A Wavelet-FIRANN Technique for High-Impedance Arcing Faults Detection in Distribution Systems

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Abstract--A novel wavelet-FIRANN based technique is proposed for detecting High Impedance Faults (HIF) in distribution systems. Wavelet transform has been successfully adopted in many power system fields such as power system protection, power quality and transients analysis. This technique uses the Discrete Wavelet Transform (DWT) as a preprocessing stage for feature extraction which prepare the data for the artificial neural network (ANN) stage. The ANN used in this work is of the Finite impulse response artificial neural network (FIRANN) type. The inputs to the FIRANN are selected to be the details' coefficients of the voltage waveform as measured at the relaying point. The proposed technique was trained using a realistic HIF model and various types of transient phenomena such as capacitor switching, load switching, linear and bolted faults. The performance of the proposed technique is verified under a variety of fault and nonfault conditions on a typical 25 kV radial distribution system.

Keywords: High-Impedance fault, Wavelet, FIR artificial neural network.

I. INTRODUCTION

HIGH impedance fault results when a primary circuit conductor makes an unwanted electrical contact which restricts the flow of current below the detection level of the protective devices. Such a situation leaves an energized conductor at ground level, creating a public hazard and threatening the reliability of electric power supply. In addition, as the arcing often accompanies these faults, they further poses a risk of fires and endanger life through the possibility of electric shock. For these reasons, the detection of high impedance faults in electric power systems has been the subject of intense research.

Form utility point of view, HIFs result in service interruptions which reduce system reliability, dependability and continuity. In addition to service interruption, HIFs can result in fires, electric shock, and the ensuing utility liability. Hence, HIFs present a source of threat to utilities' costumers and personnel. Arcing faults result in waste of energy and can damage property. Protection against these faults comes mainly from a moral point of view, i.e. improving public safety.

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For the detection technique to be reliable and secure, it must be capable of perfectly identifying and distinguishing the HIFs from other types of faults and/or power system switching conditions. For instance, switching activities can exhibit a similar burst nature and characteristic frequencies [1].

Several researchers in recent years have presented many techniques aimed at detecting HIF more effectively. These techniques include the low frequency energy components method [2], multi-layer feed forward neural network method [3], [4], kalman filtering approach [5], low order current harmonics' ratio method [6], [7], fault current flicker and half-cycle asymmetry method [8], fractal analysis method [9], wavelet analysis filter banks method [10] and morlet wavelet transform method [11].

Wavelet transform is a relatively new concept yet it has successful applications in many fields such as acoustics, signal and image processing, speech discrimination, optics and, recently, power system analysis. Its application in power systems has been researched and developed for the past several years. Typical applications include power system protection [12], analysis of power system transients [13], power quality detection and classification [14], etc. Unlike traditional Fourier transform, a wavelet transform is capable of providing the time and frequency information simultaneously, and hence, gives multiple resolutions in frequency and time, which is a potential feature for analyzing transient signals containing both high and low frequency components together.

The ANN used in this work is of the finite impulse response artificial neural network (FIRANN) type. This type of ANN performs well in time series prediction and temporal signal processing [15], [16]. It is mostly used in temporal series recognition such as speech recognition [17]. The learning algorithm of such a neural network is called temporal back propagation and the most commonly used weights updating algorithm is the batch method.

The purpose of this paper is to introduce a new protection scheme based on wavelet analysis combined with FIRANN to discriminate and identify HIFs on distribution feeders. The proposed protection technique will benefit from the advantages provided by both wavelet transform and FIRANN.

II. HIGH-IMPEDANCE FAULT AND SIMULATED POWER SYSTEM

There is an increasing demand for more detailed and accurate modeling techniques for predicting the transient response of power system caused in particular by high impedance arcing faults. This is particularly so in relation to the design and development of improved equipment and new protection techniques. An accurate prediction of the fault transients requires a detailed and comprehensive representation of all the components in a system, and the transient studies have to be conducted into the frequency range well above the normal power frequency.

The HIF is very complex phenomenon and exhibits a very high nonlinear behavior. The most distinctive characteristics are buildup, shoulder, nonlinearity and asymmetry. In the buildup, the fault current grows to its maximum value in about tens of cycles and in the shoulder; the buildup is ceased for a few cycles. The non-linearity rises from the fact that the voltage-current characteristic curve of HIF is nonlinear. It is observed that fault current has different waveform for positive and negative half cycle which is called asymmetry. Buildup and shoulder disappear in the steady state after HIF, while nonlinearity and asymmetry exist at every cycle after HIF.

Some models of HIF have been proposed in the past. A model based on connecting a linear resistance to the network at the fault point was proposed in [18]. In [7], a nonlinear impedance model based on the voltage cycle is used to simulate the HIF. Another model suggested in [6] employed two dc sources connected in anti-parallel by means of two diodes. Based on the arc theory, a more realistic model of HIF is proposed in [19], [10] and modified in [20]. In this model, the HIF is represented by two resistances connected in series and takes the form:

$$R(t) = R_1(t) + R_2(t) \tag{1}$$

In this equation, $R_1(t)$ has a periodic characteristic and is used to represent nonlinearity and asymmetry. The value of $R_1(t)$ is obtained from the voltage and current characteristic during the steady state as shown in Fig. 1. When the voltage of the faulted branch $v(t)$ is in the range $v_n < v(t) < v_{n+1}$ and the corresponding current is $i(t)$, $R_1(t)$ is given by:

$$R_1(t) = \frac{v(t)}{i(t)} = \frac{v(t)}{i_n + \frac{i_{n+1} - i_n}{v_{n+1} - v_n} \times (v(t) - v_n)} \tag{2}$$

where n is the point number on the voltage-current characteristic curve. On the other hand, buildup and shoulder don't have a periodic characteristic and exist only for a few cycles after the HIF. So, $R_2(t)$ is used to simulate such characteristics by assigning a very large value at the beginning of the HIF then gradually decreasing its value in the transient state and finally becomes zero in the steady state.

This model is adopted in this work to simulate the HIFs and incorporated using C programming language in the power system simulation program PSCAD/EMTDC following the same technique used in [21], [22] to build a HIF custom module.

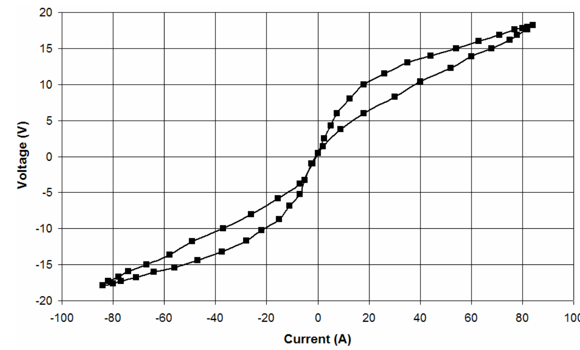


Fig. 1: The voltage-current characteristic curve for one cycle in the steady state.

Fig. 2 shows the single line diagram of the 25kV distribution system under consideration. The short circuit level (SCL) at the utility busbar is 40MVA and the feeder length is 30km feeding a 4 MW load at 0.8 power factor. A HIF is simulated in the middle of the feeder; fault current and relay point voltage are shown in Fig. 3 and Fig. 4 respectively. The fault inception time is 0.1s. The buildup and shoulder characteristics of the HIF are evident in Fig. 3(a). Other HIF properties which are nonlinearity and asymmetry are shown in Fig. 3(b). These characteristics affect and distort the voltage and current waveforms measured at the utility bus, i.e. relay point, as shown in Fig. 4.

III. DISCRETE WAVELET TRANSFORM

The wavelet transform is a powerful tool in the analysis of transient phenomena because of its ability to extract time and frequency information from the transient signal. The theory behind wavelet analysis and the comparison with Fourier analysis has been documented in [13]. This section provides a brief explanation of wavelet analysis, and highlights important considerations.

Wavelet analysis is a method of signal processing so that, after a series of decompositions, the signal is represented at different frequency ranges. This is achieved by dilation and translation of a mother wavelet over the signal. To process the data in a digital sense the discrete wavelet transform (DWT) is used which is given by:

$$DWT(m,n) = \frac{1}{\sqrt{a_0^m}} \sum_k x(k)\, g(a_0^{-m} n - b_0 k) \tag{3}$$

The signal is decomposed into two other signals which represent a smooth and detailed version of the original signal, termed the approximation and detail respectively. This process is repeated with the approximation being decomposed further to generate the next approximation and detail.

This operation is termed multiresolution signal decomposition (MSD). Fig. 5 shows how a signal is decomposed into various frequency ranges. The frequency range of each detail

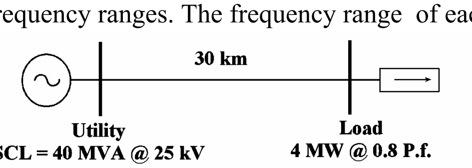
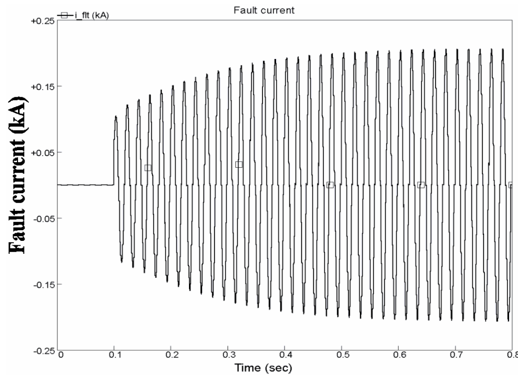
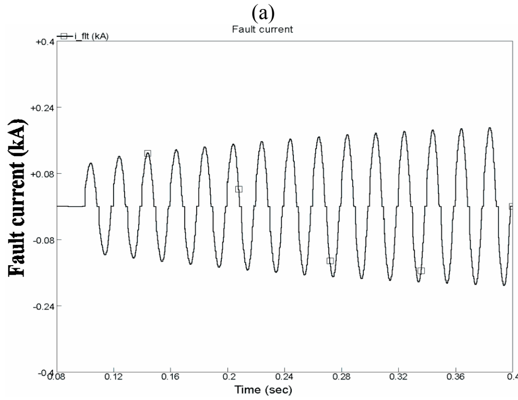


Fig. 2: Single-line diagram of the simulated 25kV distribution system.



(a)



(b)

Fig. 3: HIF current for a fault in the middle of the feeder, fault time = 0.1s. (a) showing buildup and shoulder (b) showing nonlinearity and asymmetry.

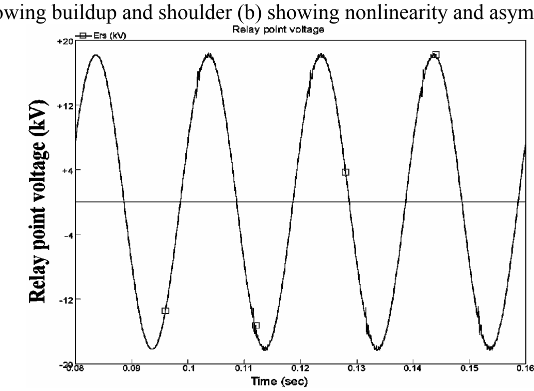


Fig. 4: Relay point voltage for a HIF at mid of feeder, fault time = 0.1s.

(D) of the DWT is directly related to the sampling rate of the original signal [23]. These frequency ranges are referred to as scales of the wavelet transform due to their special logarithmic structure [24]. The number of decomposition levels (J) can be determined by:

$$J = \log_2 N \tag{4}$$

where N is the number of samples.

By selecting $a_0 = 2$ or (a_0^{-m} =1, 1/2, 1/4, 1/8, …) and $b_0 = 1$ in eq.(3), the DWT can be implemented by using a multistage filter with the mother wavelet as the lowpass filter $l(n)$ and its dual as the highpass filter $h(n)$. Also, downsampling the output of the lowpass filter $l(n)$ by a factor of 2 (↓2) effectively scales the wavelet by a factor of 2 for the next stage, thereby simplifying the process of dilation. The implementation of the DWT with a filter bank is computationally efficient. The output of the highpass filter gives the detailed version of the high-frequency component of the signal. Also, the low-frequency component is further split to get the other details of the input signal. By using this technique, any wavelet can be implemented. The coefficients of the filters are associated with the selected mother wavelet. There are many types of mother wavelets, such as Harr, Daubichies (db), Coiflet (coif) and Symmlet (sym) wavelets. The choice of mother wavelet plays a significant role in detecting and localizing different types of fault transients. In addition to this, the choice also depends on a particular application. For short and fast transient disturbances, such as the case of this study, db4 and db6 are better, while for slow transient disturbances, db8 and db10 are particularly good [25]. The mother wavelet used in this study is db4.

IV. Finite Impulse Response ANN

Finite impulse response ANN is one of the many existing ANN architectures in which the NN synapses are modeled as Finite Impulse Response (FIR) linear filters. The most basic FIR filter can be modeled with a tapped delay line as illustrated in Fig. 6. For this filter the output $y(k)$ corresponds to a weighted sum of past delayed values of the input:

$$y(k) = \sum_{n=0}^{T} w(n)x(k-n) \tag{5}$$

In the temporal model of the neuron, input signals are passed through synaptic filters. The sum of the filtered inputs is passed through a sigmoid function to form the output of the neuron. In the feedforward network all connections are modeled as FIR filters. An alternative representation of the FIR network can be found by using a technique referred to as *unfolding-in-time*. The general strategy is to remove all time delays by expanding the network into a larger equivalent static structure.

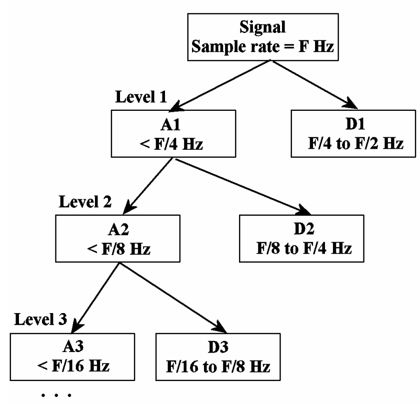


Fig. 5: Wavelet decomposition.

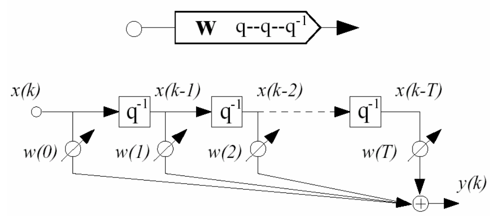


Fig. 6: FIR Filter Model: A tapped delay line shows the functional model of the Finite Impulse Response synapse (q^{-1} represents a unit delay operator, i.e. $x(k-1) = q^{-1} x(k)$.

In light of this, one can view an FIR network as a compact representation of a larger static network with imposed symmetries. These symmetries force the network to subdivide the input pattern into local overlapping regions. Each region is identically processed with the results being successively combined through subsequent layers in the network. This is in contrast to a fully connected network which may attempt to analyze the scene all at once [15].

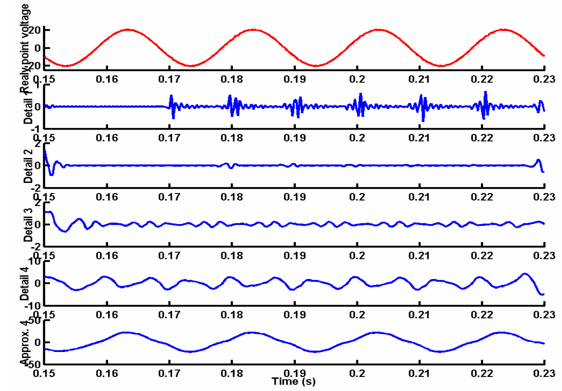
V. Simulation and Results

This section is divided into two parts; each illustrates a step towards building of the HIF protection scheme. The first step is the wavelet analysis of the relay point voltage waveform to identify its distinct characteristics as preprocessing phase to prepare the FIRANN's inputs. The second step is to build and train the FIRANN. In this step, a detailed description of the FIRANN design is presented and the features selected from the wavelet analysis phase are introduced to the FIRANN. Finally, the FIRANN is tested using new untrained cases.

A. *Wavelet analysis of the voltage waveforms*

As stated before, the Daubichies mother wavelet of order 4 (db4) is selected to analyze the voltage waveforms. Different fault and non-fault conditions are considered so that the relay can discriminate between fault and fault-like disturbances. The fault conditions considered are the HIF, linear fault (LIN) and bolted fault (BLT). Extensive series of simulation studies have been performed to obtain fault transient signals. Fault simulations are carried out at 5-, 10-, 15-, 20-, 25 km from the utility bus at different fault inception angles and loading conditions (no-, half-, full load). The sampling frequency is 3200 Hz, i.e. 64 samples/cycle for 50 Hz system. The relay point voltage is recorded for 0.08s, divided into 0.02s (one cycle for 50Hz system) before fault inception and 0.06s (three cycles for 50Hz system) after fault inception which corresponds to 256 samples at the sampling frequency 3200Hz. The output of the wavelet analysis stage, up to the 4^{th} level of signal decomposition, is shown in Fig. 7 for single phase to ground HIF, LIN and BLT faults at different system and fault conditions. The voltage waveforms resulting from non fault power system disturbances such as switching of capacitor banks and load are also analyzed. For the capacitor switching, two capacitor banks are installed at the utility bus one is fixed and the other is switchable having a rating of 1.2 MVAR each. Switching operations (on and off) at various inception angles are considered and the relay voltage is analyzed using the same procedure. The results are shown in Fig. 8.

It can be seen from the results of wavelet analysis that the details of the voltage waveform differ for each type of fault and switching operation. In particular, it is noted that detail1 is very significant for HIF. Hence, it can be concluded that the details of the wavelet decomposition of relay point voltage are the most suitable inputs to the FIRANN.



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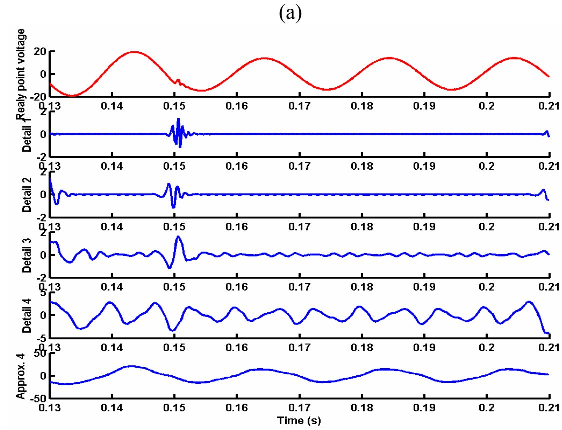

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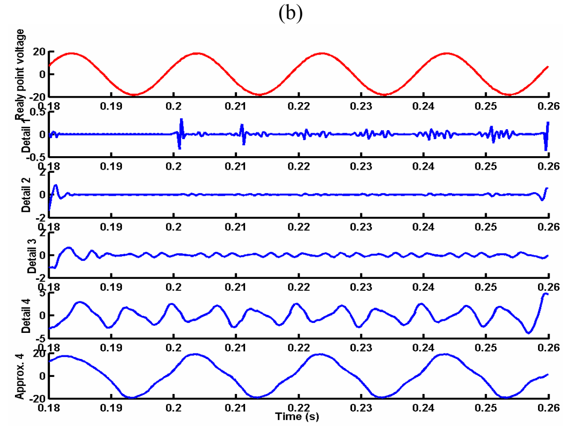

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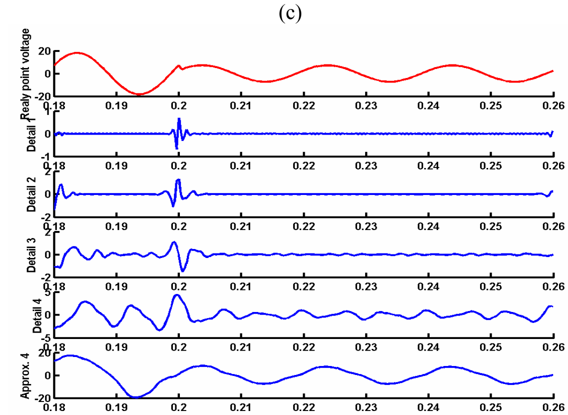


(d)

Fig. 7: Wavelet decomposition of voltage waveform for different faults.
(a) HIF with no-load at 25km from the sending end, fault time = 0.17s.
(b) LIN with half load at 20km from the sending end, fault time = 0.15s.
(c) HIF with full load at 25km from the sending end, fault time = 0.2s.
(d) BLT with full load at 10km from the sending end, fault time = 0.2s.

B. *Finite impulse response ANN*

The FIRANN proposed in this paper consists of 4 layers, an input layer, 2 hidden layers and an output layer. The input layer has 4 inputs which are the detail levels 1, 2, 3 and 4 of the wavelet decomposition of relay point voltage. The input level has a 5 tap delays. The first hidden layer has 12 neurons each has a 5 tap delays. The second hidden layer has 8 neurons each has a 5 tap delays. The output layer has 3 neurons which correspond to bolted, linear and high-impedance faults. The algorithm used to train the neural network is the Delta-Bar-Delta (DBD) algorithm [16].

Extensive simulations are performed and the relay point voltage is recorded. The FIRANN is trained using 450 different cases including bolted, linear, high-impedance faults and non-fault switching disturbances. The FIRANN is tested using different cases to validate the proposed technique. Results of the testing cases are shown in Fig. 9. The results show that the FIRANN accurately determines the type of fault for each case. Also, it is noted that the switching operations have been accurately classified as non fault case. Based on the simulation results, it can be concluded that the FIRANN accurately responded to different fault and non fault cases. Further work is underway to validate the ANN response in a real time application.

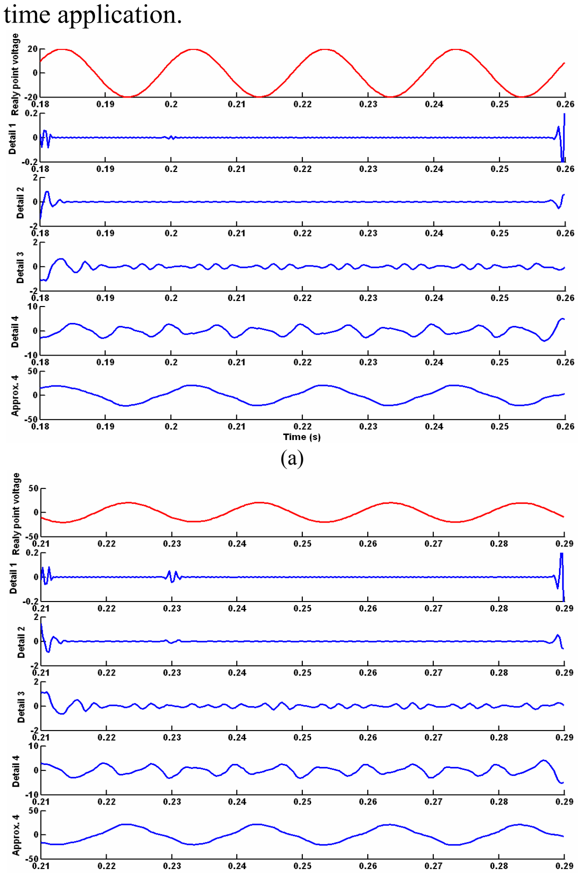
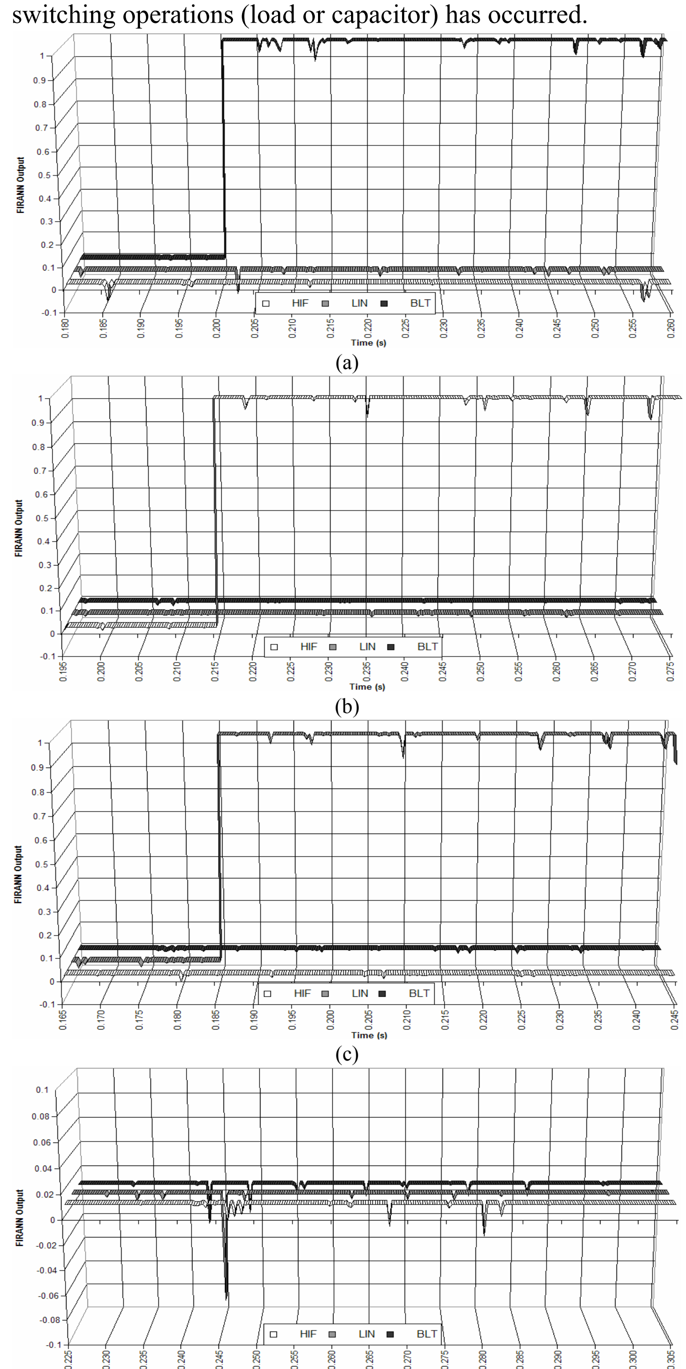
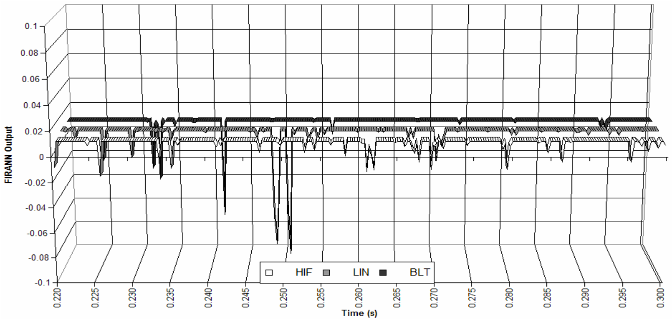


Fig. 8: Wavelet decomposition of voltage waveform for nonfault disturbances. (a) Capacitor bank switching on at 0.2s. (b) Load switching on at 0.23s.

VI. Conclusions

This paper proposes a novel wavelet-FIRANN based technique for detecting HIFs in distribution systems. The simulation results of the developed HIF arcing model, incorporated in EMTDC, are presented. The results show distinct characteristics of HIF such as build-up and shoulder. Wavelet analysis of the relay point voltage for HIF, LIN, BLT faults, load switching and capacitor switching are presented. The results of the wavelet analysis show that each fault and switching operation has its own distinct details. The FIRANN is trained using these details as inputs. Simulation results indicated that by combining wavelet transform and FIRANN a very reliable protection scheme is obtained. As it can be seen that the FIRANN discriminated reliably between HIF, LIN and BLT faults. Moreover, no confusion with normal switching operations (load or capacitor) has occurred.





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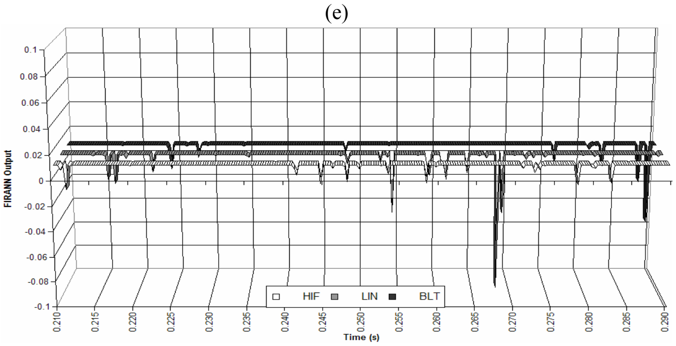

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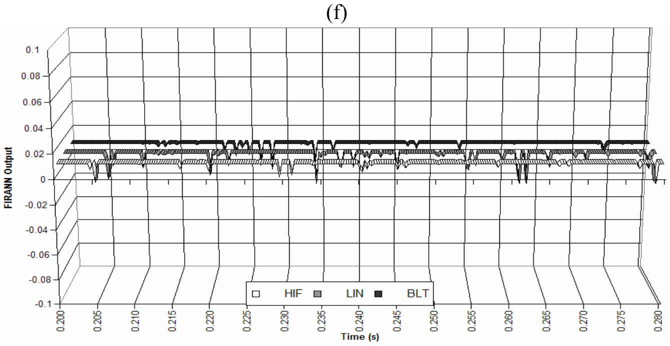

(g)

Fig. 9: FIRANN output for different test cases, (a) Bolted fault at 0.2s, (b) High-impedance fault at 0.215s, (c) Linear fault at 0.185s, (d) Load switching on at 0.245s, (e) Capacitor-bank switching on at 0.24s, (f) Load switching off at 0.23s, (g) Capacitor-bank switching off at 0.22s.

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