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Experiences with non-intrusive monitoring of distribution transformers based on the on-line frequency response

Experiencias con monitoreo no-intrusivo en transformadores de distribución basados en la respuesta en frecuencia en línea

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ABSTRACT

The following article presents the results obtained in experiences that use the Impulse Frequency Response Analysis (IFRA) method with a transformer in service. The IFRA method has been implemented in order to transform the transient signals to the frequency domain using Discrete Fourier Transform (DFT). However, it can be considered that the DFT is not the most suitable tool for this type of analysis, since, by definition, this tool is useful for processing stationary signals. Taking that into consideration, the analysis of transient signals could be hypothetically improved by using continuous wavelet transform (CWT), given their variable time/frequency resolution. The analysis of transient signals in Wavelet domain has improved the repeatability of the frequency response curves, as it has been observed in experimental results. The proposed on-line IFRA method, based on Wavelet transform, was validated under load and no-load conditions on a 150 kVA three-phase transformer 13200/225 Volts, in the Campus of the Universidad del Valle, Cali, Colombia.

Keywords: Transformers, on-line IFRA, non-Intrusive monitoring, wavelet transform, energy.

RESUMEN

El siguiente artículo presenta los resultados obtenidos durante experiencias donde se usa el método de análisis de la respuesta en frecuencia mediante impulso (IFRA) con un transformador en servicio. El método IFRA ha sido implementado para transformar la señal transitoria al dominio de la frecuencia usando la Transformada de Fourier (DFT). Sin embargo, puede considerarse que la DFT no es la herramienta más idónea para este tipo de análisis, ya que desde su definición esta herramienta es útil para el procesamiento de señales estacionarias y no para el análisis de la respuesta en frecuencia mediante impulso. Teniendo en cuenta esta consideración, el análisis de las señales puede ser hipotéticamente mejorado usando la Transformada Wavelet continua (CWT) dada su resolución variable en tiempo-frecuencia. El análisis de las señales transitorias en el dominio wavelet ha mejorado la repetitividad de las curvas de respuesta en frecuencia, como ha sido observado en los resultados experimentales. El método IFRA on-line propuesto, basado en la Transformada wavelet, fue validado bajo condiciones de carga y no carga en un transformador trifásico de distribución de 150 kVA, 13200/225 Volts, en el campus de la Universidad del Valle, Cali, Colombia.

Palabras clave: Transformador, FRA On-Line, monitoreo no-intrusivo, Transformada wavelet, energía.

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Introduction

The monitoring of the physical condition of power transformers is important to assure high reliability of electric distribution systems. One of the most used methods to determine the physical condition of transformers is the Frequency Response Analysis (FRA), which is currently worldwide accepted as a complementary support to other diagnostic techniques. FRA is specially appreciated for detecting potential mechanical problems such as displacements or deformations in windings and core sheets since these types of faults are very difficult to locate using other methods (Wang et al., 2005).

On-line deployment of the frequency response technique offers substantial benefits for a scheduled-based diagnosis in a non-stop service scenario, and, moreover, it could even be used to support condition-based maintenance. This is the main reason why this approach has generated remarkable interest among utility companies and the scientific community.

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The on-line FRA method has been implemented through an Impulse Frequency Response Analysis (IFRA). This type of on-line monitoring can be carried out by taking advantage of the transients traveling throughout the system, by measuring them at the input and output of the transformer. Given that those transients might have different causes and characteristics, problems like noise and low repeatability of results (frequency response curve) need further investigation to improve that technique (on-line IFRA) (Gomez-Luna, *et al.* 2013).

The use of Discrete Fourier Transform (DFT) in the IFRA method is not the most suitable tool for this type of analysis since, by definition, this tool is useful for processing stationary signals. Even though the Fourier Transform has some improved versions for this application, such as the short-time Fourier Transform (STFT), the results still reveal room for improvements. This can be explained from the Heisenberg uncertainty principle, which in terms of signal processing indicates that it is not possible to find out the exact frequency and the exact time when the (sinusoidal) components of a signal take place. Taking that into consideration, the analysis of transient signals could be hypothetically improved by using Wavelet transforms, given their variable time/frequency resolution (Leonowicz *et al.*, 2003; Robertson, 1996; Gomez-Luna et al., 2013).

Consequently, in this study the analysis of transient signals in Wavelet domain (time-scale) in order to de-noise the signals and compute the frequency response curve (impedance curve) that could allow assessing the transformer condition is presented. An improved repeatability of the frequency response curves has been observed in experimental results with the proposal method. The transient signals computed by using wavelet transform (CWT) exhibit a better repeatability than the one computed by using Fourier Transform. Likewise, experiments reveal the convenience of Wavelet based de-noising strategies.

Non-intrusive monitoring of transformers

Currently the on-line IFRA method uses the disturbances inherent to the normal operation of the electrical network, such as switching-type pulse waves (induced by switches opening and closing) or pulse waves induced for instance by atmospheric events (lightning), where high-frequency components predominate; however, these signals are under random occurrences. This means that the shape of the disturbance is not controlled; therefore, a sufficient spectral content is not ensured.

In this study we used controlled transient signals since they present some advantages: on one hand, the trigger timing is controlled and, on the other hand, the shape may also be controlled such that a signal with adequate bandwidth is injected (Gomez-Luna *et al.*, 2013).

Pulse Injection and measurement

The injection system consists of an electronic circuit, which is specifically designed to inject controlled pulses on the 60 Hz signal. The measurement scheme is presented in Figure1.

Figure 2 shows an example of a controlled voltage pulse injected on the 60 Hz signal for on-line IFRA purposes. The pulse is sent to the high or low voltage side of the transformer under test through a high voltage capacitor that serves as a high-pass filter. Figure 2 also shows that the response (current pulse) is in phase (coincident) with the injected voltage pulse.

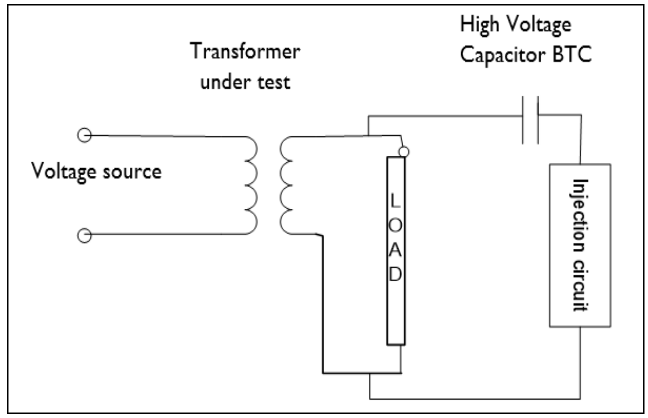

Figure 1. Pulse injection setup for the transformer under test.

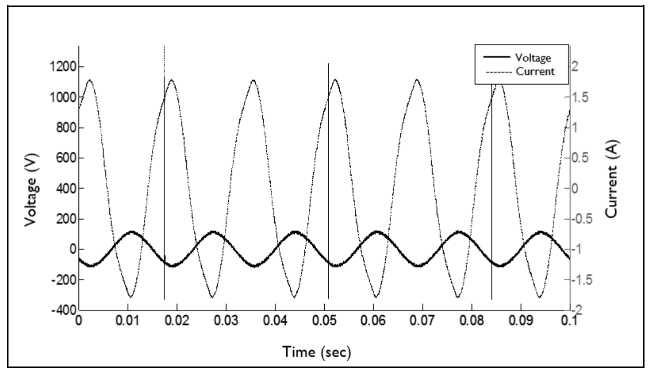

Figure 2. Example of controlled pulses on the 60 Hz signal used for the on-line IFRA method.

Taking into account that the pulses are short and content high frequency components, sensors with high bandwidths were used to measure current and voltage signals. A high voltage probe was used to measure voltage pulses and Rogoswky coils for current pulses. This allowed recording of transients without saturation problems.

Signal acquisition and processing

National Instruments sampled the voltage and current signals at a rate of 60 Ms/sec and 12 bits of resolution using the data acquisition recorder PCI-5105 manufactured. Signal decomposition and de-noising processes based on the Multiresolution analysis (MRA) of the Discrete Wavelet Transform (DWT) were implemented. The mother Wavelet Daubechies 4 (db4), which is commonly used for filtering electrical signals (Butler-Purry, & Bagriyanik, 2003; Zheng et al., 2010; Duarte et al., 2012) was applied to eliminate the background noise from the electrical system.

The power system harmonics were also removed from the signals by modifying the coefficients from a MRA using mother Wavelet Daubechies 10 (db10). Then, the voltage and current transient signals were processed to compute the respective frequency spectrum of the transformer.

The de-noised voltage and current waveforms, v(t) and i(t), were processed using Continuous Wavelet Transform (CWT) in order to compute their spectra, V(w) and I(w). For comparison purposes, the spectra based on Discrete Fourier Transform (DFT) were also com-puted. The transformer impedance Z(w) was computed as the ratio of the voltage spectrum V(w) to the current spectrum I(w) for every frequency component.

Analysis of information

The signal spectra and transformer impedance computed from on-line records were analyzed, measured while the transformer was energized in real time.

Impedance obtained in the frequency domain using wavelet transforms

The IFRA requires to transform the signal from the time domain to the frequency domain. Since the Wavelet Transform maps a signal to the time-scale domain it is necessary to integrate over the shifting time domain. In this study (1) we proposed to compute the transformer frequency response from the CWT (Gomez-Luna, et al., 2013):

$$|Z_a| = \sqrt{\frac{\int \left|CWT_{v(t)}(\tau, a)\right|^2 d\tau}{\int \left|CWT_{i(t)}(\tau, a)\right|^2 d\tau}} \qquad (1)$$

Where:

Z_a is the impedance for a given scale a.

CWTV and CWTI are the CWT of voltage and current signals, respectively.

For comparison purposes, (2) was applied in order to compute Z(ω) from the Discrete Fourier Transform (DFT):

$$Z(\omega) = \frac{DFT_{v(t)}(\omega)}{DFT_{i(t)}(\omega)} \qquad (2)$$

Experimental Results obtained in field

The proposed method was applied to actual transformers, and more than 70 tests either under load and no-load conditions were per-formed in the Campus of the Universidad del Valle, Colombia.

Figure 3 shows the experimental setup in field, indicating the main components in the on-line tests, that was employed to obtain the frequency response by injecting controlled pulses.

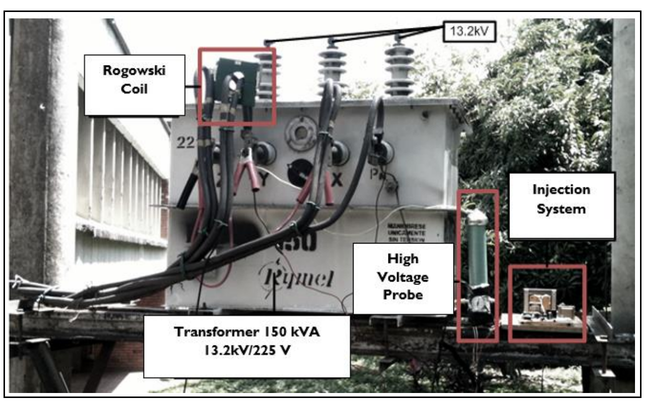

Figure 3. Experimental setup for on-line IFRA in field.

The proposed method was applied under load and no-load conditions on a 150 kVA three-phase transformer 13200/225 Volts, the connec-tion diagram is Dyn5. From Figure 4 to Figure 9 the correspondent results in the case of the on-line IFRA tests under load condition are presented. The time-domain measurements usually exhibit some non-repetitive behavior and, therefore, not just one but three different time-domain measurements were obtained in order to take it into account. Thus, three different responses are also shown in the graphs, respectively for the Discrete Fourier Transform and the Wavelet Transform processing.

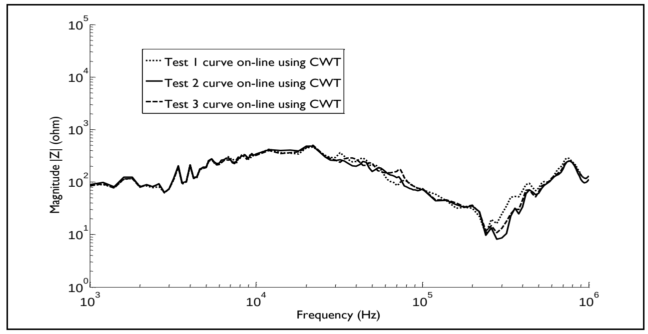

Figure 4. Measurements and pulse injection at loaded by low voltage winding (X-Pn) with high voltage winding energized by power system.

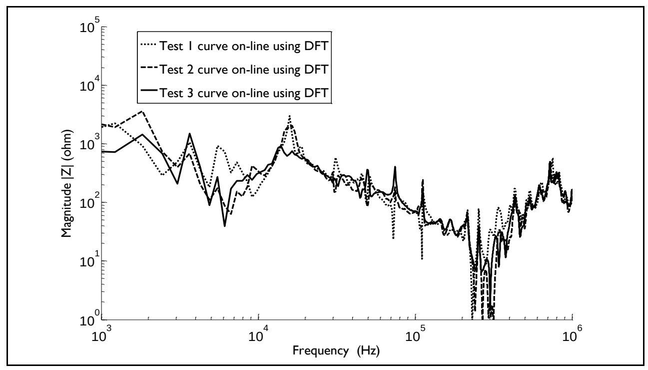

Figure 5. Measurements and pulse injection at loaded by low voltage winding (X-Pn) with high voltage winding energized by power system.

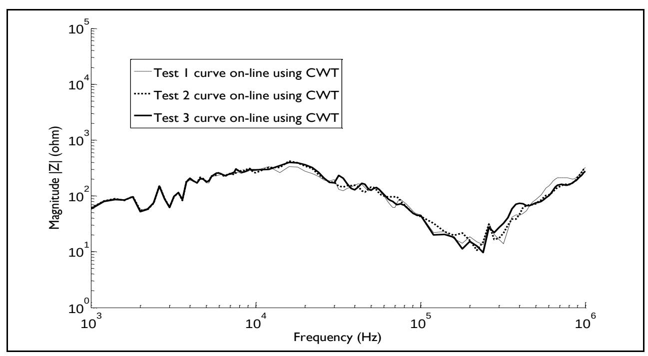

Figure 6. Measurements and pulse injection at loaded by low voltage winding (Y-Pn) with high voltage winding energized by power system.

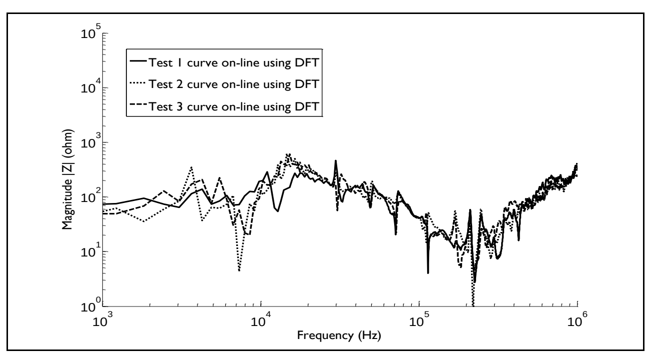

Figure 7. Measurements and pulse injection at loaded by low voltage winding (Y-Pn) with high voltage winding energized by power system.

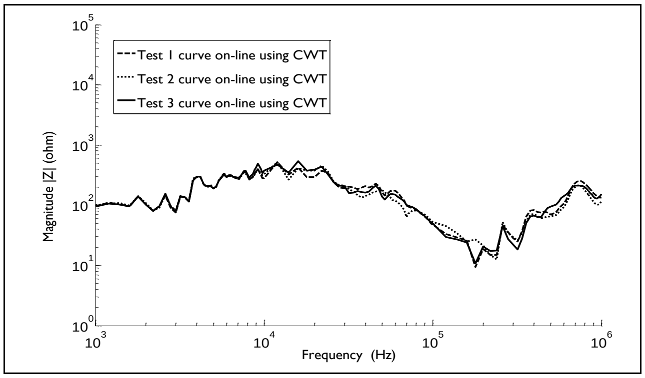

Figure 8. Measurements and pulse injection at loaded by low voltage winding (Z-Pn) with high voltage winding energized by power system.

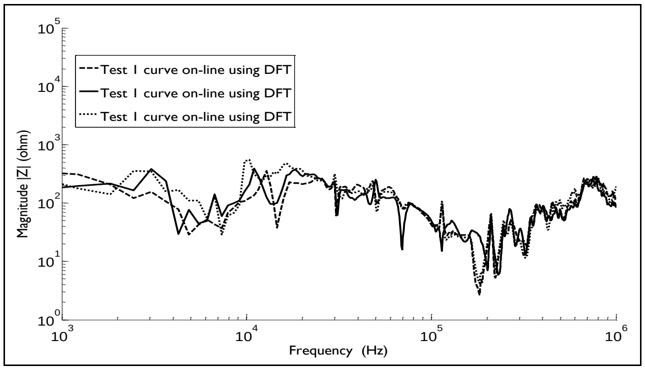

Figure 9. Measurements and pulse injection at loaded by low voltage winding (Z-Pn) with high voltage winding energized by power system.

The curves repeatability is the relevant feature to be investigated in a given frequency response analysis technique. The results shown in Figure 4, Figure 6 y Figure 8 present the on-line frequency response curves computed from 3 measurements taken at different time on transformer, under no variations on its physical structure. It can be observed that the curve computed by using CWT exhibits a better repeatability than the one computed by using DFT, Figure 5, Figure 7 and Figure 9.

Table 1. Comparison of influence features for the computation of On-Line IFRA curves based on continuous wavelet transform (CWT) and Discrete Fourier transform (DFT).

Influence Feature	CWT-based	FFT-based
Noise attenuation	Good (Figure 4, Figure 6, Figure 8)	Poor (Figure 5, Figure 7, Figure 9)
Smoothness	Good (Figure 4, Figure 6, Figure 8)	Poor (Figure 5, Figure 7, Figure 9)
Mean relative error (MRE)	Figure 4 =10.19 %	Figure 5=55.47%
	Figure 6=13.36%	Figure 7=35.12%
	Figure 8=11.25%	Figure 9=29.04%
Computing time	Longer (~39.1 s/curve)	Shorter (~29.8 ms/curve)

Considering that, in a real situation, transformers will be normally tested under load conditions, the frequency response curves comput-ed by using CWT demonstrated high repeatability along the 10 kHz – 1MHz frequency range, where the load does not have significant influence, and the transformer could then be monitored over this range. Low frequency signals (<10 kHz) can be considerably affected by the load, and high repeatability might not be easily achieved at this frequency range. Therefore, the CWT-based method discussed in this study can meet the basic repeatability requirement for diagnosing power transformer windings based on on-line IFRA technique (Gomez-luna et al., 2014).

Table 1 shows a qualitative comparison between the results obtained using Continuous Wavelet Transform and Discrete Fourier Transform based on-line IFRA for the transformers under test, according to the results shown above.

Conclusions

With the work performed in field the on-line IFRA method is potentiated due to the fact that the results are reliable and repeatable using the established methodology in laboratory.

The effectivity of the Continuous Wavelet Transform (CWT) of transient signals in the computation of on-line Frequency Response curves for power transformers remains evidenced in this study to obtain good results. Under different experimental conditions in field, the results obtained of on-line IFRA based on CWT outperformed the correspondent one based on Discrete Fourier Transform (DFT) in terms of repeatability, smoothness and signal de-noising.

On the other hand, the signal injection process proposed in this study successfully worked in several experiments. The use of controlled signals is preferred, given their better controllability and repeatability; nevertheless, the injection setup is much more complex.

The potential of the on-line IFRA technique using the Continuous Wavelet Transform has been experimentally exposed in this study. Therefore, further investigation is necessary in order to make the on-line IFRA method as effective and useful as the standard off-line FRA method.

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