Experimental analyses for the determination of lifetime expectancy of transmission line conductors

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ABSTRACT: This paper presents a study for the determination of the lifetime expectancy of transmission lines conductors. A vibration recorder model PAVICA was installed on transmission line conductor with large span, a 670 m length, which is situated over Guama River crossing, in Belem – PA, Brazil. The lifetime expectancy of the conductor was estimated using the Poffenberger-Swart equation that converts the bending amplitude measured into dynamic curvature and bending stress in the outer strand layer at the mouth of the clamp in order to obtain the accumulated stress curve. By analyzing the results it was possible to verify that this transmission line conductor has a small probability of failure by fatigue damage during its operation time.

1 INTRODUCTION

The fatigue of conductors causes enormous economical damages to electric energy companies. This phenomenon is caused by the abrasion at locations where the transverse mobility of the conductors are dynamically restrained to the movement induced by the aeolian vibrations, mainly vertical displacements.

According to Hardy (2001) it has been known that severe sustained aeolian vibrations of overhead conductors and cables may lead sooner or later to progressive strand fatigue failures. This phenomenon is complex. In view of abrasion does not only occurs at points of contact of the external layer of the conductor with restrictions; it is highly aggravated by fretting at interfaces between strands themselves.

Wind vibrations had always been one of the main mechanical problems of the conductors of transmission lines of electric energy. According to Labegalini et al (1992) there are three types of vibrations in transmission lines conductors, all of them have the wind as excitement source. These vibrations are: aeolian, gallop and mat. The vibration caused by the movement of the electric current in the conductor also exists, although it is not relevant, being generally rejected. The most observed type of vibration in Brazil is the aeolian vibration with high frequency and low amplitude Labegalini et al. (1992).

In order to avoid future problems in the transmission lines, aeolian vibrations have become the object of numerous observations, analysis for forecast of the lifetime of the cable takes place.

In this study, it was made an experimental analysis of a transmission line conductor over a river crossing, a plain area without obstacles to the incidence of winds which represents a severe case of vibrations.

2 CHARACTERISTICS OF THE TEST SITE

All the field measurements were carried out on 230 kV Vila do Conde-Guama transmission line, in operation. The conductor is an ACSR type, model Grosbeak 636, with normal suspension clamps and all conductors fitted with armor rods. This line is located over Guama River crossing, in Belem, Para, Brazil, Figure 1.

Figure 1. Transmission line Vila do Conde – Guama

The transmission line span is approximately 678 m in length. It is composed of a 79.65 m high tower situated in the middle of the river and a 73.65 m high tower situated in the right margin. The reason for choosing this place is based on the fact that the wind intensity is generally influenced by the characteristics of the terrain, distance of the conductor to the ground and temperature.

Generally, places with low temperature, plain areas and where the direction of the wind is predomantly perpedicular to the conductor are more susceptible to the vibration. All these mentioned conditions happen commonly in the rivers crossing.

3 PROCEDURE OF MEASUREMENT

3.1 *Measure Equipment*

According to Cigré (1979) the conductor vibration can sometimes be observed visually by looking at the vibration conductors themselves, by hearing the clinking of fittings on insulator strings, by touching the tower. Often, however, more precise information may require vibration measurements on energized lines.

A vibration recorder model PAVICA was installed directly onto armor rods conductor in the vicinity of clamps to investigate the levels of frequency and bending amplitude of the conductor, Figure 2.

Figure 2. Equipment installation on the energized conductor

This equipment stores the amplitude and frequency data and the number of cycles peak to peak to accomplish an analysis of prediction of the lifetime expectancy if there is not an armor rods fitted on the conductor. It consists of a gagged cantilever beam sensor, fastened to a clamp, which supports a short cylindrical housing. A feeler in contact with the conductor transmits motions to the sensor.

The acquired data are stored at the equipment and may be transferred a computer via the RS 232 interface for readout of accumulated measurements. This arrangement requires software for the readout and storage of data, definition of measure parameters, such as amplitude and frequency ranges, sampling and pause periods and start and end of measurements.

The data are stored in a matrix with at least 16 frequency plus 16 amplitude classes. The main characteristics of the instrument are listed below, see Table 1

Table 1. Main characteristics of PAVICA

Sensor type	Strain-gaged cantilever beam
Amplitude range	0 – 1285.2
Frequency range	0 – 127
Matrix size	4096 conters corresponding to 64 amplitude intervals and 64 frequency intervals
Matrix memory capacity	100 million counts per matrix cell
Active monitoring period	1 to 12 seconds
Total period	1 to 60 minutes
Operating temperature (°C)	-40 to +85
Autonomy	Up to 3 months
Weight (kg)	Aprox. 0.5

3.2 *Measurement principle*

To relate the conductor motion at a conventional suspension clamp to the likehood of fatigue, the Institute of Electrical & Electronic Engineers - IEEE (1969) implemented a standardization of conductor vibration measurements in 1966. It is based on the differential vertical displacement (Yb), peak to peak of the conductor as related to a suspension clamp, measured 89 mm (3.5 inches) from the last point of contact between the clamp and the conductor, Bückner (1996).

Later, Poffenberger and Swart formulated the dynamic deflection field of the conductor in the vicinity of a fixed clamp and provided relations to convert the bending amplitude into a dynamic curvature and bending stress in the outer strand layer, Hardy (1991).

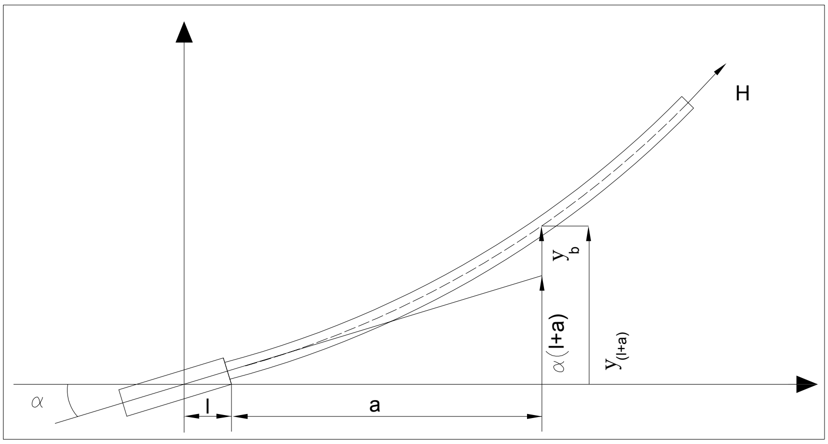

Figure 3. Bending amplitude (Y_b).

The calculation of conductor life expectancy before first strand fatigue failure from bending amplitudes has been proposed by Cigré Working Group 22.04 (1979).

In 1981, a method known as the inverted bending-amplitude was proposed. This principle consists in fixing a recorder onto the conductor and the clamp. The vibration recorder converts automatically the inverted bending amplitudes to bending amplitudes.

Starting from the bending amplitudes and using the Poffenberger & Swart (1965) equation, Equation 1, it was possible to determine the bending stresses.

$$\sigma_{fi} = QY_{bi} \tag{1}$$

Where:

$$Q = \frac{(q^2 E_e d_e)}{4(qa - 1 + e^{-qa})} \tag{2}$$

$$q = \left(\frac{T}{EIP}\right)^{1/2} \tag{3}$$

And:

E_e= Young's modulus of the envelope material (aluminum);

EIP = conductor minimum bending stiffness;

d_e = envelope wire diameter;

T = current conductor tension;

a = 89 mm, the PAVICA sensor blade length, the standard measuring distance from the last point of contact.

The partial fatigue damage D_{fi} due to the *i* th vibration cycle in the *f* th sample may be expressed as:

$$D_{fi} = \left(\frac{\sigma_{f_i}}{k}\right)^{a} \tag{4}$$

Where, for single layers conductors:

k = 420 and α = 6 for σ_{fi}< 26,6 N/mm²

k = 730 and α = 5 for σ_{fi} > 26,6 N/mm²

And, for multilayer conductors:

k = 257 and α = 6 for σ_{fi}< 15,6 N/mm²

k = 450 and α = 5 for σ_{fi} >15,6 N/mm²

According to Miner's rule, Miner (1945), which considers linear cumulative damage, the fatigue damage due all the cycles of the *i* th sample is given by:

$$D_f = \sum D_{fi} \tag{5}$$

D_f is the fatigue damage cumulated over the sampling period extending over time t_{meas}. The expected fatigue damage for the total time period before the start of the next sampling episode is extrapolated as follows:

$$D_F = (\frac{t_{tot}}{t_{meas}})D_f \quad (6)$$

Where:

t_{tot} = total time period before the start of the sampling episode;

t_{meas} = period extended over time;

Total cumulative fatigue damage must be updated:

$$D_{cur} = D_{prev} + D_F \quad (7)$$

Where:

D_{cur} = total cumulative damage at the completion of the *f* th sampling episode;

D_{prev} = total cumulative damage at the completion of the preceding sampling;

And finally the current conductor life expectancy is evaluated as:

$$V_{cur} = 3{,}17.10^{-8} N_f \frac{t_{tot}}{D_{cur}} \quad (8)$$

Where:

N_f = total number of sampling episodes up to the current *f* th episode;

3.3 *Field measurement parameters*

In order to evaluate the conductor behavior in different weather stations, two tests were realized at the energized conductor of the transmission line Vila do Conde – Guama. These analyses followed the same parameters of period and amplitude range; the vibration recorder was programmed to collect data during the period of 10 seconds to each 15 minutes and the amplitude range was 0 to 1285.2 μm.

The frequency range adopted was 0 to 63 Hz for the first measure, although the frequency range adopted in the second test was 0-127Hz.

The recorder collected data during 39 days at the first measurement. It results in a final sampling of 36420 seconds. And, in the second measurement, the recorder collected data during 19 days, resulting in a final sampling of 18720 seconds.

The conductor stiffness and the effective stiffness (EIE) were calculated considering the armor rods. This information is necessary to convert the reverse bending amplitude to bending amplitude. The effective stiffness (EIE) is assumed to be 40% of the maximum stiffness of the conductor.

4 EXPERIMENTAL DATA MEASUREMENT ANALYSIS

4.1 *Experimental data results*

The cells of the Table 2 and Table 3 show the number of cycles occurred for each amplitude and frequency levels for the first and second measurements, respectively. The cell corresponding to the frequency of 61 Hz and the amplitude interval of 26 to 52 × 10^{-6} m presented the highest number of cycles of the sample.

Table 2. Result Matrix of PAVICA (57 – 62Hz)

Amplitude (μm)	Frequency (Hz)					
	57	58	59	60	61	62
130. – 157.	0	0	0	0	0	0
104. – 130.	0	0	0	0	0	0
78. – 104.	0	0	0	0	5	0
52. – 78.	700	0	149	1030	11637	214
26. – 52.	1218	0	214	2041	13255	215
0. – 26.	0	0	0	0	0	0

In the Table 3, the cell corresponding to the frequency range of 60 to 61 Hz and the amplitude interval of 22 to 44 × 10 $^{-6}$ m presented the highest number of cycles of the sample.

Table 3. Result Matrix of PAVICA (52– 63 Hz)

Amplitude (μm)	Frequency (Hz)					
	52-53	54-55	56-57	58-59	60-61	62-63
133. – 155.	55	179	380	377	8577	88
111. – 133.	283	1226	2828	4405	28094	842
89. – 111.	25	723	1456	5623	34005	538
66. – 89.	52	465	760	6707	44090	24
44. – 66.	414	456	1659	16794	91570	1
22. – 44.	597	3209	4897	21370	249789	0
0. – 22.	394	1487	1414	4494	26418	0

However, it was noticed in the Figure 4 that the highest number of accumulated cycles, independently of the amplitude level, occurred at the frequency of 31 Hz, for the first measurement.

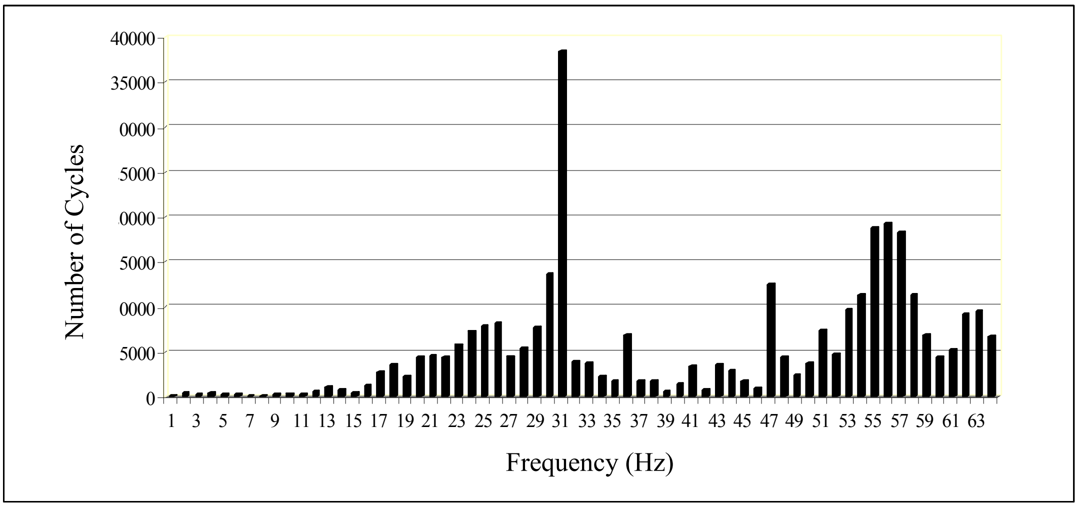

Figure 4. Number of cycles for different frequency levels, first measurement.

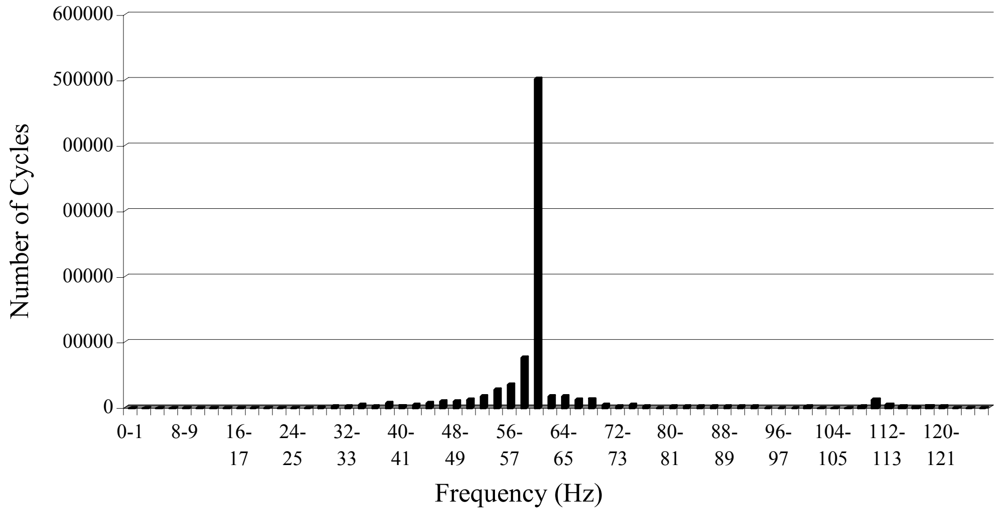

Figure 5. Number of cycles for different frequency levels, second measurement.

For the second measurement, Figure 5 shows that the highest number of accumulated cycles, independently of the amplitude level, occurred at the frequency range of 60 to 61 Hz.

4.2 *Experimental data analysis*

The conductor material performance can be characterized by an S-N curve, also known as Wöhler curve.

The bending amplitude collected was converted to dynamical bending stress using Equation 1, already mentioned. So, it was possible to represent an accumulation curve of service stresses. It consists on a graphical representation of the number of cycles for each stress levels for one year. Figures 6 and 7 represent the accumulation curve of service stresses, for the first and the second measurement, respectively.

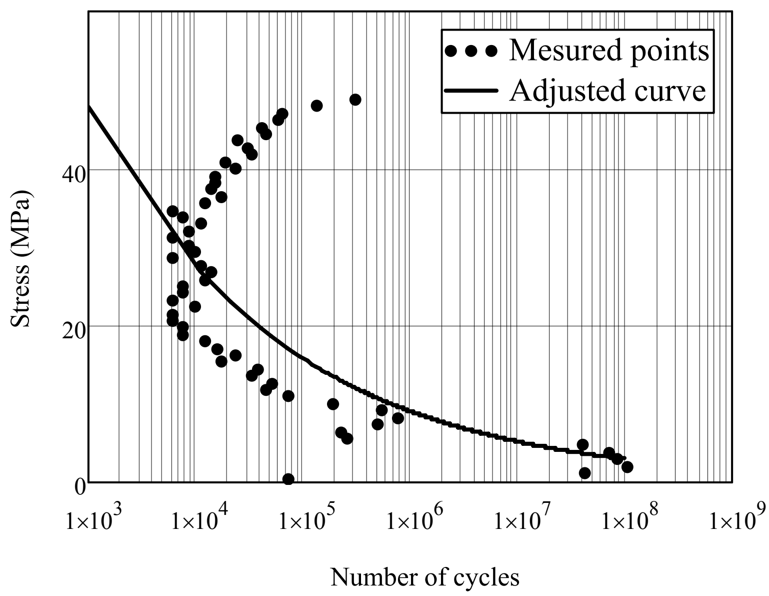

Figure 6. Number of cycles for each stress level for the first measurement.

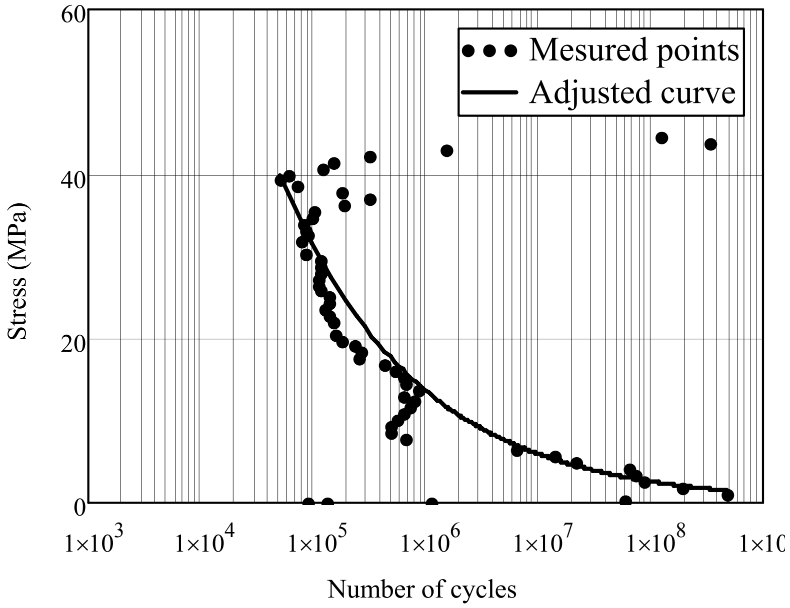

Figure 7. Number of cycles for each stress level, for the second measurement.

After that, a comparison between the accumulated stress curve and the safe border line suggested by Cigré (1979) was realized.

This comparison was made for the purpose of obtaining the conductor life expectancy by using software developed for it, based on the Miner's theory, already mentioned.

5 DISCUSSIONS

The measurements carried through different periods of the year had registered occurrences of cycles in different ranges of frequency. These differences were caused by the climatic variations that have an effect on the mechanical behavior of the conductor (alteration in the conductor shape and tension resulting in modification of its natural frequencies) and on the wind action.

Therefore, it is verified the importance of carrying measurements at different periods of the year for the determination of the life expectancy of transmission lines.

Finally, the results showed an infinite life expectancy for the transmission line analyzed. A very large value for lifetime indicates that the transmission line has a small probability of failure by fatigue damage during its operation time; in the case of Brazilian transmission lines this period is about 30 years. On the other side, the case of very small life expectancy indicates high probability of fatigue damage. In that case there will be necessity of measures for prevention by the energy company.

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