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High impedance fault detection in radial distribution network using discrete wavelet transform technique

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Abstract: Detecting high impedance faults (HIFs) is one of the challenging issues for electrical engineers. This type of fault occurs often when one of the overhead conductors is downed and makes contact with the ground, causing a high-voltage conductor to be within the reach of personnel. As the wavelet transform (WT) technique is a powerful tool for transient analysis of fault signals and gives information both on the time domain and frequency domain, this technique has been considered for an unconventional fault like high impedance fault. This paper presents a new technique that utilizes the features of energy contents in detail coefficients (D4 and D5) from the extracted current signal using a discrete wavelet transform in the multiresolution analysis (MRA). The adaptive neuro-fuzzy inference system (ANFIS) is utilized as a machine learning technique to discriminate HIF from other transient phenomena such as capacitor or load switching, the new protection designed scheme is fully analyzed using MATLAB feeding practical fault data. Simulation studies reveal that the proposed protection is able to detect HIFs in a distribution network with high reliability and can successfully differentiate high impedance faults from other transients.

Key words: high impedance fault (HIF), multiresolution analysis (MRA), overcurrent relay, discrete wavelet transform (DWT)

1. Introduction

High impedance fault (HIF) occurs when a primary conductor circuit makes an unexpected electrical contact that restricts the flowing current below the detection level magnitude of the overcurrent protection [1]. This condition leaves "an energized conductor" at the level of the ground posing a public hazard and jeopardizing the power supply reliability. Moreover, these faults are accompanied by arcing, which can cause fire and risk of electric shock. For these reasons, detection of HIF in distribution power systems is intensely researched [2]. HIFs detection has been an interesting matter since 1970, nevertheless, the process of detecting is not yet completed [3]. In the case of a conventional fault, when the fault current is greater than the relay setting, protection will react to the fault and HIF will not happen because the setting of the relay has lower values than the HIF current, see Fig. 1 [4]. A technique based on the lower type order harmonic ratio is proposed in [5]. The drawback of this kind of technique requires a few threshold settings that affect the detection technique performance. The analysis based on time-frequency presented in [6–10] perfectly exposed the detection process performance. However, the false percentage of detection seems to be a major setback, especially in practical applications. Several studies in many of last year's technique-based research have set out aims for effective HIF detection. These techniques involve the algorithm of frequency-time [11], multi-layer, neural-network feed-forward type [12], the Kalman-filter approach [13], the ratio of low order harmonics [14]. Wavelet transform WT has been extensively utilized for signal processing for its ability to detect the component of frequency and its position with time [15].

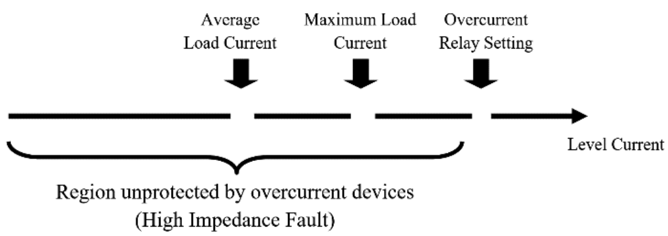


Fig. 1. Overcurrent device setting against high impedance fault current

This technique has been used in power system protection for over a decade [16]. Wavelet transform developed in recent years, is a comparatively new concept, this technique is successfully used in many fields like signal processing, acoustics, optics, speech discrimination, and, recently, in the power system. Typical applications include analysis of transients, protection, detection and classification, power quality, etc. [17]. Unlike the "Fourier transform", WT is capable of providing information on frequency and time simultaneously, and hence gives multiple resolutions, which is the most important feature when analyzing signals in transient containing high and low-frequency components. This study proposes an identifying protection scheme based on the DWT technique in common with ANFIS, it also discriminates HIFs that happen on distribution feeders. Conventional "overcurrent protection" is not capable of detecting HIF because of the level of current. According to the mentioned, related literature, the main HIF characteristics show the low level of current amplitude. A typical feeder's current levels are shown in Table 1, which presents them for different types of surfaces [18].

In general, the conductivity will increase with moisture content, mineral content, and temperature. It is important to validate the experiments that are shown in Table 1.

The current levels vary from 0 A to 75 A at 12 kV depending on the surface [19]. In the condition when a line falls to the surface like soil, the soil is the main resistivity source where the resistance of ground will be accounted "fault resistance". The surface resistance is a function of the overall resistance of fault in the contact with the environment.

Table 1. Current versus surfaces types at 12 kV

Surface type	**Feeder current (A)**
Dry asphalt	0
Concrete	0
Dry sand	0
Wet sand	15
Dry sod	20
Dry grass	*25*
Wet sod	40
Wet grass	50
Reinforced concrete	75

2. Modelling HIF using DWT

Wavelet transform technique is a powerful system tool for transient response phenomena because of the ability for extracting both frequency and time information of the signal [20]. The DWT theory analysis process is compared to the fast Fourier transform (FFT), documented in [21]. The wavelet transform is a technique for signal processing after an extruding process of a series of decomposition steps, it can represent various ranges of frequency. This is done by dilation and S-signal "mother wavelet" translation through the data signal. Wavelet analysis is a method of signal processing so that, after a series of decompositions, the signal is represented at different frequency ranges. DWT is presented by [22] and shows the processing of the signal in a digital form:

$$f(x) = \frac{1}{\sqrt{M}} \sum_k W_\varphi\left(j_0, k\right) \varphi_{j_0,k}(x) + \frac{1}{\sqrt{M}} \sum_{j=j_0}^{\infty} \sum_k W_\psi(j, k) \psi_{j,k}(x), \tag{1}$$

where an approximation coefficient is:

$$W_\varphi\left(j_0, k\right) = \frac{1}{\sqrt{M}} \sum_x f(x) \varphi_{j_0,k}(x), \tag{2}$$

and a detailed coefficient is:

$$W_\varphi\left(j_0, k\right) = \frac{1}{\sqrt{M}} \sum_x f(x) \psi_{j,k}(x), \tag{3}$$

where: W is the mother of wavelet signals, $f(x)$ is the signal that indicates the input and translation parameter as well as scaling, M is the function of integer parameters. When divided by the approximate coefficient symbol (A) and detail coefficient symbol (D), the result is geometric scaling (i.e., $1,\ 1/a,\ 1/a2,\ \ldots$) and translation by $0,\ n,\ 2n,\ \ldots$. This scaling gives the DWT logarithmic frequency coverage. DWT can be implemented by a multistage filter with the "mother wavelet" as both the "low pass filter" L(n) and its dual, the "high pass filter" H(n). Down sampling the low pass filter output (n) by factor 2 that scales the wavelet in the "next stage" using the same factor 2, is intended to simplify these dilation processes. The output of the high pass filter gives a detailed version of the high-frequency component of the signal [23]. The component of low-frequency is also more split to give further details of the input signal. The signal is then decomposed into different ranges of frequency by successive high pass and low-pass filtering. This is shown in Fig. 2. Using the DWT technique, any signal details can be implemented. Filter coefficients are selected according to the S-signal (mother wavelet). The S-signal is decomposed into two types of "approximation and details" that represent the data of the mother signal.

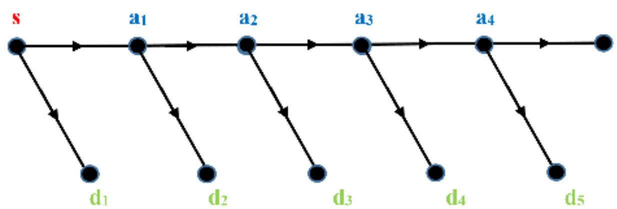


Fig. 2. DWT analysis of signal S

This process of extrusion is repeated in the approximation process for further decomposition that generates the detail (D) of the next step and also generates the approximation (A). The discrete wavelet parameters, "approximation and details", are directly related to the sampling rate of the mother signal [24]. Figure 3 shows the signal process named multi-resolution analysis (MRA). MRA process algorithm steps deliver a description signal either in the form of voltages or currents that function in different scales time, in which large scales are related to the components of low frequency and small scales are related to the components of high frequency. For many years, protection engineers and researchers have looked for solutions to this long-standing problem.

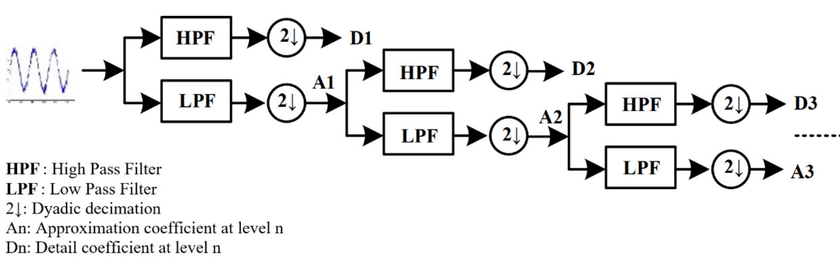


Fig. 3. Multiresolution diagram of approximation and details

Although the DWT technique is more complex in analysis than other types of signal processing, DWT is more appropriate to deal with "non-stationary signals", such as HIFs. There are many types of mother wavelets like, for example, Daubiches (db), Harr, Symmlet (sym), Coiflet (coif), and others. The mother wavelet type selection plays an important role in detecting different fault transients' types. The choice also depends on a specific application. In this work, the Daubiches (db) type was chosen for better resolution, the current data signals were decomposed into five levels and detail-coefficients such as (CD1-CD5) were utilized for feature extraction. The next feature was obtained from the signal data extracted from the feeder (three phases) employing detailed coefficients of the wavelet transform (WT) for one dimension (1D), (wave menu-MATLAB). The energy of detail 4 and detail 5 (D4 and D5) are calculated using:

$$E = \sum x(i)^2, \tag{4}$$

where E denotes the energy content, calculated using the sliding window technique covering a half cycle on each level and compared with the threshold values which are equal to 0.1 pu [25]. After the energy of D4 and D5 is calculated, the rms of the original signal becomes the input to the Adaptive Neuro-Fuzzy System (ANFIS) with a duration time of about 100 cycles. The output of the ANFIS gives information on HIF that occurs in the system. Figure 4 shows the block diagram of the proposed HIF detection.

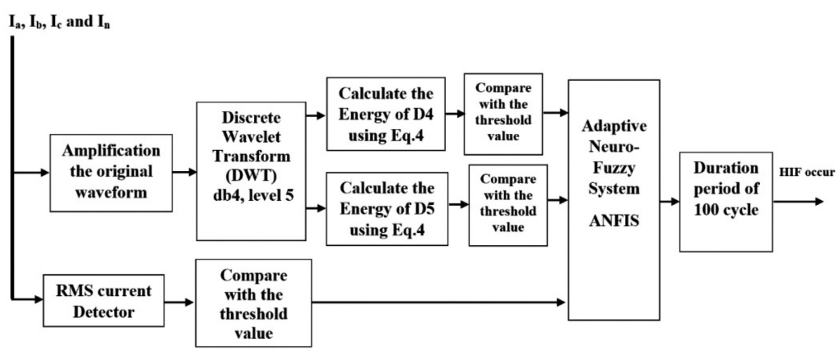


Fig. 4. Control system model

3. Control design based on DWT

Neuro-Fuzzy controllers are appropriate for approximate logic mostly for the system where it is complicated to implement a "mathematical model". This type of controller plays a significant role in many practical applications [26–28]. There are many types of inference mechanisms in the fuzzy logic control FLC system, "Takagi-Sugeno" is selected in this research [29]. This control system has many inputs via membership functions (MFs), depending on related coefficients, and via output membership functions (MFs) through outputs.

In this study, the Neuro-Fuzzy system employs a combination of "back-propagation and least square estimation" to estimate the parameters of (MFs) [30]. The main thing for data classification is to achieve fuzzy logic rules [30]. The controller inputs are three parameters: energy of details D4 and D5 and also the rms value of the original signal as shown in Fig. 4. The three-phase signals are extracted using DWT and the obtained details D4 and D5 of the extracted mother wave show the energy calculated for a given period and are compared with the threshold value. The output of comparators is the input to the ANFIS controller, the third signal to the ANFIS is coming from the rms value of the three-phase signals after comparison with the threshold value.

The selected practical model consists of a feeder of 400 V with a load of 4 kW, the signal data were recorded. Controller inputs – "three-phase and ground wire"- are sampled then, a decision concerned HIF depends on the DWT extrude coefficients D4 and D5.

To analyze the HIF behavior, the fall of one of the conductors onto wet sand was recreated, as is shown in Fig. 5. The 4-inputs for lines and neutral currents were measured by current probes. These signals contain high-frequency components due to high impedance fault conditions, scaling these signals to match with electronic circuits. The signal enters the microcontroller through input to output ports and is stored in the memory, then it is loaded to the workspace in MATLAB-19 to extrude the signal to obtain D4 and D5 and the energy contained in both D4 and D5.

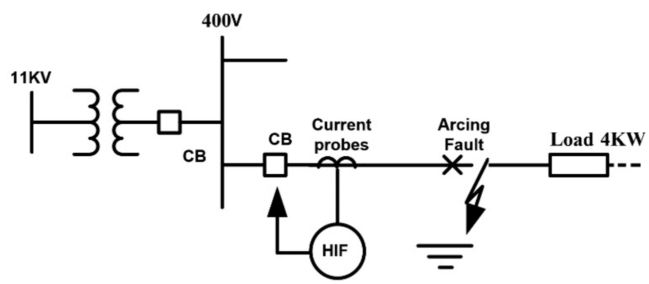


Fig. 5. Circuit under study

As mentioned before the input data signals sent to the designed controller are the data of three vector energies of D4, D5, also the rms value of the mother wavelet signal, respectively, as shown in Fig. 6. The input to the controller of FLC was designed by splitting the membership function into three triangles which overlap by 50%. For three inputs, 36 controlling rules based on the result of the "linear function" relation should be determined. This procedure is achieved by Fuzzy Logic Toolbox in MATLAB/Simulink (Neuro-Fuzzy). Also, the discrete wavelet transforms can be done using MATLAB/Simulink. The rms increased and exceeded the threshold value as in Table 1. Figure 6 shows the ANFIS controller design for the HIF detection.

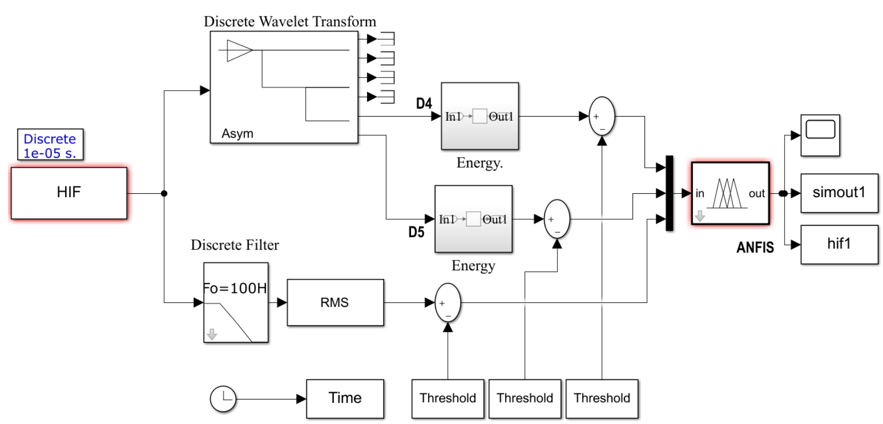
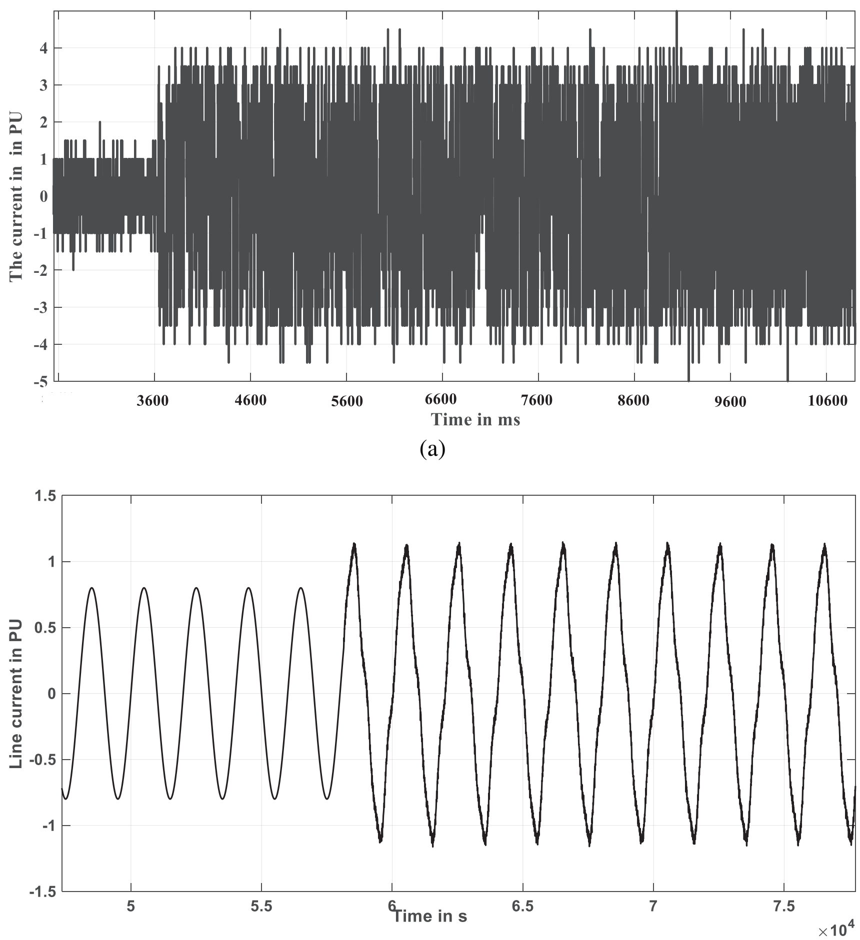


Fig. 6. Control design using MATLAB

4. Laboratory test

Before triggering the HIF action by lowering the conductor, we assumed that steady-state conditions had been reached and the transient conditions had ended. The laboratory model includes mainly a host microcomputer interfaced with a microcontroller "Arduino mega 2560", the three-phase signal currents and neutral currents were registered by using (ACS712) for detecting currents. The designed controller was developed in MATLAB. The power model consisting of 400 V three-phase power fed a 4-kW load as mentioned before. Current signals were taken from 3-line and neutral currents with a sampling frequency of 5 kHz, these signal fault conditions were registered through a microcontroller and stored in the MATLAB/workspace. High impedance fault had been done experimentally by lowering a single conductor of three phases to the wet sand surface. Figure 7(a) shows the data signal coming from the current probe and stored in the



(a)

(b)

Fig. 7. Measured current after: (a) HIF occurs; (b) after conditioning

workspace through microcontroller (Arduino-type). Figure 7(a) shows the steady-state HIF after conditioning started at $t = 4.5$ s.

Figure 8 shows the DWT analysis results based on the waveform extrudes amplitude coefficients of D4 and D5, which were 0.007 and 0.003, related to the steady-state nominal current.

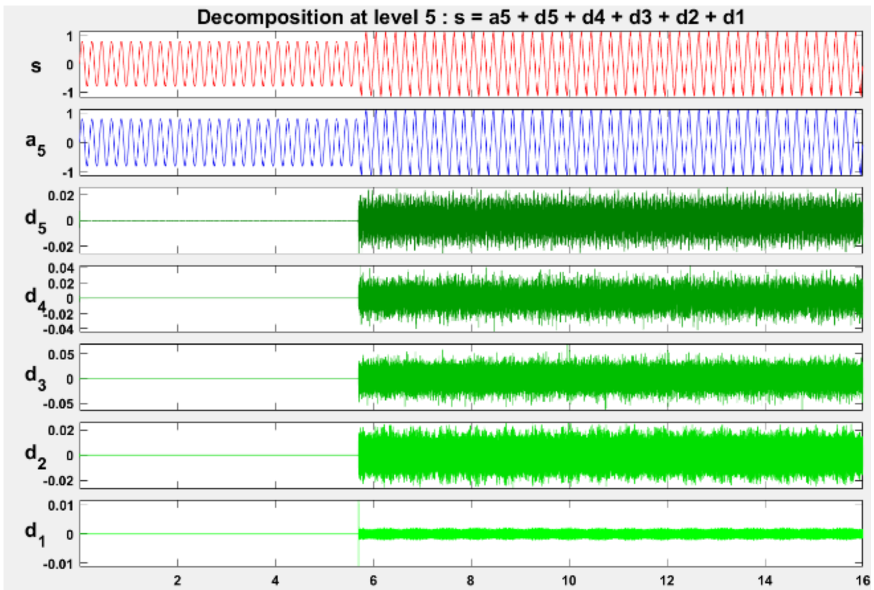


Fig. 8. DWT analysis after HIF

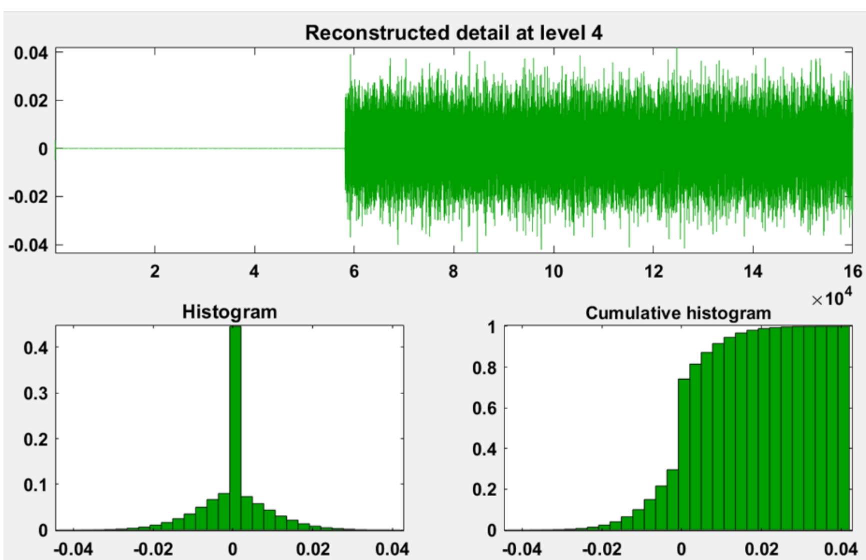


Fig. 9. Detailed D4 of HIF

The details of D4 and D5 are shown in Figs. 9 and 10, respectively. To discriminate the HIF, the energy contents in D4 and D5 were calculated using (Eq. (2)).

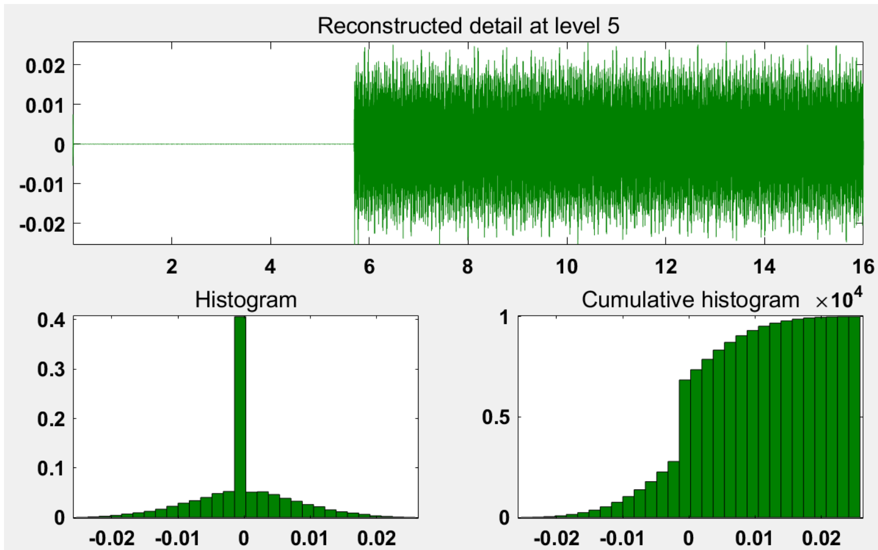
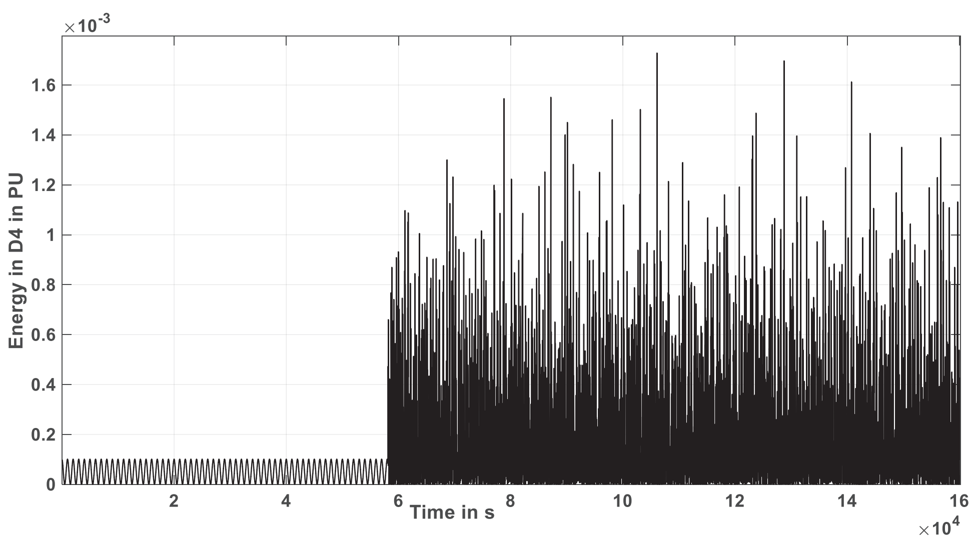
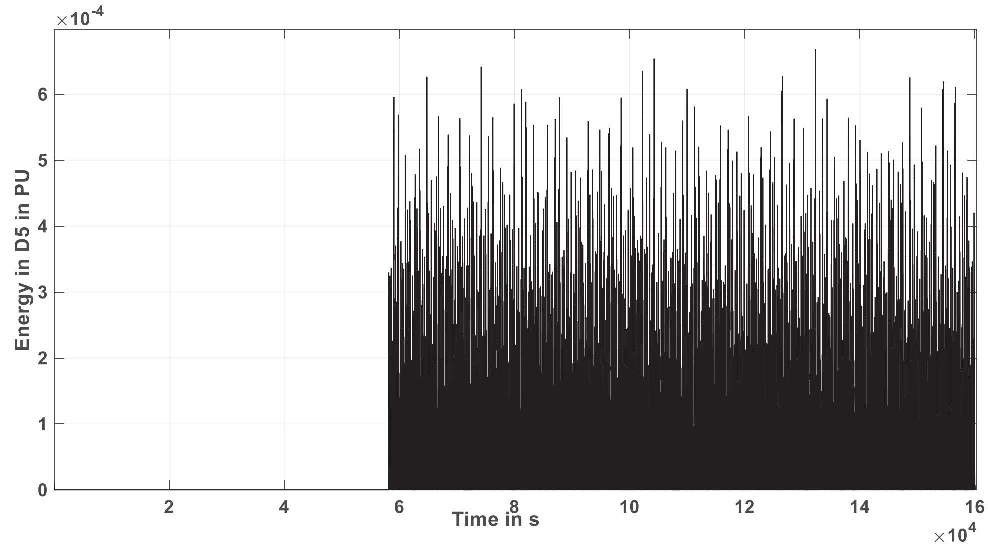


Fig. 10. Detailed D5 of HIF

Figures 11 show the energy content in D4 and D5, respectively. The energy level in D4 was 0.12 pu and in D5 was 0.3 pu and these values exceed the threshold values. The results can be compared with the transient phenomena (capacitor switching), the current waveform shown in Fig. 12, and its DWT, shown in Fig. 13.



(a)



(b)

Fig. 11. Energy contained in: (a) D4; (b) D5

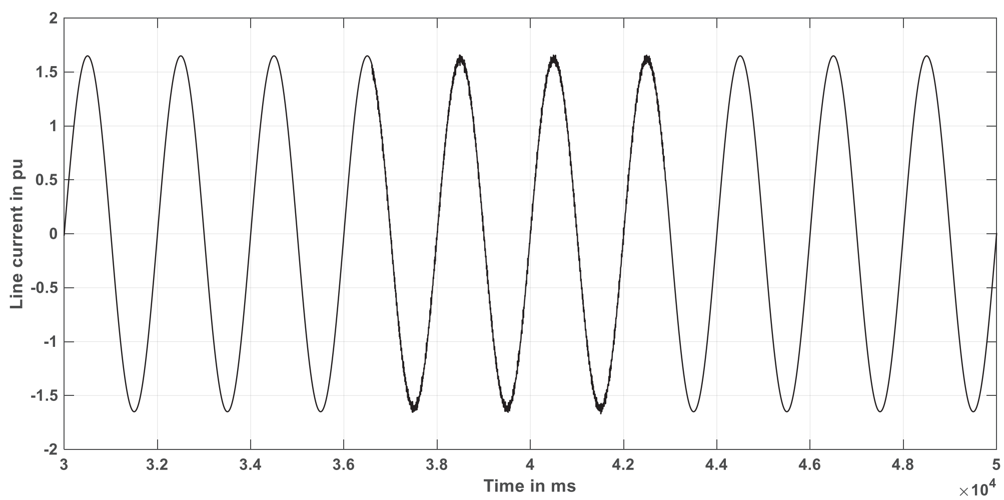


Fig. 12. Capacitor switching current signal

By comparing Fig. 8 and Fig. 13, one can clearly see that DWT is a good tool to determine HIF and other phenomena (capacitor switching). The laboratory test circuit for capacitor switching (for three-cycle transient duration) is shown in Fig. 14.

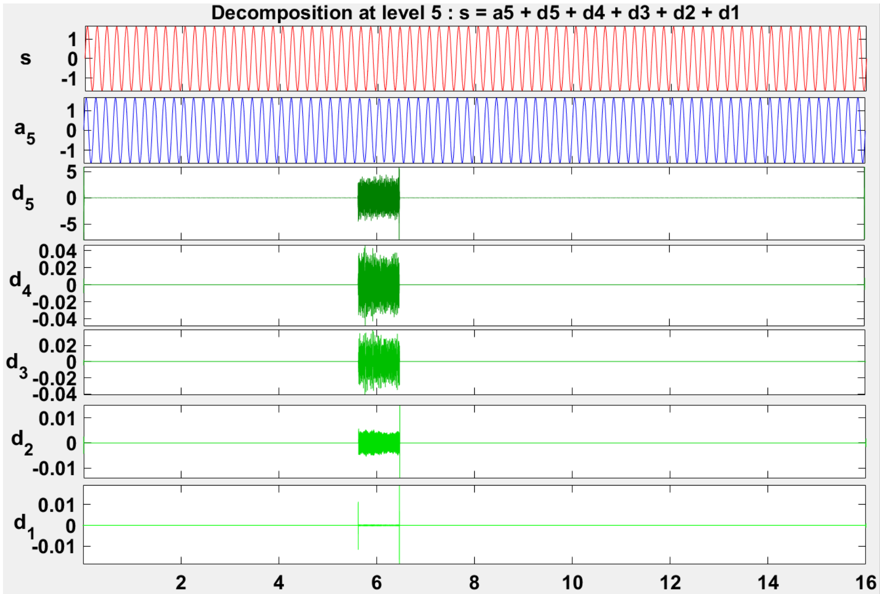


Fig. 13. DWT analysis during capacitor switching

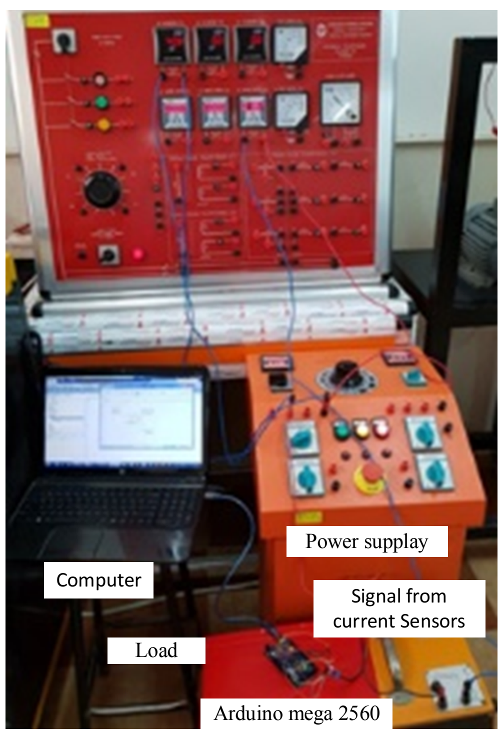


Fig. 14. The lab's test circuit

5. Conclusion

In this study, a neuro-fuzzy controller combined with DWT was used for HIF detecting.

Tuning of the controller algorithm was performed "off-line", employing the concept of neuro-fuzzy inference systems. HIFs aren't detectable by a conventional type of protection system thus a special technique was developed with the use of DWT to extrude the detailed coefficients for the declared fault condition. In this study, energy contained in D4 and D5 were applied in the detection process. The controller is designed in MATLAB/Simulink. A new approach presents the existence of HIF that depends on three parameters: energy contained in D4 and D5, detail coefficients and the rms value of the original signal for a duration of more than 100 cycles. The practical experiment results approved the scheme that provides an adequate achievement in detecting and discriminating from other transient phenomena like capacitor switching. The practical results show that DWT was a very good tool for detecting HIF, but more samples are required in order to achieve the required accuracy. The results obtained showed that the suggested technique is more accurate than the other techniques used in previous studies presented in [19–21].

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