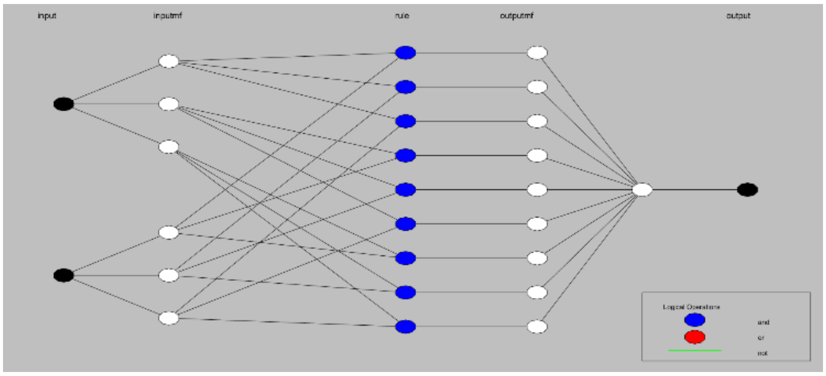


Figure 4. ANFIS design structure

Table I. Fuzzy rules

D4	D5	output
0	0	0
0	1	0
1	0	0
1	1	1

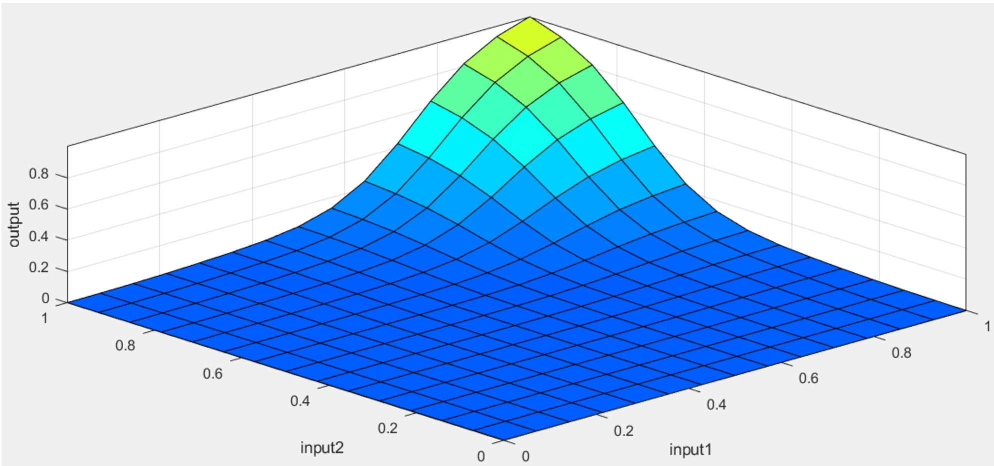


Figure 5. ANFIS design surface

First step is concerned to design the power transformer model for accurately data collect that needed. The required data mainly consists of unloaded transformer (magnetizing inrush current) for switching conditions and many types of faults conditions as internal fault (single phase, phase to phase and 3-phase). From the collected information it can be employed to choosing the mother wavelet and also a resolution levels number. In presented work, a 250 MVA, 400/133 KV, core type with connection (Y- Δ), 50 Hz, the power transformer is used for collecting differential current, sampling data with sampling frequency 1MHz as shown in figure 6. Simulation of the power system during steady-state, energization conditions, and internal faults (on 100% of transformer windings) is done using MATLAB simulation package. The inputs for sampling the signals of three phase differential current, a decision to declare there is inrush current occur depends on the DWT the extrude D4 and D5. To analyze the behaviour of the inrush current, it was reproduced by switching on the power and energized the transformer in a no-load condition. As shown in the algorithm the current signal first loading to the workspace to extrude the signal to obtain D4 and D5 and the energy contained in both D4 and D5 are calculated using equation 5. The inputs data to the controller are as mentioned 2 vectors energies of D4 and D5 respectively as shown in figure 7.

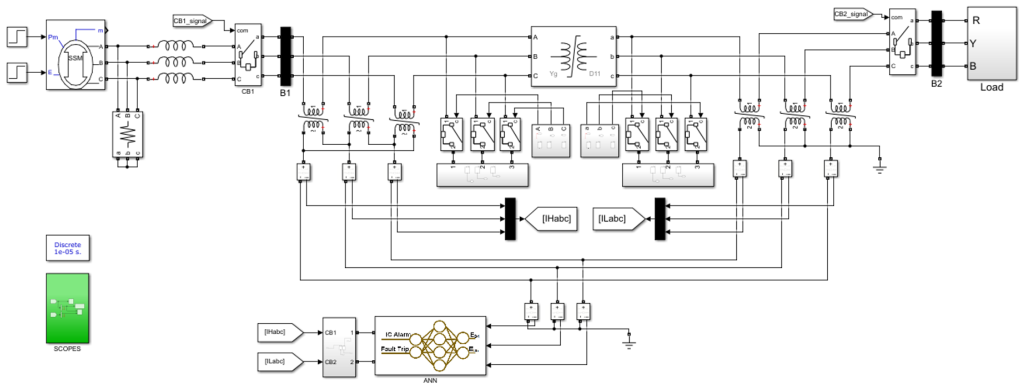


Figure 6. MATLAB simulation model proposed study

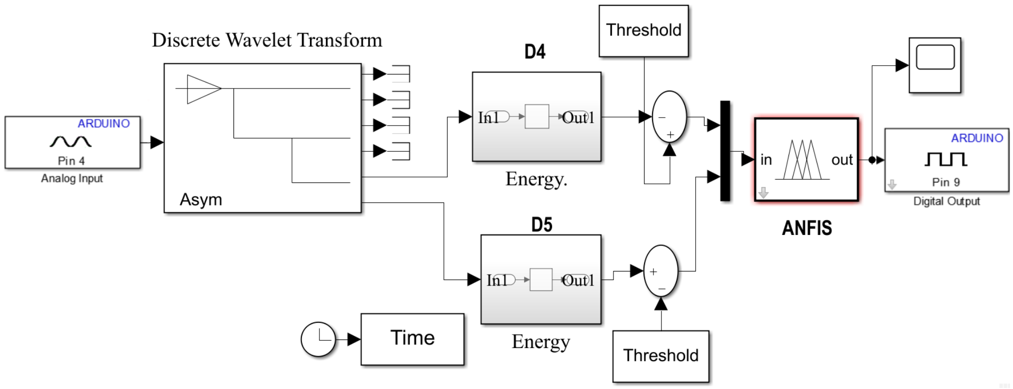


Figure 7. Controller circuit design

4. Simulation Results

To validate the proposed technique methodology three cases of internal faults are presented: line-to-ground, line-to-line, and three line-to-ground, the algorithm was implemented using MATLAB. The CTs that were utilized on both sides the primary and secondary are 400:5 and 1200:5 respectively. It was applied a Y- connection for CTs in Δ-side and Δ-connection for CTs in Y- side as shown in Figure. 4.The conditions of inrush current were simulated with the secondary side without load i.e. the transformer secondary open.

a. Case 1: Inrush Magnetizing current

To achieve the magnetizing inrush current condition, the transformer is starting with no-load in secondary, then the transformer switching on the inrush current will flow in transformer depending on magnetizing characteristic of the tested transformer, the inrush level is about 10-times of the steady-state. The inrush current transient condition is seen like a spike train. These trains in sharp spikes happen instantly following the inception of fault time. This difference in wave form can be used effectively as important feature to make discriminate with the internal faults. The results of simulation, for transformer no-load, is given in Figure 8. From Figure 8 the transient cycle takes time to settle and also the amplitude of about 6 times of the rated current. The inrush current analysis utilizing DWT for extracting the differential current signal (S) shown in figure 9. From the analysis result, it’s clear the level of D4 and D5 coefficients were 0.005 with and 0.003 forms the nominal value of steady-state current where they used in this study for discriminating the inrush current from the internal faults. The energy contains in D4 and D5 coefficients are calculated using equation 5, Figures 10 (a) and (b) show the energy contain in D4 and D5 respectively. The energy level in D4 was 5pu. and in D5 was 7pu. The ANFIS controller decides the occurs of internal faults or inrush current conditions depending on the energy level of the coeffeicients D4 and D5 as shown in Figure 11, it clearly shows the ANFIS based DWT action and the trip signal is shown in Figure 11. It's clear the ANFIS signal is Zero level which mean no internal faults were occur.

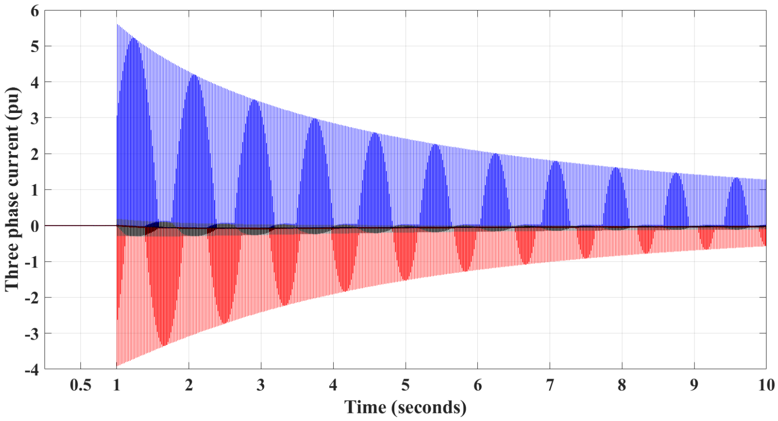


Figure 8. Inrush magnetizing current

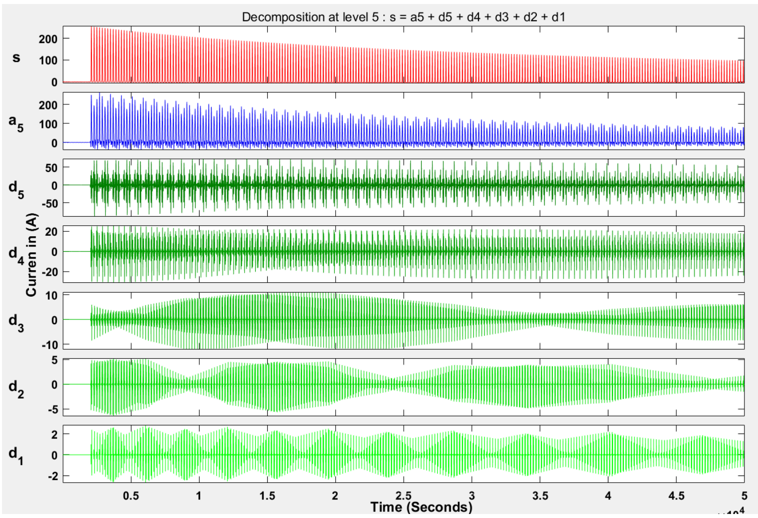
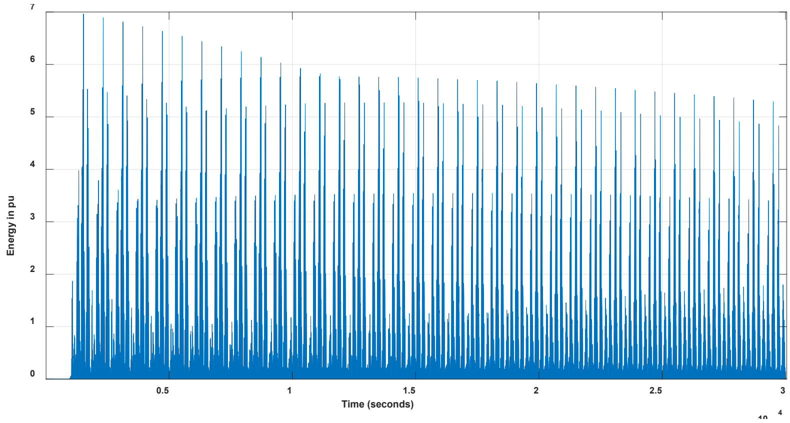
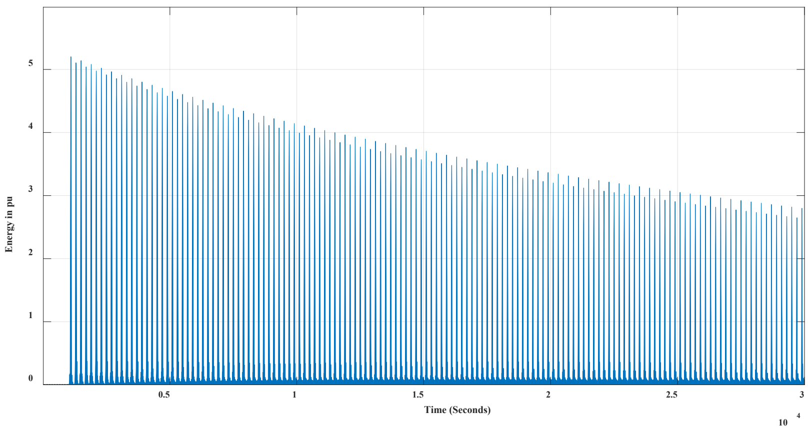


Figure 9. DWT analysis of inrush current



(a)



(b)

Figure 10. The energy in details coefficients (a) D5 (b) D4

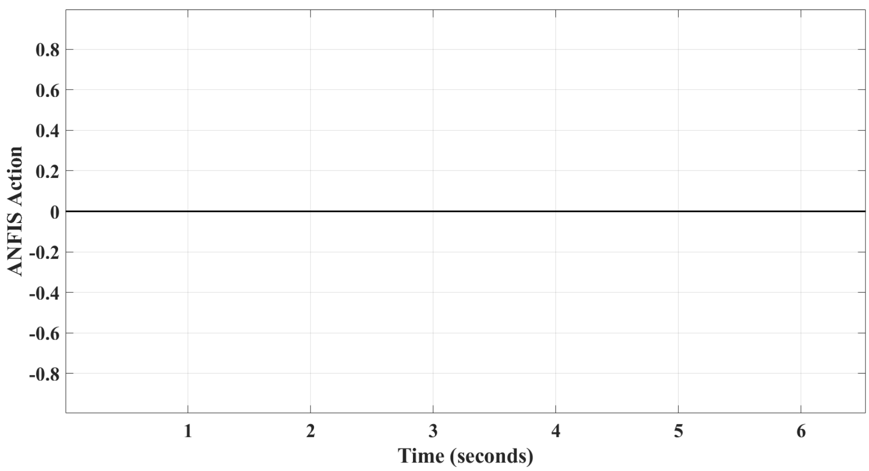


Figure 11. ANFIS based protection responses

b. Case 2: Single-Phase to ground Fault

To achieve fault condition the test carried out by connected one of the phases to ground (phase a). Figure 12 shows the single line to ground fault (internal fault), the differential current will flow in the protection relay. The differential current analysis-based DWT for three phases are shown in Figure 13, its clear to show the energy of D4 and D5 coefficients. During the single phase to ground fault condition, the transient condition with high frequency is generated in the fault current. The Transient spike occurrence and then decay rapidly is noticed in about a cycle and less than in the inrush current condition duration time. The energies of D5 and D4 are calculated as in the case 1, and shown in Figure 14 (a) and (b) respectively. It clears the energies contents is very little and less than the threshold value of the ANFIS controller and generates only in high-frequency transient edge. Figure 15 shows the response of the ANFIS controller and gives a trip signal on an internal fault condition the ANFIS output changes from Zero to One level.

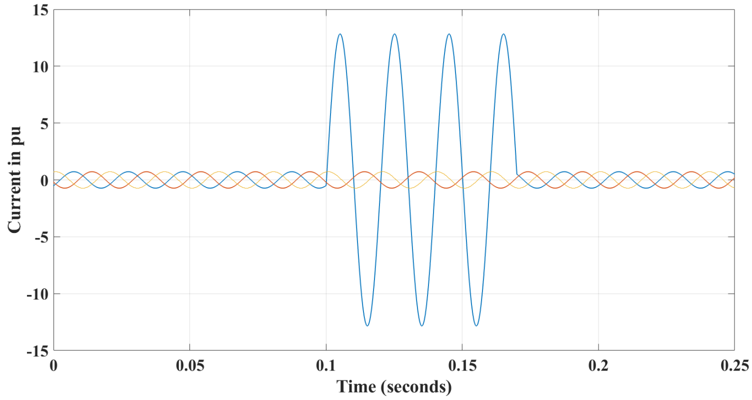


Figure 12. SLG internal fault

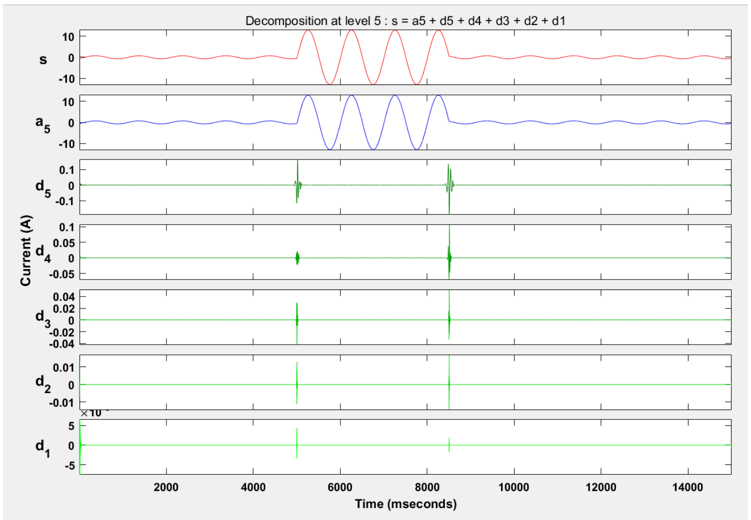
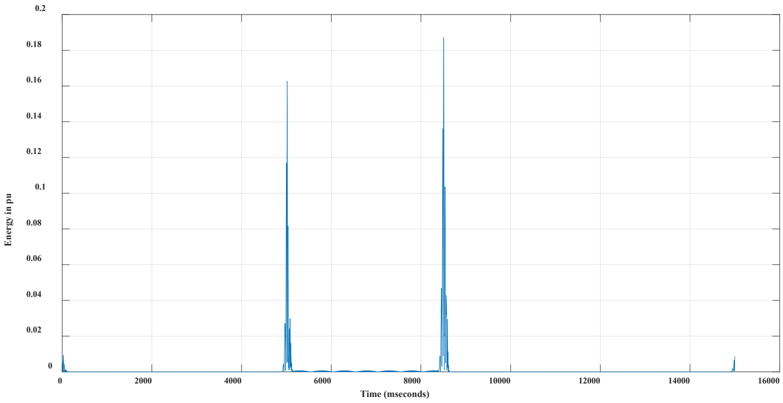
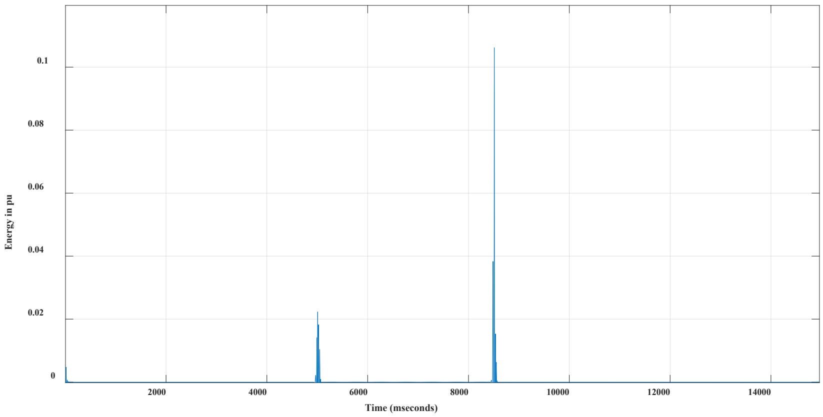


Figure 13. SLG fault DWT analysis



(a)



(b)

Figure 14. SLG fault energy coefficients (a) D5 (b) D4

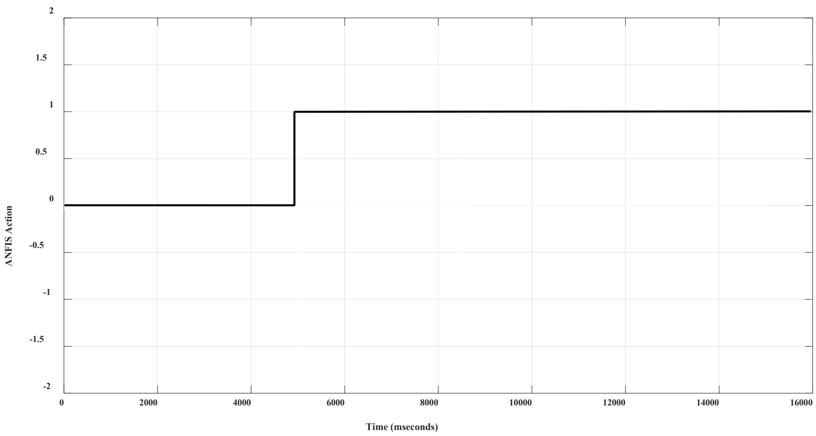


Figure 15. The responses of the ANFIS (Trip)

c. Case 3: Line to Line Fault:

The test carried out through Connecting two phases phase "a and phase b" as shown in Figure 16. The fault current will flow in the differential path of the differential relay. The differential current analysis-based on DWT for the three-phase is shown in Figure 17. As in case 2, During the transient condition, the spike generated the details coefficients D4 and D5 shown that signals approximate a zero, the energies contents of D5 and D4 are shown in Figure 18 (a) and (b) respectively. From Figure, it's clear the energies are about zero. The trip signal representing ANFIS based DWT response was zero until the fault occur then the level had become One as shown in figure 19.

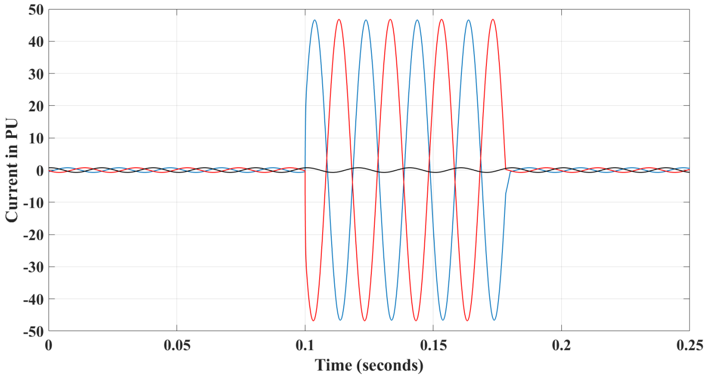


Figure 16. LL internal fault

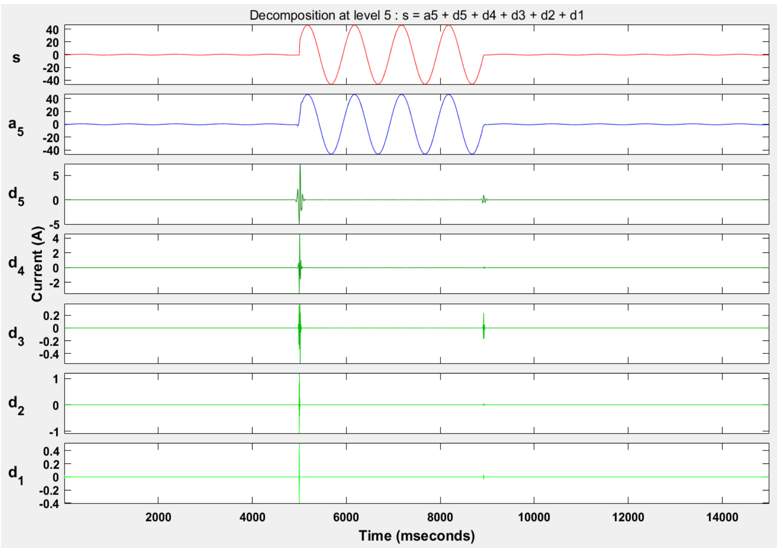
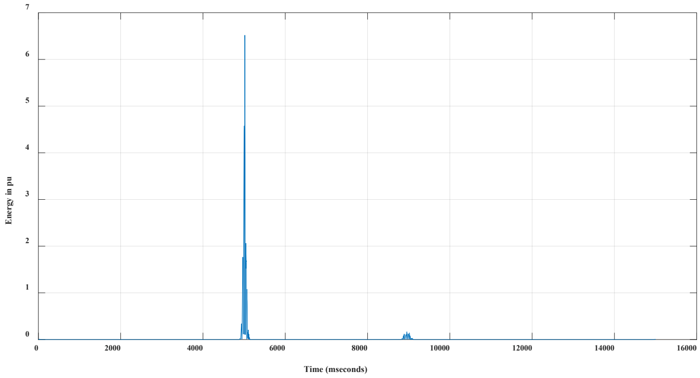
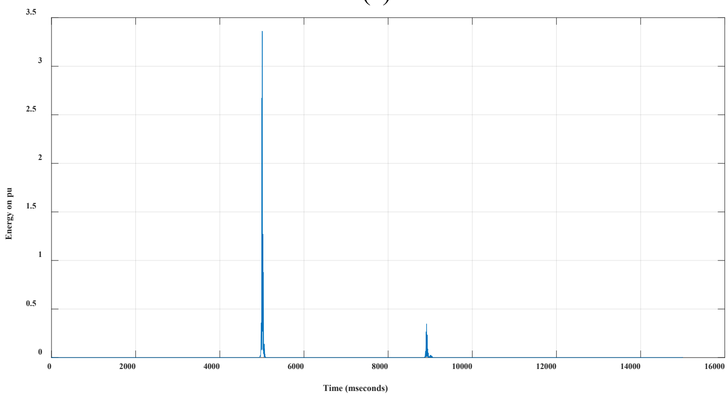


Figure 17. LL fault DWT analysis



(a)



(b)

Figure 18. LL fault energy coefficients (a) D5 (b) D4

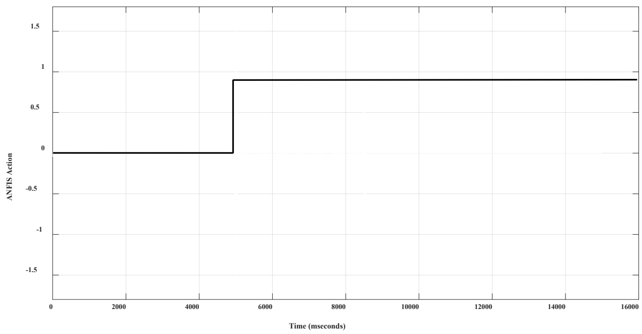


Figure 19. ANFIS responses (Trip)

5. Lab Test

The lab model used in this study includes, the host computer that was interfaced with microcontroller (Arduino type mega 2560) the signals from the three phase line currents of differential current detect by using current sensor (ACS712). The controller algorithm is developed in MATLAB (Figure 7). The prototype model of power circuit consists of three phase supply of 400V, 1KW load and power transformer with 100KVA (Y-Δ) the connection diagram shown in Appendix A. The sampling frequency of the input signal is fs=5KHz or t=0.2 msec, the measured values of differential current taken through microcontroller and stored in M-file of Matlab (workspace). To validate the protection designed two cases were implemented inrush magnetizing current and single-phase to ground fault current. First case, the power transformer is starting with no-load, inrush transient current is shown in Figure 20 and DWT analysis is shown in Figure 21.

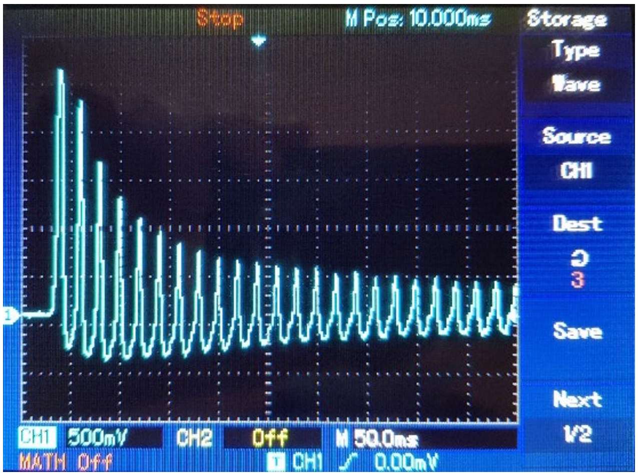


Figure 20. Measured inrush magnetizing current

The energy level in D4 and D5 are shown in Figures 22 a and b respectively. The output controller shown in Figure 23. Second case is single-line to ground fault current this test is done by connected one of the phases to ground (with small limiter current resister). Figure 24 shows the single line to ground SLG fault (internal fault).

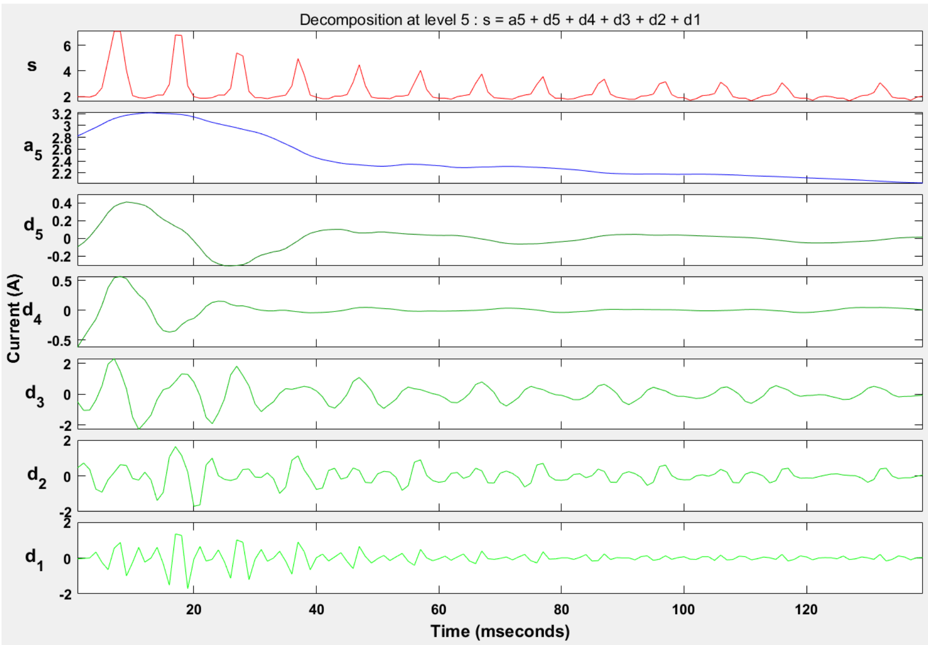
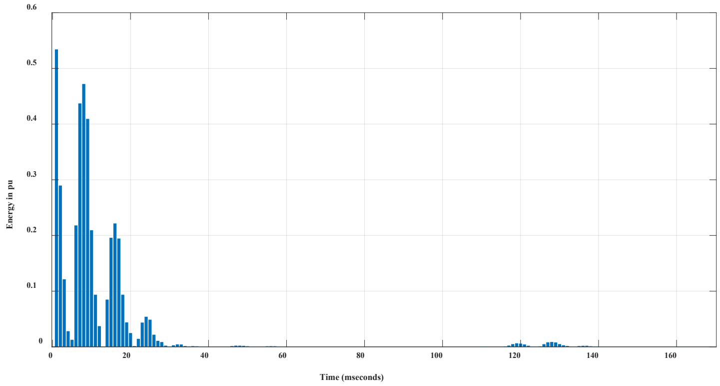
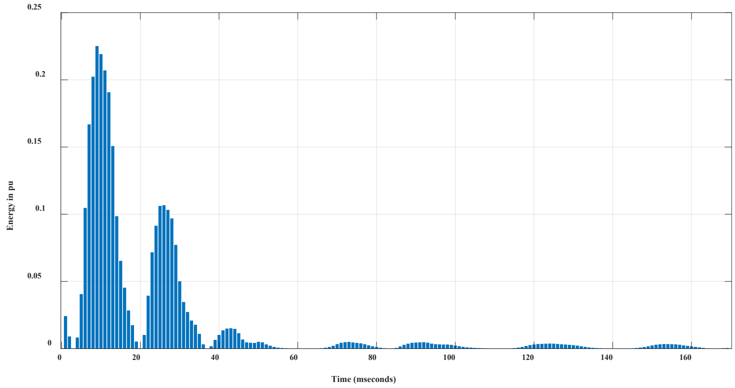


Figure 21. DWT of the inrush magnetizing current



(a)



(b)

Figure 22. Energy level in details (a) D4 (b) D5

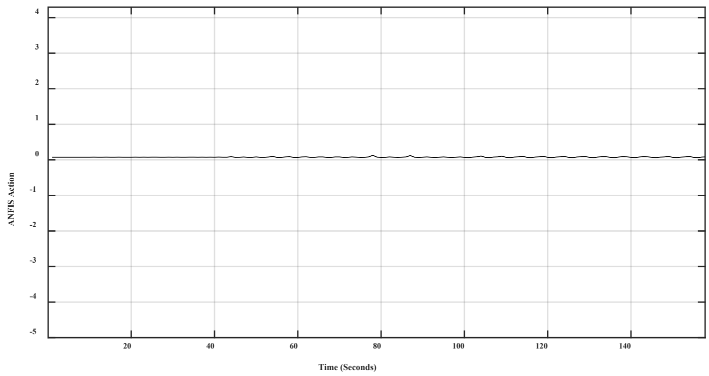


Figure 23. Controller response

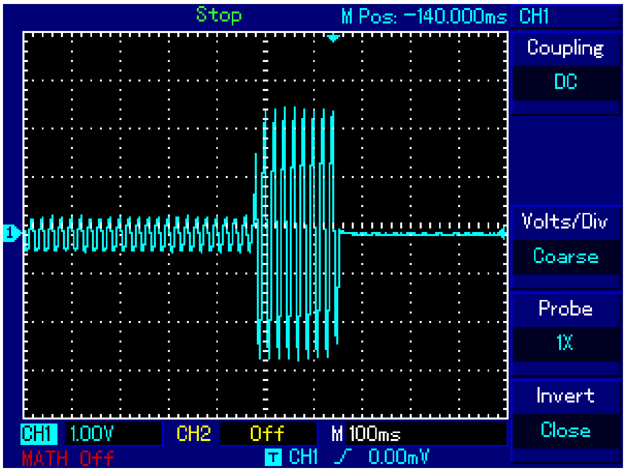


Figure 24. SLG internal fault test

Differential current analysis-based DWT for three phases is shown in Figure 25. The energies of D5 and D4 are shown in Figure 26 (a) and (b) respectively, energies are very small and generates only in high-frequency transient edge. Figure 27 shows the response of the ANFIS controller and gives a trip signal on an internal fault condition. Figure 28 shows the prototype lab experiments. The practical results showed that they matched the results obtained from the simulation analysis for inrush current case and fault current case.

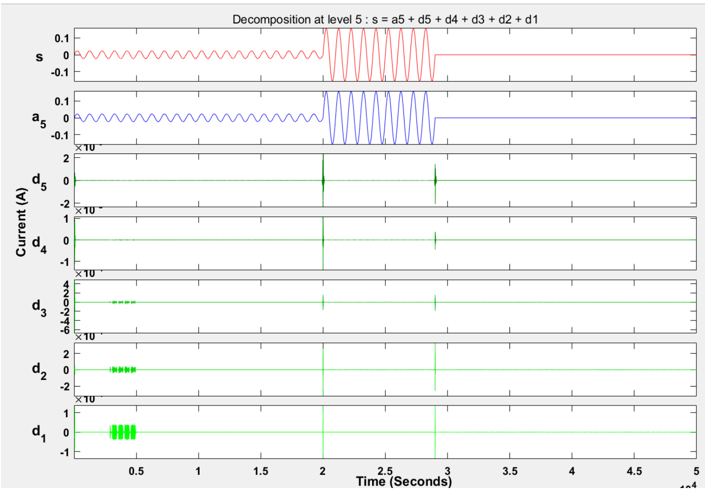
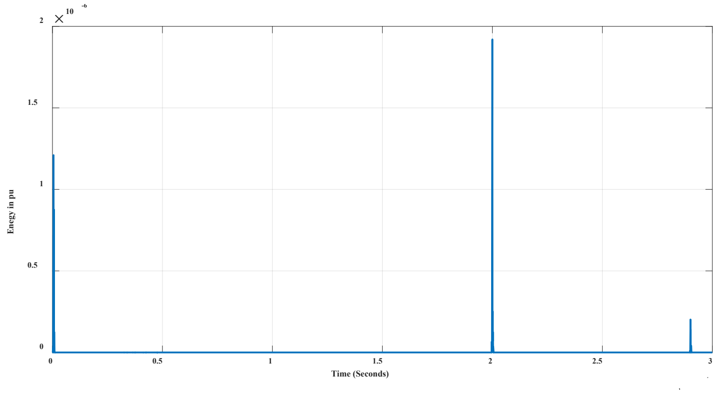
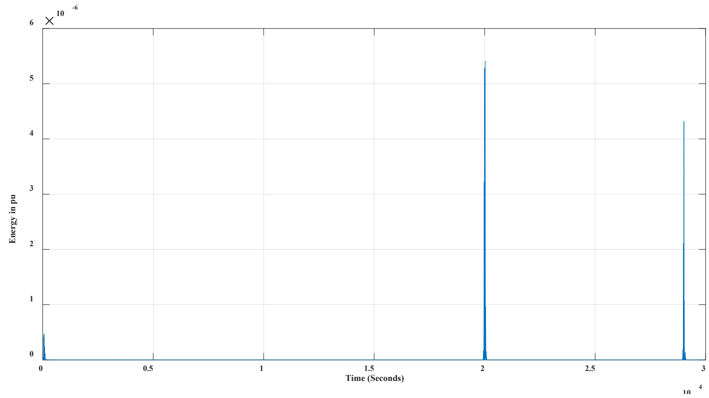


Figure 25. DWT analysis of the measured SLG fault



(a)



(b)

Figure 26. Energy level in details (a) D4 (b) D5

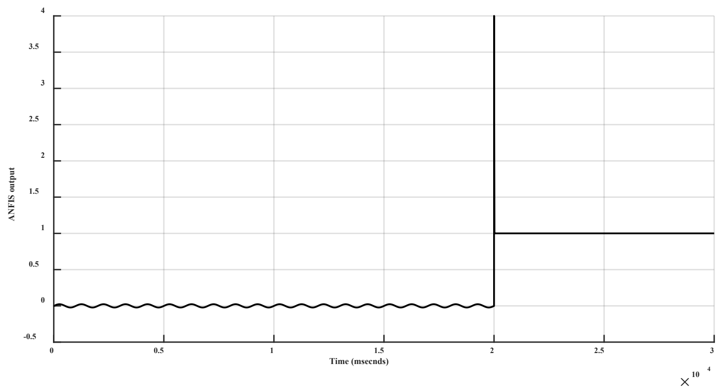


Figure 27. The responses of ANFIS (TRIP)

6. Conclusion

DWT is an appropriate approach for waveform analysis. A new algorithm technique was proposed for discrimination between magnetizing inrush and internal fault currents. The previous approach used the harmonic restraint differential relay takes at least one cycle to operate for internal faults but DWT identifies an internal fault immediately after the fault inception. The controller algorithm is developed in the Matlab. A new approach ANFIS based DWT presents the discrimination depends on two parameters: the energy contained in D4 and

D5 detail coefficients. To validate the new algorithm simulation and lab tests have been implemented, for simulation results the experiments for different fault cases show that the proposed approach provides an adequate performance to discriminate the magnetizing inrush current (no fault) from other internal faults, where the energy level in D4 is 5pu and D5 is 7pu (inrush current case), while in the other types of faults the energies levels were about Zero. Experimental results for inrush and also line to ground fault approved the scheme provides an adequate in achievement into discrimination. The practical results showed that they matched the results obtained from the simulation analysis for inrush current case and fault current case.

Figure 28. The practical prototype

7. Acknowledgment

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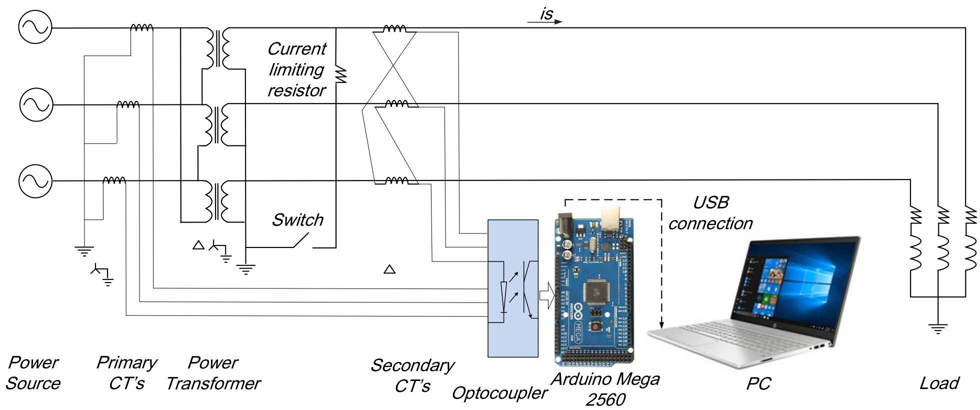
Appendix A
Prototype connection diagram:



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