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Magnetic Flux Entropy as a Tool to Predict Transformer's Failures

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Abstract

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Abstract:
This paper proposes magnetic flux entropy as another technique to assess electric transformer failures. The obtained tool based on entropy may reveal some irregularities, distortions, aging, overloading, and harmonics, all of them reflected over the electrical sine wave that supplies power to dwelling and industry. Some entropy concepts are reviewed and the basic equations are applied to data obtained from magnetic and infrared waves radiated by the (18 watts 110-20 V) prototype. Several experiments were made through non-invasive and indirect measurements of magnetic and thermal fluxes. Entropy, as an accepted indicator of physical complexity, is proportional to the logarithm of the number of states in a thermodynamic system. Failure prediction based on entropy of radiated magnetic waves could be easier, faster, and cheaper.

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 **Contents**

SECTION I.

Introduction

The transformer is an essential component of the transmission and distribution system. Transformers represent one of the key components in utility systems requiring a constant monitoring. For this reason, it is necessary to improve the techniques and methods for keeping good function of the network that helps to prevent transformer faults. The machine electric life is a decisive factor for managing the risk associated with the network reliability and of course provides a quality server directly impacting the availability. Currently are executed various preventive tests in energized transformers which use technics as ultrasound, power factor, physics and chemical analysis.

The approach presented to addressing this problem has been motivated by the transformer complexity; it reflects its ability to adapt and function in a changing environment and needs to operate across multiple diversity of loads, and hence their complexity is also multiscaled. Wide classes of faults in power equipment are electrical, thermal, and chemical stresses, closely related to the performance and lifetime of the equipment. Thus, gain/loss of complexity may be a sign of pathologic dynamics. Accordingly, this approach to define a complexity measurement for a transformer focuses on measuring the radiated magnetic/infrared waves over multiple scales. Multiple scale entropy is a new method to analyze the complexity of physical events time series. It has been applied to a wide diversity of phenomena [1]. First, it is necessary to characterize changes in the transformer dynamics complexity due to aging, harmonics and overload. This analysis is an

extension of previous work that focused on application of MSE to

entropy and coefficient of variation (CV) as tools for assessing power quality [2].

In this paper, it was analyzed the multiscale entropy and frequency spectrum of the magnetic waves radiated by a transformer for several conditions. The built electric model is resistive loaded in several steps: from no load up to overload. The concepts of entropy could lead to develop a theory of transformer aging. This may be understood as a multistep process leading the transformer through a sequence of defined stages characterized by a lower level of entropy production and finally to a critical low level of power delivery to load, causing permanent damage to the transformer. Then, if the entropy history is known, it is possible to predict the life span of the device.

Traditional approaches to measure the aging of electromechanical machines fail to consider the magnetic flux complexity as an age indicator. Complexity, understood as the sum of the individual entropies, is lower for older transformers. Time series multiple scales were analyzed using multiple scale entropy algorithms. These algorithms also yielded interesting findings when applied to other physical entities like high voltage transmission lines and motors. Fluctuations of the transformer's radiated magnetic waves under stress conditions were analyzed. The data obtained indicate complexity loss for aging and damage.

Ali et al. [3] discuss the application of several techniques that are used for life assessment of transformer insulation. These include: High Performance Liquid Chromatography (HPLC) of oil to measure the product concentrations; Size Exclusion Chromatography (SEC) of insulation paper (Presspan) to measure changes in molecular weight distribution (related to the Degree of Polymerization DP) and computer modeling of degradation process to relate chemical degradation rates to changes in physical properties, such as tensile strength, which is of critical importance in assessing the probability of damage to the paper under fault conditions.

Measuring harmonics in high voltage power systems with inductive and in particular Capacitive Voltage Transformers (CVTs) may cause great errors. Test carried out by The Norwegian National Grid Company (Statnett), Bergenshalvoens Kommunale Kraftselskap (BKK) and The Norwegian Electric Power Research Institute (now SINTEF Energy Research) revealed errors from 80% to +1200% (0,2–12 p.u.) of correct values [4].

There are methods for determining transformer overload level when it is energized, by means of devices that intervene in equipment for measuring electrical variables, i.e., to evaluate the nominal power in normal conditions as indicated by the standard IEEE C57.91 1995 [5] proposed by Pierce [6] (other developments: [7]–[8][9][10]) and IEC 354 [11]. It is possible to determine the overload by means of temperature levels that the transformer could have. The standard IEC 60076-7 2005 [12] defines admissible limits for temperature and current. These levels are checked periodically by the operating personnel. Currently, there is technology for monitoring transformers like transformers controlled with a microcontroller and sending data through serial communication to a host computer has been implemented [13]. Also, several electrical transformers are allowed to communicate with host computer within a closed network [14]. However, these kinds of methods require a process of implementation and require time and economic resources. It is necessary to think in practical methods that meet the needs and the different situations that an energy supply

company could have. For example, to evaluate the overloading of

transformers in rural areas is harder because of topography or weather conditions.

The structure of the paper is as follows: In Section II is provided the mathematical background for calculating the entropy rate and its physical meaning discussed. It is also presented a short description of the approximate entropy ApEn. In Section III, the Multi-Scale Entropy (MSE) method is applied to some magnetic radiated waves measurements taken near the transformer circuit, through noninvasive and indirect measurement of the current's complexity transported by the supply. This section shows data and results obtained from the experiment system consisting of 1 coil based electronic sensor plus a IR sensor, both located 1 meter from transformer. The acquired signal was read by a laptop and the data was processed to obtain graphs of entropy versus several variables. Furthermore, this study also analyzed the frequency spectrum of the magnetic waves generated by the 18 W prototype. All of the measurements were conducted at the Universidad Nacional de Colombia, Electrical Department Laboratory. Under the classical recommended experimental conditions, the data conducted to the entropy figures. It was confirmed that no extraneous electromagnetic waves occurred in the experimental system. In Section IV, conclusions and the path to future work are presented.

SECTION II. MSE Mathematical Background

Entropy is an intuitive procedure, because it is possible to visually distinguish between a clean and distorted signal. Furthermore, entropy is independent of absolute scales such as signal's amplitude or frequency. Shannon proposed the entropy H of a random variable X , with multiples values $x_1, \dots, x_n$ as

$$H(X) = E(I(X)). \quad (1)$$

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E is the value one expects and $I(X)$ is the amount of information of X .

$I(X)$ is defined as a random variable, p indicates the probability function of X , then, the entropy can be written as [15]

$$H(X) = \sum_{i=1}^n p(x_i) I(x_i) = \sum_{i=1}^n p(x_i) \log_b p(x_i). \quad (2)$$

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For the D-dimensional dynamical system, certain instant t_i is determined by its history, $t_1, t_2, \dots, t_{i-1}$ and each new system state carries an additional amount of new information. The Kolmogorov-Entropy (H_{KS}) is an appropriated tool for calculation the mean rate of creation of information

$$H_{ks} = -\limlim_{\delta \rightarrow 0} \lim_{\varepsilon \rightarrow 0} \lim_{n \rightarrow \infty} (H_{n+1} - H_N). \quad (3)$$

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New studies estimate the entropy of finite length time series in practical applications [16]–[17][18][19].

Moorman [20] proposed the Approximate entropy (ApEn). Calculation

(4) has the advantage of being less dependent on time series length. From $\{X_i\} = \{x_1, \dots, x_i, \dots, x_N\}$ that represents a time series of length N contains vectors of m -length $u_m(i)$. The vector $n_i^m(r)$ represents the number of vectors $u_m(j)$ that are close to the vector $u_m(i)$ and satisfies $d[u_m(i), u_m(j)] \leq r$ where d is the Euclidean distance, so

$$A_p E_n(m, r, N) \cong \frac{1}{N-m} \sum_{i=1}^{N-m} \ln \frac{n_i^m}{n_i^{m+1}}. \quad (4)$$

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ApEn is derived from (2) [1]. It is a statistic quantifying regularity and complexity, which has many potential applications to a wide variety of areas with relatively short (greater than 100 points) and noisy time-series data, and is applied in this paper to magnetic wave radiated transformers, permitting us to analyze a great amount of power. The theory of complex systems is not completely delineated yet. As electric engineers begin to work on complex systems, they will obtain better comprehension of their properties and how to use them to analyze power. However, the idea differs from engineer to engineer. Until now, the complex systems studied are the biological ones. Systems are related to people: individuals, groups, culture, internet, electric power networks, etc. [2].

The MSE calculation is obtained with discrete time series based in coarse graining. The original time series is divided into nonoverlapping windows of length η . Then each window is the result of averaging the data points contained therein. By mean of this procedure we obtain a new time series y_k^n with a scale factor η [1]

$\{x_1, \dots, x_i, \dots, x_N\}$ discrete time series

$$y_k^\eta = \frac{1}{\eta} \sum_{i=(k-1)\eta+1}^{k\eta} x_i, \quad 1 \leq k \leq N/\eta. \quad (5)$$

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For every scale factor η is submitted to measure entropy calculation. The procedure described above is called MSE, and the results are used to compare the relative complexity of normalized time series [1].

A. Magnetic Flux Entropy

The term B in the (6) represents the magnetic flux density (ϕ_{mag}), which is proportional to the magnetic field intensity [21]

$$B = \mu_0 H \quad (6)$$

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where μ_0 represents the vacuum permeability.

Abdelhady [22] introduced a relation to express the magnetic flux in terms of entropy. The magnetics can be expressed as:

$$\phi_{\text{mag}} = \int H dS_{\text{magnetic}} \quad (7)$$

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where ϕ_{mag} is the magnetic flux imparted to a system, H is the magnetic

field intensity, and dS_{magnetic} is the generated entropy by the transferred magnetic flux.

SECTION III.

Results

Entropy means higher complexity, understood as higher harmonics content; this affects and distorts the wave form. Please see Figs. 1 and 2.

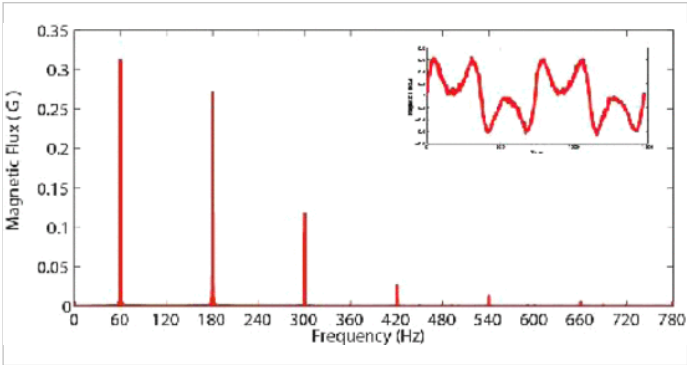


Fig. 1.
Spectrum showing harmonics caused by overload. The easy instrumentation proposed here, reveals the loaded transformer full spectrum.

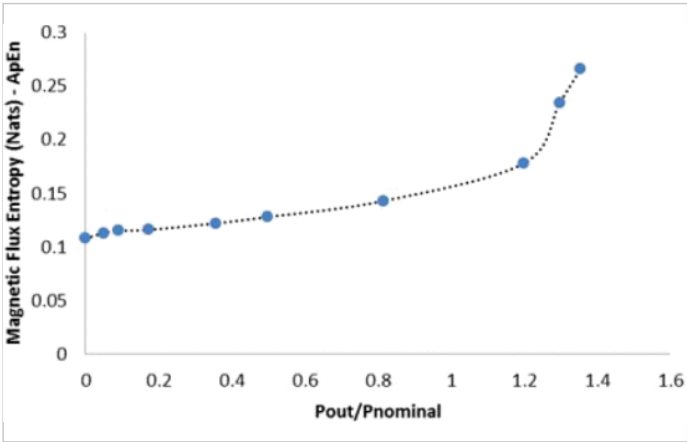


Fig. 2.
Entropy increases, linked to overload. The overheated transformer increases the magnetic flux entropy. Entropy value higher than 0.15 nats reveals overload. The ApEn of each evaluated magnetic signal has been called Magnetic Flux Entropy.

Frequency spectrum from 60 to 780 Hz is suitable for diagnosing abnormal conditions by detecting radiated electromagnetic waves emitted by power transformers. Entropy values higher than 0.15 indicate overload. Therefore, the generation of magnetic waves at unwanted frequencies ought not be allowed to grow without limit, because it may cause load damages. As a consequence, the harmonic content on dwelling and industries networks has to be limited.

Another improvement is the fast and easy THD measurement, as shown in Fig. 3. Equation (8) illustrates the relationship between entropy and radiated magnetic waves harmonic index. This value is related to the load current.

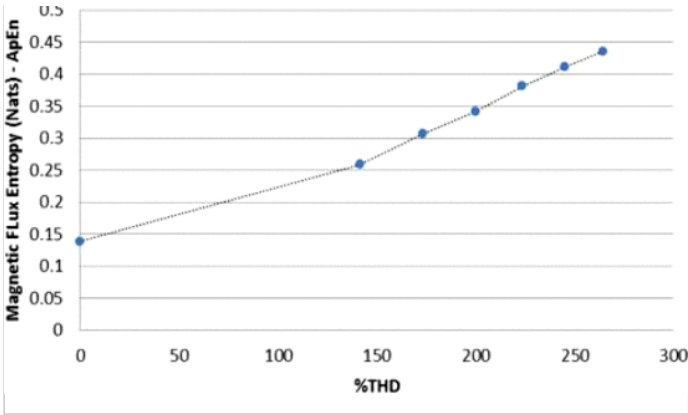


Fig. 3.
This graph suggests the possibility of obtaining the harmonic THD index by measuring of magnetic radiated waves entropy.

Another experiment on infrared radiate waves tell us about the perfect magnetic-thermal connection with transformer power as shown in Fig. 4.

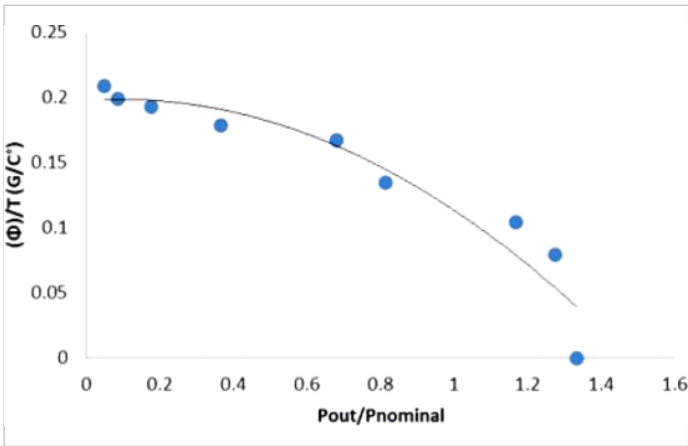


Fig. 4.
Magnetic flux/infrared flux ratio is related with overload. Values lower than 0.1 warns overload.

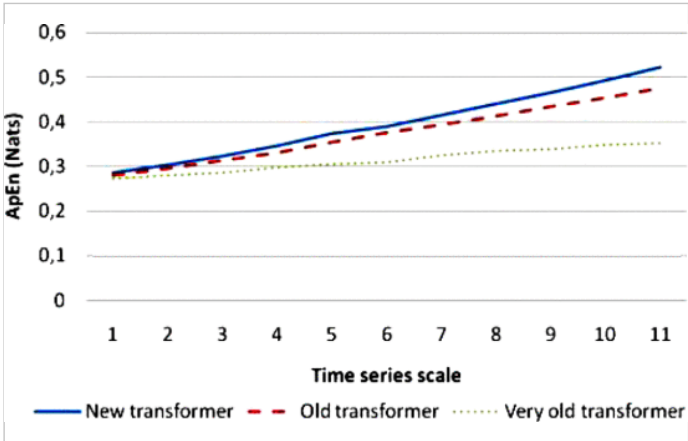


Fig. 5.
Oldest transformer shows the minor entropy. Based on this kind of relation between age and entropy could be feasible to predict the transformer lifespan.

The last experiment leads to propose a transformer age indicator. Three transformers were compared. The first is a new transformer, the second and third are older and were under electrical stresses. Fig. 5 proposes

that the electrical stress consequences make the radiated magnetic waves entropy decrease

$$THD = \frac{1}{0.0044} \ln \left(\frac{ApEn}{0.1402} \right). \tag{8}$$

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SECTION IV.
Conclusion

This study conducted a basic investigation to develop an online diagnostic technique for the power assembled equipment in industry and dwelling. The proposed tool could be an instrument to predict transformer failures. Then, to carry preventive and predictive maintenance, identifying the source and timing of events causing damages or malfunctioning would be easier and less expensive.

Future work would verify the developed method. The first stage would be to make the laboratory experiment with a distribution transformer under nonlinear loads (e.g., variable speed drive). The second stage would allow us to collate the previous experiment with real measurements from industrial costumer transformers. Finally, it will be possible to compare and to evaluate the proposed method performance against another noninvasive method for transformer diagnostics (e.g., Emission of Infrared Radiation Method).

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