

Application of multiscale entropy production theory to hydro-turbine maintenance

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Resumen. El mantenimiento de las turbinas hidráulicas sería más fácil mediante la medición de la entropía de múltiple escala de las ondas sonoras y magnéticas que produce, debido a que la entropía, como un indicador aceptado de la complejidad de las realidades físicas, es proporcional al logaritmo del número de estados en un sistema termodinámico. Los métodos actuales incluyen el modelado paramétrico, análisis FEA, simulación CFD, diseño CAD, programación de PLC y SCADA, protecciones, pruebas de calidad de la energía y otros. En este trabajo se describe un nuevo método para calificar el resultado final del mantenimiento de la turbina. El método utilizado para el análisis de las series de tiempo de las ondas generadas por la turbina sugiere una ganancia de la entropía de la turbina hidráulica con el envejecimiento. Se presentan varios conceptos y técnicas para cuantificar la entropía de las señales mencionadas con el fin de evaluar el rendimiento de la turbina. Se revisan estos conceptos y se presentan algunas gráficas de la entropía de las ondas tomadas cerca de turbinas hidráulicas y alternadores ubicados en Manizales, Colombia.

Palabras Claves: campo magnético, entropía de múltiple escala, mantenimiento, sonido, turbina hidroeléctrica.

Abstract. Maintenance of hydro turbine would be easier if it could be measured the multi-scale of its sound and magnetic waves produced by the entropy, as an accepted indicator of the physical complexity of the system, it is proportional to the logarithm of the number of states in a thermodynamic system. The following methods were applied: Parametric solid modeling, FEA analysis, CFD simulation, CAD design & drafting, PLC & SCADA programming, protection engineering & testing, power quality testing and others techniques. This paper describes a new approach to qualify the final turbine well-working.

The obtained results showed that the time sound wave series obtains from the turbine suggests a rise of the hydro-turbine complexity with aging. As well, several concepts and techniques to quantify the magnetic and sound wave signal entropy are presented, which are aimed to assess the turbine performance. Such concepts are explored and some entropy vs age plotting are depicted to show the behavior of the sound waves taken nearby the hydro-turbines and alternators located in Manizales-Colombia.

Keywords: hydropower turbine, magnetic field, maintenance, multi-scale entropy, sound.

1. Introduction

As one of the stages in electric hydropower station, the hydro turbine is one of the most important components for the performance of the system. Nowadays, reducing the loss of energy in hydro turbine as well as dealing with the aging effect that causes decreasing of electric energy production, there are issues of high interest. In this regard, Multi-Scale Entropy (MSE) and Mutual Entropy (ME), through software applications used for analyzing sound and magnetic waves produced by magnetic fluids. MSE and ME are approaches not very explored within the context of turbine performance assessing. Nonetheless, it may be interesting to exploit the entropy properties in this context, under

the premise that the waves generated by the turbine may have a relationship with the entropy production. The entropy production occurs during energy conversion showing an irreversible thermodynamic process. When the water reaches the turbine, produces mechanical energy, similarly, the rotor being connected through axis with the turbine, it interaction with the stator produces an electromagnetic field. Therefore, the entropy information production can be used to evaluate the dissipation of mechanical energy from a thermodynamic point of view.

The correct analysis of the MSE in turbines will create appropriate predictive maintenance routines, so that timely diagnose the state of the machine and it will facilitate the correct within the system and provide the service expected [1]. These maintenance routines put into action, reduced human, equipment and materials resources, and this will lead to point for reducing resources [2].

In the testing campaign carried out on May/2014 at several high heads hydro power plants equipped with 6MW, 15MW and 45 MW turbines, turbine's magnetic and sound waves entropy processing were performed. The experiments were made at electric generators located at Manizales, Colombia. Analysis Innovation methods of electrical and electronic circuits can provide the generated signals processing and will pose new procedures that can enhance the people perception of the physical phenomena. The goal of the engineer and scientist is to understand to complexity of the circuit, close it is essence and then will be able to change the traditional approach the same system. The electromagnetic waves and sounds varying in time are generated near hydro-turbines. The electric field is always associated to the presence of electric charges, and the magnetic field is created when the electric current flows. Estimate the magnetic fields to the turbines, it is necessary to know the intensity, frequency and direction of each ones.

The present study shows a comparative framework between Maxwell's equations of electric charge and magnetic flux, and as an analogy, the basic equation of thermodynamic entropy; in this context, the concept of entropy analysis means radiation of magnetic fields. The novelty of this work relies in the use of entropy approaches for assessing the turbine performance. The new view of this research begins with the development of the thermodynamic entropy theory 100 years ago by Clausius y Boltzmann and adds it by the entropy concept by Shanon's entropy or Information's entropy, it changed the electronic communications. This it shows that the entropy is a pure mathematical concept and fact [3].

This paper is organized as follows: Section 2 states some basics on entropy, section 3 describes the materials and methods, section 4 presents the results and discussion. Finally, in section 5 the conclusions and final remarks are outlined.

2. Entropy Basis

The purpose of this section is to show an overview of basic concepts of entropy required for the experiment construction.

2.1 Maxwell's equations and entropy

Maxwell's equations being partial differential equations, relate the electric and magnetic fields together with electrical charges and currents. The results of these equations cover all the various phenomena in the entire field of classical electromagnetism. According to Maxwell:

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \vec{E} = 0 \quad \text{Equation (1)}$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}\right) \vec{B} = 0 \quad \text{Equation (2)}$$

The general solution to this equation is a set of wave form:

$$E = (r, t) = g(\omega t - kt) \quad \text{Equation (3)}$$

$$B = (r, t) = g(\omega t - kt) \quad \text{Equation (4)}$$

Loads and electric flux produce magnetic waves whose entropy changes can be measured in the electrical appliance just mentioned. It is possible to make an analogy between the electric charges and magnetic flux with the heat, where the last it is the product of changes in temperature and entropy. This consideration leads to the following equations [4].

$$Q_{thermal} = \int T dS_{thermal} \quad \text{Equation (5)}$$

$$Q_{elec} = \int E dS_{elec} \quad \text{Equation (6)}$$

$$Q_{mag} = \int B dS_{mag} \quad \text{Equation (7)}$$

$Q_{thermal}$, Q_{elec} and Q_{mag} are flows supplied to the turbine. E is the electric field and B is the magnetic density field. $dS_{thermal}$, dS_{elec} and dS_{mag} entropies, are associated with the transferred energy.

$$\Phi_{mag} = \int H dS_{mag} \quad \text{Equation (8)}$$

Φ_{mag} is the flux through the coil of the turbine

H is the magnetic field strength

2.2 Shannon's theory

Shannon [5] proposed the entropy of a random variable with values multiple values $\{x_1 \dots x_n\}$ as:

$$H(X) = E(I(X)) \quad \text{Equation (9)}$$

E is the expected value,

I is the amount of information of X

$I(X)$ is defined as a random variable and p indicates the probability function of “ X ”. Therefore, the entropy can be written as [6]:

$$H(X) = \sum_{i=1}^n p(x_i) I(x_i) = \sum_{i=1}^n p(x_i) \log_b p(x_i) \quad \text{Equation (10)}$$

$I(X)$ is defined as a random variable and p indicates the probability function of X

Moorman [7] proposed approximate entropy (A_E). This calculation has the advantage of being less dependent on the length of time of the series. As $\{X_i\} = \{X_1, \dots, X_i, \dots, X_N\}$ represents a time series (11) of length N , containing vectors length m - $u_m(i)$. Vector $n_i^m(r)$ represents the number of vectors $u_m(j)$ that are near the vector $u_m(i)$ and $d[u_m(i), u_m(j)] \leq r$ is the Euclidean distance.

$$A_E(m, r, N) \cong \frac{1}{N-m} \sum_{i=1}^{N-m} \ln \frac{n_i^m}{n_i^{m+1}} \quad \text{Equation (11)}$$

The above equation represents approximate entropy. It is a quantification of the statistical regularity and complexity, which has many potential applications for a wide variety of areas with a series of relatively short length (of more than 100 points). The calculation in this paper is applied to magnetic waves radiated by turbines.

2.3 Multi-scale entropy

Multi-Scale Entropy [8] is calculated indiscrete time series using coarse graining. The original time series is divided into non-overlapping windows of η length. Then the data in each window contained in it, are averaged. By this procedure y_k^η , scale η new series is obtained.

$$\{x_1, \dots, x_i, \dots, x_N\} \text{ Discrete time series} \quad \text{Equation (12)}$$

$$y_k^\eta = \frac{1}{\eta} \sum_{i=(k-1)\eta+1}^{k\eta} x_i, \quad 1 \leq k \leq \frac{N}{\eta} \quad \text{Equation (13)}$$

The new time series (new level) is used to calculate the entropy. The process described above is called multi-scale entropy (MSE), and the results are used to compare the relative complexity of standardized time series.

2.4 Mutual entropy

The differential entropy of a continuous random variable X is defined by:

$$h(X) = - \int_s f(x) \log f(x) dx \quad \text{Equation (14)}$$

Measure of the differential entropy is done by the mutual information between two signals, [9]. Mutual information between Bands “P”, corresponding to the magnetic and sound signals intensity respectively, is expressed as:

$$h(B) = \frac{1}{2} \log_2 [2\pi e \sigma_B^2] \quad \text{Equation (15)}$$

$$h(I) = \frac{1}{2} \log_2 [2\pi e \sigma_I^2] \quad \text{Equation (16)}$$

I is sound intensity symbol

$$M(B, I) = \frac{1}{2} \log_2 [(2\pi e)^2 |K|] \quad \text{Equation (17)}$$

$|K|$ is the covariance matrix

$$M(B, I) = h(B) + h(I) - h(B, I) \quad \text{Equation (18)}$$

$$M(B, I) = \frac{1}{2} \log_2 [(1 - \rho^2)] \quad \text{Equation (19)}$$

ρ is the correlation coefficient symbol.

3. Materials and methods

The sensors used to acquire sound signals and magnetic waves are basically audio microphone and coil followed an audio amplifier. Both are connected to the microphone jack of a personal computer PC. Soundcard PC digitalizes the signals, which are captured by the recorder of Windows 7. Then generated files were analyzed with the software: Excel and MSE. The procedure is shown in Figure 1.

4. Data and Results.

Figure 2 illustrates the relationship between magnetic field and sound MSE, regarding the age. It shows the entropy in 15 scale of six turbines, two for each site: Insula, Esmeralda and San Francisco.

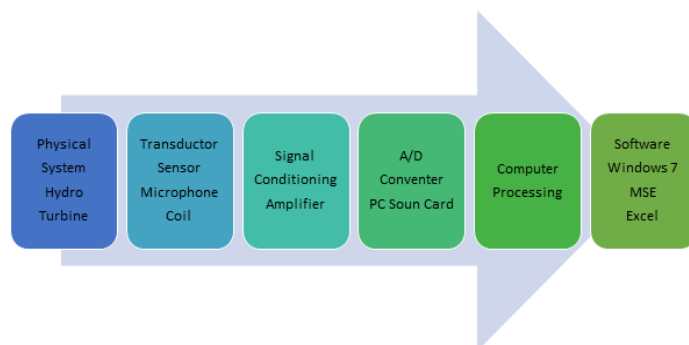


Figure 1. Block diagram of acquisition circuit.

To understand the entropy of the sound produced by the turbine, it helps imagine the system as follow: when the water reaches to the turbine is denominated “up water” and this when crush it the blades produce an unestable fluctuant charges in the surfaces, which are proportional to the acoustic pressure are radiated. It is expected to induce the creation of more complex entropy by the sound signal noise generated. The noise of water turbines are similar of wind turbines and marine propellers. It is well known that wind turbines and propellers produce two types of acoustic known signatures, namely, the harmonic and broadband noise.

The relative importance of these two acoustic signatures for hydrokinetic turbines has not been determined yet and will not be possible until the baseline measurements are taken. Therefore, this paper will focus on the harmonic noise, specifically the harmonic noise generated profiles formed gap upstream speed of the blades [10].

Figure 2 compares two turbines for each plant, the entropy of sound and magnetic field are grouped in order to compare this two turbines according the age, considering that age is the elapsed time since the last overhaul. Regardless of factors such as load, type of turbine, temperature, height above sea level and other factors that are standard on every plant. The figure also shows the direct relationship between the age of the turbine and entropy. When show it that the turbine that has the highest entropy is the older, which means, the turbine that has the highest entropy had largest lead time between the maintenance and the last measurement.

Entropy of sound can be generated from the mechanical structure, particularly the impeller, in the case of the turbine with the highest entropy values means that the machine is nearest of the malfunctioning

Impeller cracks, worn surfaces, buckets and the passage “cangelon”, bucket rotor, switch points, seating and deflector blades nozzles, bolted connections, pins and flawed wallpaper.

The magnetic field entropy creating waves in relation to the age of the turbines is affected by:

Stator insulation aging of contamination, stability of the insulation, unintended damage, insolation Alternator, changes of the values of the insulation resistance, time detects degeneration isolation, contamination or excessive moisture. Aging of the lubricating oils: kinematic viscosity, oxidation, acid, water content, metal content and additives wear and contamination.

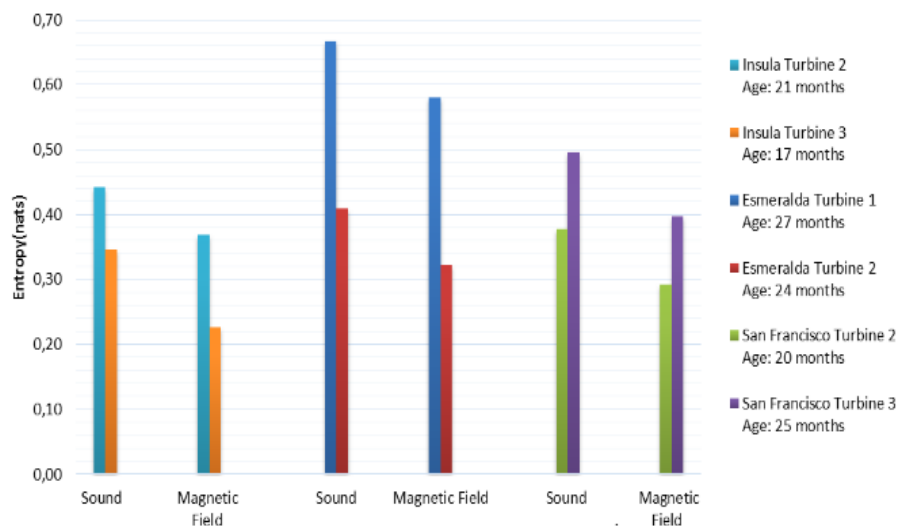


Figure 2. Comparison between magnetic field and sound entropy in 15 scale for each plant.

5. Conclusions

Complexity of the electromagnetic fields produced by the hydro turbines, can be explained through the study of multiscale entropy. It is possible to determine the multiscale entropy by turbine through its sound and magnetic field, it can determine the direct relation between the age of the hydro turbine and its entropy value

Multiscale entropy measure in a turbine through a predictive maintenance routine can determine the maintenance schedule reducing the maintenance cost and avoiding the possible wrecks.

Good maintenance of a turbine establishes an excellent condition of the equipment and large goods cycle, the multiscale entropy is a corrective procedure, which is in turn a quality indicator of the maintenance program execution too.

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