Identifying Transformer Incipient Events for Maintaining Distribution System Reliability

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Abstract

This paper presents the time domain and time-frequency domain analysis results of incipient events in single-phase distribution transformers. This analysis will aid in the development of an automatic detection method for internal incipient faults in the transformers. The detection method can provide information to predict failures ahead of time so that the necessary corrective actions are taken to prevent outages and reduce down times. The analyzed data was obtained from simulations and experiments. Time-frequency analysis was performed using Discrete Wavelet Transform (DWT). The obtained results are discussed.

Keywords: Transformer, incipient fault, discrete wavelet transform

1. Introduction

The trend toward a deregulated global electricity market has put the electric utilities under severe stress to reduce operating costs, enhance the availability of the generation, transmission and distribution equipment and improve the supply of power and service to customers. Further electric power systems was identified by the U.S. government as a critical infrastructure. Incipient fault detection in transformers can provide information to predict failures ahead of time so that the necessary corrective actions are taken to prevent outages and reduce down times. Hence protecting a critical infrastructure.

The faults that occur within the transformer protection zone are internal faults. Transformer internal faults can be divided into two classifications: internal short circuit faults and internal incipient faults. Internal short circuit faults are generally turn-to-turn short circuits or turn to earth short circuits in transformer windings. These faults occur suddenly and usually require fast action by protective devices to disconnect the transformer from the electric system [1].

Incipient transformer faults usually develop slowly, often in the form of a gradual deterioration of insulation due to some cause. When the condition of system equipment degrades because of some electrical, thermal or chemical effects, intermittent incipient faults begin to persist in the system. If not detected, this may lead to catastrophic failure, which degrades quality of service and eventually longer outages. Service cannot be restored until the source of the failure is repaired [2-3]. Major damage may require shipping the unit to a manufacturing site for extensive repair, which results in an extended outage period. If the condition can be detected before major damage occurs, the needed repairs can often be made more quickly and unit placed back into service without prolonged outage.

Incipient faults are not detectable at the transformer terminals using the normal protection methods such as fuse and relay protection. Over the years, various incipient fault detection techniques, such as dissolved gas analysis [4] and partial discharge analysis [5] have been successfully applied to large power transformer fault diagnosis. Since these techniques have high-cost and some are off-line, a low-cost, on-line incipient fault detection technique for distribution transformers using terminal measurements is being proposed. Accordingly, a method for on-line condition monitoring of distribution transformers based on advanced signal analysis is developed to detect internal incipient faults. Wavelets, which provide greater resolution in time for high frequency components of a signal and greater resolution in frequency for low frequency components of a signal, can identify transformer incipient events for maintaining distribution system reliability.

A part of an ongoing project at Power System Automation Laboratory (PSAL) at the Texas A&M University focuses on the detection and classification of incipient faults in distribution transformers. This paper discusses a methodology to identify transformer incipient events in single-phase distribution transformers using discrete wavelet transforms (DWT). In the paper, data collected using both simulations and experiments for a custom-built transformer are used for DWT analysis. The characteristics of incipient faults are obtained. The discussed results show great potential for using these characteristics for predictive maintenance and maintaining reliability of transformers.

2. Discrete Wavelet Transform (DWT)

Wavelet analysis is a recently developed mathematical tool for signal analysis. The first mention of wavelets appeared in Haar's studies in 1910 [6]. A wavelet is a waveform of effectively limited duration that has an average value of zero as shown in (1).

$$\int_{-\infty}^{+\infty} \Psi(t)\, dt = 0 \qquad (1)$$

where, $\Psi(t)$ is the wavelet function.

Wavelet transforms are based on a set of signals derived from a basic mother wavelet by adjusting the time-shifting and time-dilation parameters.

The continuous wavelet transform (CWT) is defined as the sum over all time of the signal multiplied by scaled shifted versions of the wavelet function Ψ as shown in (2), where *a* represents the scale, *b* represents position along the time axis (translation), *x(t)* is the signal function, and *C(a,b)* is the wavelet coefficient.

$$C(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} x(t)\, \Psi\left(\frac{t-b}{a}\right) dt \qquad (2)$$

The result of CWT are many wavelet coefficients which are a function of *a* and *b*. Multiplying each coefficient by the appropriately scaled and shifted wavelet yields the constituent wavelets of the original signal.

Discrete wavelet transform (DWT) is derived from a continuous wavelet transform. Instead of continuous dilation and translation, the mother wavelet may be dilated and translated discretely by selecting $a = a_0^m$ and $b = nb_0 a_0^m$ where a_0 and b_0 are fixed constants with $a_0 > 1, b_0 > 1, m \text{ and } n \in Z$, and Z the set of positive integers. The discretized mother wavelet and corresponding discrete wavelet transform become as shown in (3)-(5).

$$DWT_\Psi x(m,n) = \int_{-\infty}^{\infty} x(t)\, \Psi_{m,n}^*(t)\, dt \qquad (3)$$

where * represents the complex conjugate, and

$$\Psi_{m,n}(t) = |a_0|^{-m/2}\, \Psi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right) \qquad (4)$$

Let *x(t)* be a discrete sequence thus,

$$DWT[m,n] = \frac{1}{\sqrt{a_0^m}} \sum_{k=-\infty}^{+\infty} X[k]\, \Psi\left(k - \frac{a_0^m n b_0}{a_0^m}\right) \qquad (5)$$

Since the purpose of the discretization process is to eliminate the redundancy of the continuous form and to ensure inversion, the choice of a_0 and b_0 must be made so that mother wavelets form an orthonormal basis. This condition is satisfied for instance, if $a_0 = 2$ and $b_0 = 1$. This choice leads to multiresolution analysis (MRA).

DWT can be easily and quickly implemented by filter bank techniques if the coefficients are throught of as a filter as shown in (6).

$$DWT(m,n) = C(i,j) = \sum_{n=0}^{N-1} x(n)\, 2^{-j/2}\, \Psi(2^i n - j) \qquad (6)$$

Mallat developed in 1988 an efficient and practical filtering algorithm. His algorithm decomposed the original signal into the approximation (low frequency) and detail (high frequency) components using complementary filters, low-pass and high-pass. The signal is then downsampled to throw away every second data point so that the length of the signal doesn't change. At the next stage, the low-pass output is decomposed using a low-pass and a high-pass filter. In essence, the wavelet procedure adopts a mother wavelet. Detail analysis is performed with a contracted, high-frequency version of the mother wavelet, while approximation analysis is performed with a dilated, low-frequency version of the same wavelet [6-8].

Multi-stage filter bank implementation of DWT is shown in Figure 1, where x(n) is the original signal, *h(n)* and *g(n)* are high-pass and low-pass filters, respectively. (2↓) represents downsampling of the input signal, a1 and d1 represent approximations and details at first scale

3. Simulation Method

A simulation method was developed at PSAL to study internal short circuit and internal incipient faults in distribution transformers. The method is based on Finite Element Method (FEA) and circuit analysis [3]-[9]. The parameters for an equivalent circuit representing a transformer with internal faults are calculated using ANSOFT's Maxwell Software [10].

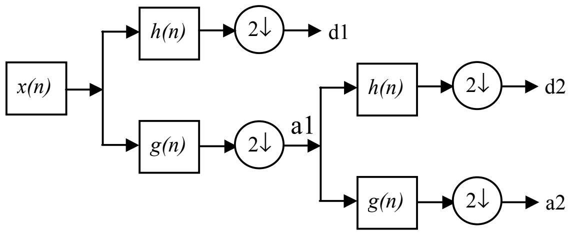

Figure 1. Wavelet decomposition tree.

Deteriorating insulation between the turns is a major reason for incipient internal winding fault in transformers. During the operation of the transformer, some factors such as thermal stress, electrical stress, mechanical stress and moisture cause the aging and deterioration of insulation. The simulation model takes into account both the aging phase and the arcing phase[3].

The aging part of the model consists of parallel-connected resistance R_p and capacitance C_p as shown in Figure 2. This traditional approach is for considering the electrical behavior of dielectric material. In this model, R_p represents the lossy part of the dielectric, and C_p represents the capacitance of dielectric.

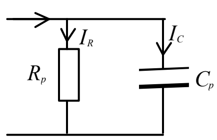

Figure 2. Parallel equivalent circuit of a dielectric material.

The arcing part of the model is represented by using an equivalent circuit as shown in Figure 3. Various cases such as non-arcing, burning period, and extinction period, can be obtained by controlling the switches *S1* and *S2* in the circuit. *E* is a random square wave representing the equivalent arcing voltage, and $R_e(t)$ is a high resistance that increases with time.

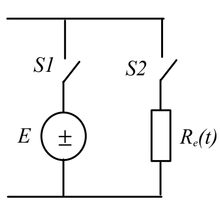

Figure 3. Arcing model for incipient internal winding faults

4. Experiment Setup

Additionally experiments were performed at Texas A&M University Riverside Campus Downed Conductor Test Facility to collect data and verify the simulation methodology [11].

The main components of the experiment setup were a custom-built transformer, a custom-built resistive load bank and overhead 7200V(rms) L-N voltage supply. The custom-built, single-phase, 7200V/240V/120V, 25kVA, 60 Hz distribution transformer was equipped with externally accessible taps on selected turns of both the primary and secondary windings to make it possible to stage internal faults at various locations within the transformer. Figure 4 shows the custom-built transformer and the experiment setup. The primary winding had a total of 780 turns and the secondary had 26 turns. A lateral from a distribution system connects to the full winding of the transformer primary. The load bank, capable of loading the transformer between 75% - 110% of its nominal 25kW rating, is connected to the transformer secondary. To provide easy access to the transformer taps, the taps are connected to busbars fixed on panel boards.

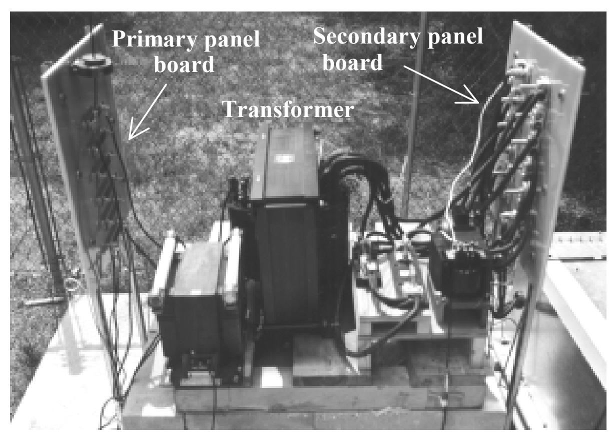

Figure 4. Custom-built transformer and experiment setup.

A portable data acquisition system was used to monitor the appropriate signals during the experiments staged at the test facility. The currents and voltages on both the primary and the secondary sides were monitored and acquired using a real-time data-acquisition system by National Instruments, an interface box comprised of voltage dividers and shunt resistors, a signal conditioning unit comprised of analog filters, and potential transformers (PT) and current transformers (CT). The voltage and current signals were recorded at a sample rate of 3840 samples per second. Also the measured primary current data was passed through a 60 Hz notch filter and a high pass filter (2000Hz-8000Hz) contained in the signal conditioning unit. Their outputs were sampled at 15360 samples per second.

5. Experiment Results and Observations

The development of the experimental methodology for staging incipient faults is still going on. However, it was noticed at some point during the short circuit field tests that the tests were conveying arcing phenomena. Then some time later, the transformer experienced a catastrophic failure during the experiments. The signals recorded in the field experiments were analyzed for the purpose of identifying the incipient events in the single-phase distribution transformers preceding its catastrophic failure. Then the characteristics from the field tests were compared with the characteristics obtained from the simulations. In this section, some interesting characteristics in time and time-frequency domain of those possible incipient events are discussed.

5.1 Time Domain Results

The time domain results involve the time domain waveforms of the primary current signal including unfiltered, notched filtered, and notched and high phase filtered signals.

The experimental data of incipient-like behavior were measured on the custom-built transformer while the field experiments were performed. After 94 internal short circuit fault cases were performed over a twenty months period, some phenomena appeared during the experiments indicating that the transformer was in a deteriorating condition. For instance, a buzzing sound was heard in some experiments, a smell was noticeable, and arcing-like phenomena was observed in the waveforms of the recorded signals. This suggested that the insulation in the transformer was severely degraded. At this point, a series of load and short circuit tests were performed on two separate days to get more information about the transformer condition.

During the experiments after about the 19th month, the test in which arcing like behavior apparently was seen was a secondary short circuit fault between the 10th and 13th turns. When this experiment was performed, a smell was emitted by the transformer windings. The time domain waveforms of unfiltered, notched filtered and notched-high pass filtered primary current signals are given in Figure 5. The arcing phenomenon at various time instants between 28.7 and 31 seconds can easily be seen from this figure. The filtered signal waveforms indicate that there are many high frequency components in the signal.

Another test performed on that same experiment day, in which arcing like behavior apparently was seen, was a short circuit fault between the 20th and 26th turn of secondary winding. Figure 6 presents the time domain unfiltered and filtered primary current waveforms between 30.2 and 30.5 seconds. In this case, observed arcing current was larger than the case given earlier.

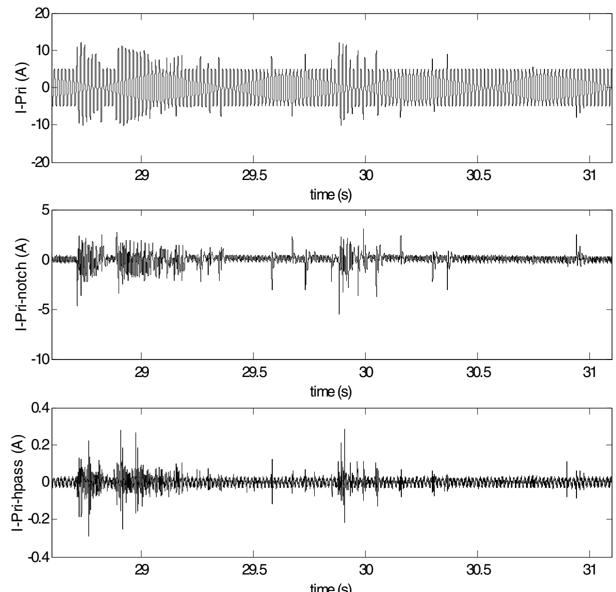

Figure 5. Time domain waveforms of unfiltered, notched filtered and notched-high-pass filtered primary current measured for short circuit field test fault between the 10th and 13th turn of secondary winding.

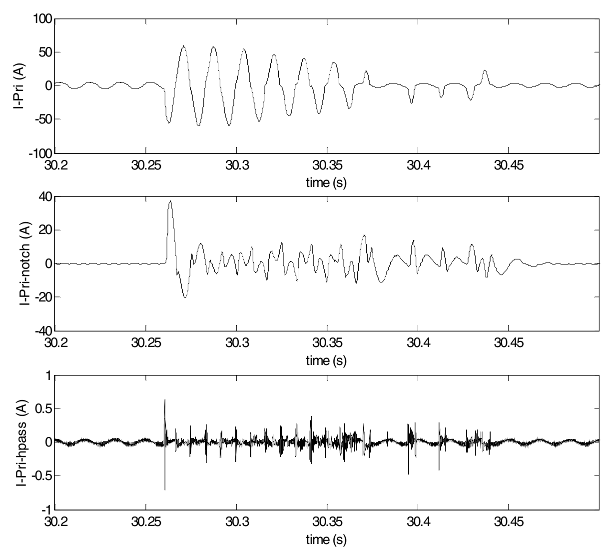

Figure 6. Time domain waveforms of unfiltered, notched filtered and notched-high-pass filtered primary current measured for short circuit field test fault between the 20th and 26th turn of secondary winding.

After those severe arcing-like behavior fault cases, two weeks later, seven load tests were performed to check the condition of the transformer. In these loads test cases, several combinations such as using only the top secondary sub-winding, using only the bottom secondary sub-winding, and considering different load levels, were experimentally studied. In some tests, almost continuous arcing was apparently observed in the waveforms. Figure 7 shows the unfiltered and filtered primary current signals between 11.5 and 11.8 seconds obtained during the fourth load test. This test was performed using only the first ten turns in secondary top sub-winding (there were a total of 13 turns in each of the two secondary sub-windings) and a load power rating of 25 kW.

These load tests indicated that some insulation in the transformer secondary winding was severely damaged and some turns on the secondary winding were lost.

As a result of time domain studies, it can be seen from the figures that arcing occurs randomly in earlier stages in aged transformers. Once it starts, it may be interspersed with segments of normal current. The rms value of arc current and energy is less than that of a short circuit fault.

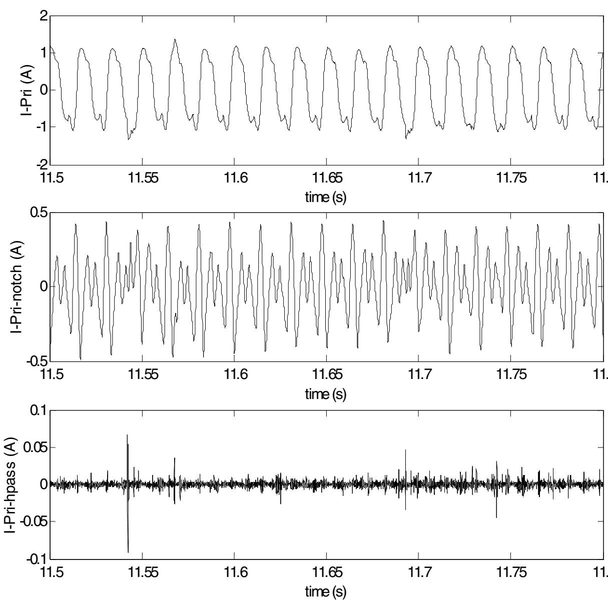

Figure 7. Time domain waveforms of unfiltered, notched filtered and notched-high-pass filtered primary current measured for fourth load test.

5.2 Time-Frequency Domain Results

The DWT approach has been applied to investigate the characteristics of incipient events in single-phase distribution transformers. The data obtained from field tests and computer simulations were used to observe the variations. The MATLAB program was used to calculate DWT of the signals. The sampling rate for experimentally measured signals was 3840 Hz. A sample rate of 5000 samples per second was considered for sampling of the signals obtained from simulations. For the DWT of the signal, the Daubechies Db-4 type wavelet was used as a mother wavelet. The signals were decomposed up to the fourth-scale. The frequency bands at each scale are shown in Table 1.

Table 1. The frequency bands at each scale.

	For the signals obtained from experiments	For the signals obtained from simulations
d1	960-1920 Hz	1250-2500 Hz
d2	480-960 Hz	625-1250 Hz
d3	240-480 Hz	312-625 Hz
d4	120-240 Hz	156-312 Hz
a4	0-120 Hz	0-156 Hz

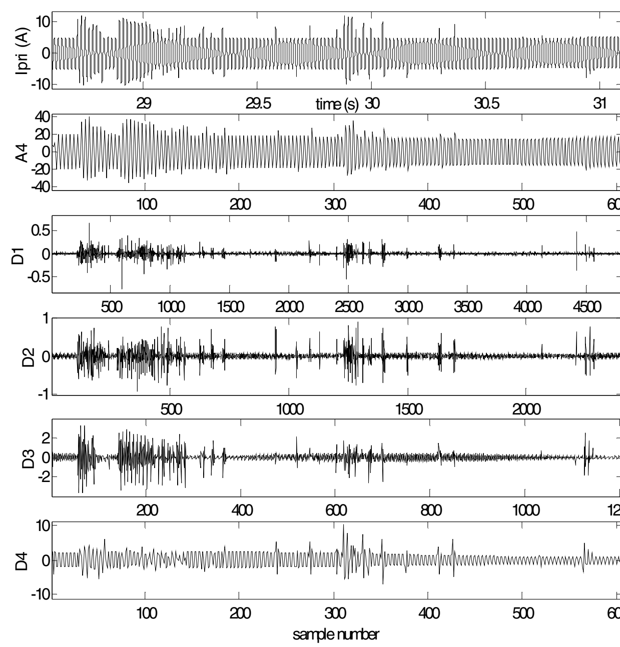

Figure 8. DWT of primary current for short circuit fault between the 10^{th} and 13^{th} turn of secondary winding in Figure 5.

The results of applying the DWT to the cases shown in Figures 5-7 are discussed in Figures 8-10. The signal, four detail coefficients, and the fourth approximation coefficients are shown in Figures 8-10. It can be seen from the figures that using detail coefficients, these transients can be easily extracted. There are spikes in details of DWT in all figures for incipient events. The times of the spikes in the DWT are simultaneous to the time of the arcing. This gives time information about when the arcing occurred. The spikes in the incipient fault cases randomly occurred and have different magnitudes. In other words, the time interval between two sequential spikes is not consistent.

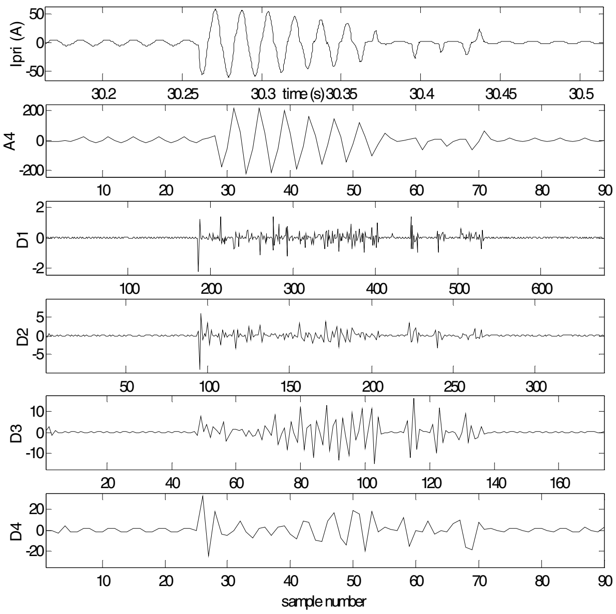

Figure 9. DWT of primary current for short circuit fault between the 20th and 26th turn of secondary winding for Figure 6.

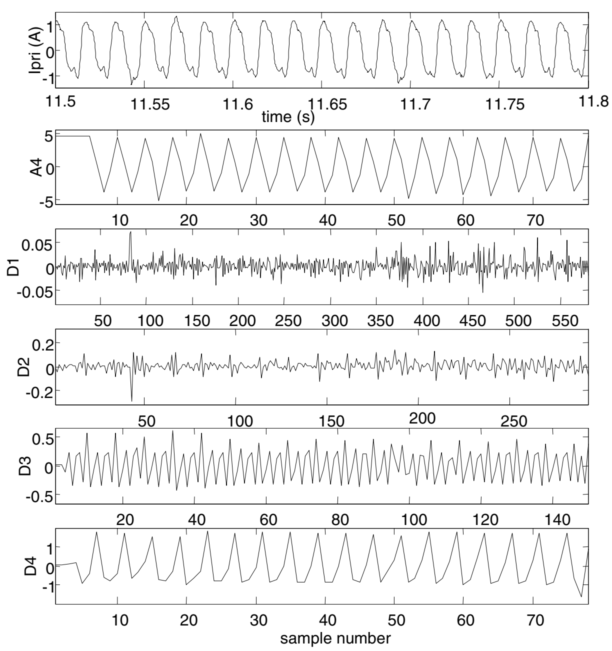

Figure 10. DWT of primary current for Load Test 4 in Figure 7.

6. Simulation Results

Incipient event behavior given in Figure 11 was simulated using the simulation method developed in PSAL. The simulation data was obtained using the deteriorating insulation model discussed earlier, which includes aging and arcing models. Figure 11 presents the waveform of primary current when the resistance R_p, in the aging model was 0.1 Ω and dissipation factor, *tanδ*, was equal to $5.4*10^5$. In the scenario, a secondary incipient fault was simulated between the 10th and 13th turns at intermittent time instances. The DWT of the simulation data shown in Figure 11 is similar to results shown in Figure 12. Figure 12 represents a part of the incipient case between 29.8 and 30.1 seconds obtained from field experiment for short circuit field test fault between the 10th and 13th turn of secondary winding.

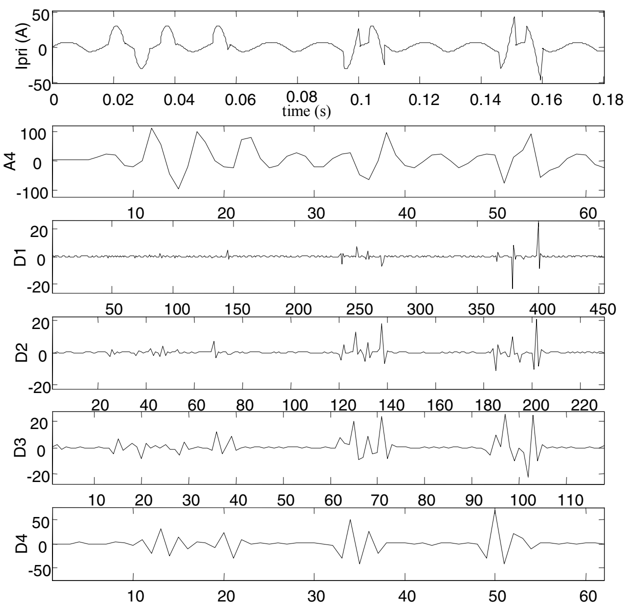

Figure 11. DWT of primary current obtained by simulation of incipient fault between the 10th and 13th turns of the secondary winding.

The main features of the internal incipient events can be summarized as: the spikes occur randomly; there is no consistency; and the rms values of the currents increase but not as much as the short circuit current.

Using these features, the incipient events can be distinguished from other cases of internal faults. The DWT of primary and differential currents will help the discrimination process.

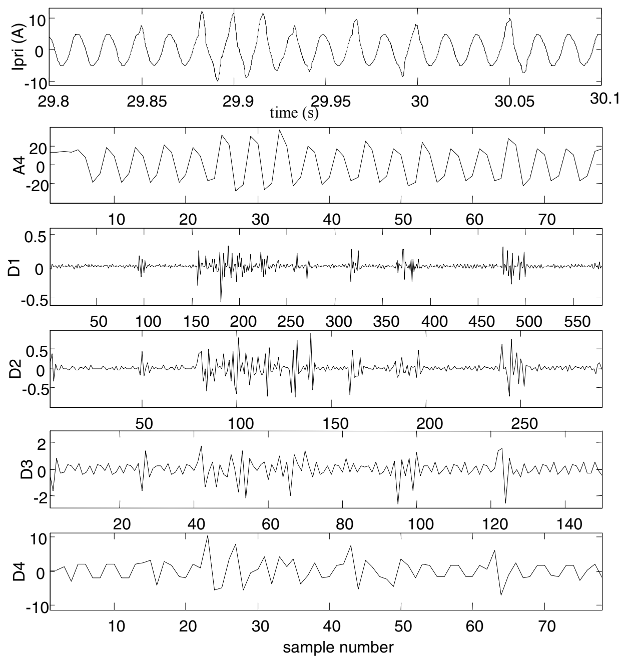

Figure 12. DWT of primary current for experimental short circuit fault between 10th and 13th turns of secondary winding that conveyed incipient behavior.

7. Conclusions

This paper discussed efforts to characterize internal incipient events in single-phase distribution transformers. Time domain analysis results were presented for data obtained from transformer experiments for internal incipient events. Also time-frequency domain analysis results from using discrete wavelet transforms (DWT) were presented for experimental and simulation data from internal incipient events.

From the time-domain results, it is observed that district spikes are conveyed in the high frequency bands during incipient activity. Further from the time-frequency domain results, this activity is seen to be localized in the detail coefficients.

The results show the potential for using a DWT-based method for predictive maintenance and maintaining reliability of transformers. This ultimately improves the protection of electric power systems, a critical infrastructure. Future work will investigate terminal behavior of the transformers with an intelligent method such as neural networks to perform discrimination and life estimation of transformer.

8. Acknowledgment

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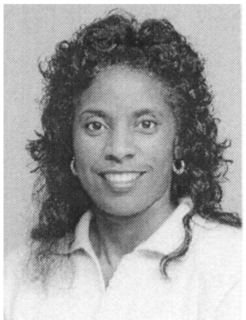
10. Biographies



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