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Using structural health monitoring to estimate the remaining lifetime due to fatigue at a conductor from an overhead high-voltage transmission line

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ABSTRACT: This article presents the work developed in the context of the study of the turbulent wind effects on a high-voltage transmission line. Turbulent wind loads are in the origin of vibrations, namely Aeolian vibrations, inducing damage at the cable conductors and accessories. With the purpose of investigating such effects, a continuous dynamic monitoring system was developed and installed on a span of a de-activated transmission line. In order to validate existing fatigue models applied to the estimation of the remaining life of conductors, measured accelerations are processed, and CIGRÉ's standard rules for the fatigue evaluations are applied. The experimental results are then mathematically manipulated according to the Poffenberger-Swart procedure, and the remaining lifetime estimation of the conductor is determined using the Rainflow method and Miner's rule.

KEYWORDS: Aeolian vibrations; Conductors fatigue; Conductor remaining lifetime; Dynamic monitoring; Cable failure.

1 INTRODUCTION

Despite the high level of standardisation currently adopted in the design of overhead high voltage transmission lines (LMAT), there remains a considerable lack of knowledge regarding the characterisation of the turbulent wind effects, the structural behaviour of conductors, their dynamic interaction with the towers, and also the definition of damping levels achieved in service and extreme conditions. The occurrence of damage and collapse in LMATs is not uncommon, both in terms of conductors and insulators, as well as in towers, which can cause disturbances in the distribution of electricity with significant economic repercussions. On the other hand, the difficulties related to the instrumentation of live-lines have limited the experimental characterisation analysis of these structures' behaviour.

However, technological developments in recent years have opened new perspectives in the monitoring of these structures. In this context, the Laboratory of Vibrations and Structural Monitoring (ViBest) at FEUP has designed a continuous dynamic monitoring system and implemented it on a LMAT's representative span of the electricity transmission network's infrastructure, taking into account the greenfield location and the atmospheric conditions. The monitoring system aimed at studying, among others, the effects of aeolian vibrations, which are the leading cause of the conductors' fatigue failure.

This article aims to present the continuous monitoring system, and some results of a study focused on the assessment of the remaining lifetime of a conductor, comparing the dynamic cable behaviour before and after installing Stockbridge vibration dampers.

2 CHARACTERISATION OF THE LMAT

2.1 *Location*

The monitored span is part of the Riba de Ave - Vermoim 1 Line, which runs along the cities of Vila Nova de Famalicão, Santo Tirso, and Valongo and is currently de-activated. This span has an approximate length of 595 m, crossing an area of rural characteristics, with sparse vegetation and low construction density. Images of this span and the instrumented tower are shown in Fig.1, and an aerial view of the crossed area in Fig. 2. The choice of this span was based on the length greater than 500 meters and the location outside urban area with good exposure to the wind.

Figure 1. LRA.VM1 Line: a) span e b) instrumented tower.

Figure 2. Aerial view of the zone crossed by P43-P44 span.

2.2 Cables

The conductor cables in the monitored span are of the ACSR (Aluminum Conductors Steel Reinforced) type, consisting of aluminium wires with a reinforcement core of steel wires, and the cross-section as shown in Fig.3a. The LMAT also has a guard-cable of the same type but with a smaller number of wires and a smaller cross-sectional area, schematically shown in Fig.3b.

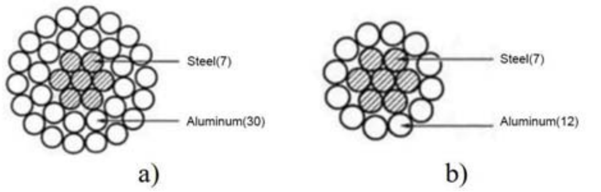

Figure 3. Cables cross-section a) conductor and b) guard-cable.

The instrumentation was applied to a conductor cable with a 24 mm diameter and reference BEAR - ACSR 325. With the purpose of subsequent calibration of the numerical model, a topographic survey was carried out, which allowed defining the installed tension and the cable profile. This information is systematised in Fig.4. It is also noted that no connection joints or repairs were observed at the cable during the installation of the monitoring system.

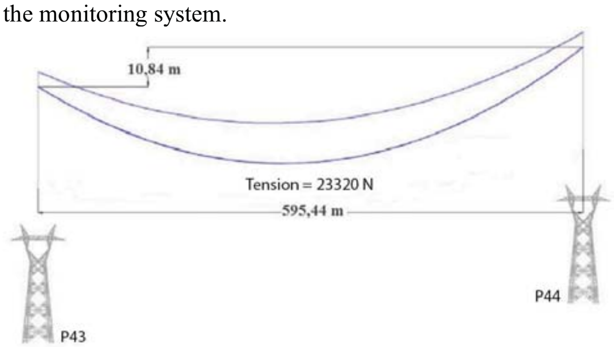

Figure 4. Cable profile and installed tension force.

2.3 Towers

The towers P43 and P44 supporting the LMAT's monitored span, are equal and designated as T1-29, belonging to the "T" family towers with 29m height. These are common trussed steel structures constituted by angle profiles and connected by bolts and gusset plates.

2.4 Structural health monitoring system

With the main aim of characterising the conductor's vibrations and the potential dynamic interaction with the towers, a structural health monitoring system has been designed and implemented. Having the intention of using this system in an activated line, fibre optical technology was incorporated into the system by means of specific developed Bragg sensor setups installed in five sections of the cable according to the representation of Fig.5.

The measurement of in-plane and out-of-plane strains in the conductor at more than one section allows the identification of modal components associated with the conductor's vibration. Simultaneous measurement of the tower vibrations using two accelerometers in two horizontal directions allows the characterisation of the dynamic interaction between these two substructures. The monitoring system was complemented with four accelerometers, located in the first and third measurement sections closest to the tower. Images of the accelerometers installed at the tower and conductor are shown in Figs. 6 and 7. Finally, to characterise the wind actions on the conductor and tower, a sonic anemometer was installed at the top of the tower (see Fig. 8).

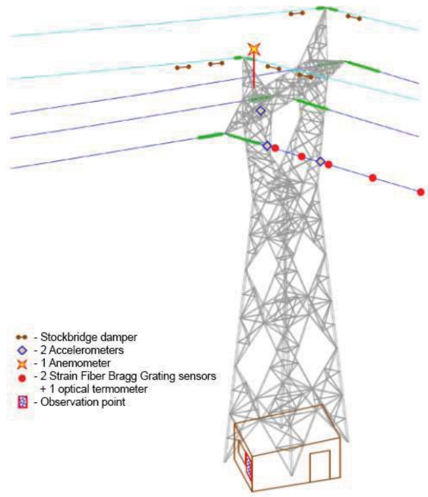

Figure 5. Instrumented section locations in the P43-P44 span.

Figure 6. Accelerometers: a) piezoelectric (tower) and b) MEMs (conductor).

Figure 7. Accelerometers installed: a) piezoelectric (tower) and b) MEMs (conductor).

Figure 8. Anemometer installed at the top of the tower.

2.5 *Data acquisition*

The acquisition system was installed near the base of the P43 tower, accommodating all devices for data acquisition, storage and management, as well as communication and power supply. The monitoring system was active for a period of two years. In order to assess the performance of Stockbridge dampers, a conventional damping solution for the span was designed and implemented, which permitted the monitoring of the damped conductor during a period of 6 months.

3 FATIGUE, DAMPERS, AND VIBRATION RECORD DEVICES

3.1 *Fatigue at cable conductors*

Significant attention should be given to cable conductors since these components represent up to 40% of a transmission line's total investment. Hence, maintenance is essential for electricity distributor companies. However, it is not uncommon in this kind of structure to confront one of the most complicated mechanical problems related to damage and failure: fretting fatigue. Fretting happens due to relative movement between the conductor's internal wires and by their contact with clamps and dampers. In overhead high-voltage transmission lines, this phenomenon occurs mainly due to aeolian vibrations, also designated as vortex-shedding resonance. These vibrations occur for particular wind velocities and are due to the formation of alternate vortices at the top and bottom of the conductor, inducing a vertical cable movement that results in bending at the anchorage or suspension point near the tower. The association of bending and tension stresses at the cable may conduct to fatigue of the wires.

Aeolian vibrations in cable conductors occur at low wind velocities from 0.5m/s to 7m/s, in a frequency range of 3Hz to 150Hz, and the vibration amplitudes are expressed as a function of the conductor's diameter, with values around 0.01 to 1 diameter [1].

3.2 *S-N curves and CIGRÉ's Safe Border Line (CSBL)*

The characterisation of the fatigue performance of a material is commonly achieved using the stress-life method with the aid of S-N curves (Wöhler curves), which plot in a graph the cyclic stress (S) versus the number of cycles to failure (N) during a laboratory test. The test stop criteria are either the failure of 10% of the cable's wires or of a specific number of wires. Due to the difficult execution and expensive costs involved in this kind of test, the International Council on Large Electric Systems (CIGRÉ) provided a safe curve, called Safe Border Line, in order to make it easier for companies to determine the lifetime of conductors without a substantial investment. Fig.9 shows the CSBL curve in comparison with other test results for a variety of cable compositions [1].

The following equation can express the Safe Border Line curve

$$\sigma_a = A \cdot N_i^B \quad (1)$$

The constants A and B are related to the number of fatigue cycles N_i for a specific level of stress and number of aluminium wire layers of the conductor. The stress amplitude is designated as σ_a and expressed in *MPa*. Table 1 shows the values of these parameters according to [1].

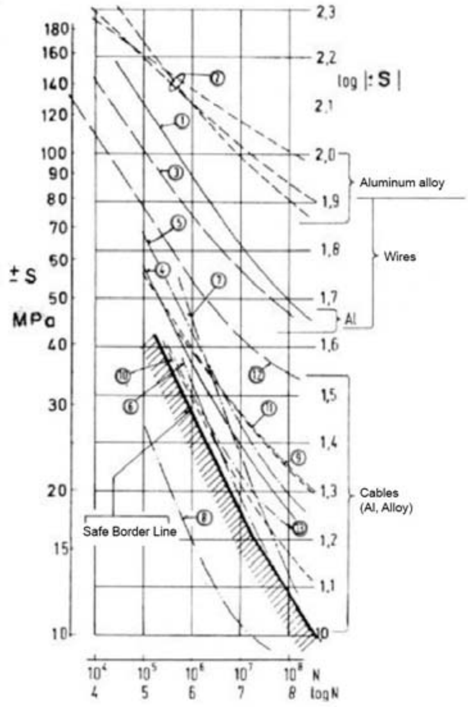

Figure 9. CIGRÉ Safe Border Line and S-N curves [1]

Table 1. Constant values A and B for the CSBL curve.

# of layers	N < $2x10^7$		N > $2x10^7$	
	A	*B*	*A*	*B*
1	730	-0.2	430	-0.17
> 1	450	-0.2	263	-0.17

3.3 *Every Day Stress (EDS) and bending stress concept*

The Every Day Stress is the tensile strength established by CIGRÉ as a portion of the cable conductor's Rated Tensile Strength (RTS). In general, in overhead high-voltage transmission lines, EDS values vary in a range of 15% to 20% of the RTS. Although fatigue failure in conductors is intimately linked with high EDS values, the increasing energy demand has been leading companies, over the years, to use higher values of EDS, which can easily achieve 35%.

The accurate assessment of stress and strain at conductors is a difficult task. Poffenberger and Swart [2] developed an analytical formulation that establishes a relationship between the dynamic bending stress (σ_{PS}) at the wires' outer layer and the peak-to-peak vibration amplitude (Y_B). The Poffenberger-Swart equation can be expressed as

$$\sigma_{PS} = K \cdot Y_B \quad (2)$$

The constant K in this equation converts the vertical amplitude measured at 89 mm from the last point of contact (LPC) into bending stress (0-to-peak), as shown in Fig.10, and is defined as

$$K = \frac{E_a \cdot d \cdot p^2}{4 \cdot (e^{-p \cdot x} - 1 + p \cdot x)} [N / mm^3] \quad (3)$$

where E_a is the aluminium Young's modulus, expressed in *MPa*, d is the wire diameter in the outer layer, expressed in *mm*, x is the distance between the measurement point and LPC, usually adopted equal to 89 mm, and the parameter p is described by

$$p^2 = \frac{T}{EI} \quad (4)$$

In equation (4), T is the tension force at the conductor calculated using EDS, expressed in *N*, and EI is the conductor's minimal flexural stiffness in $N.mm^2$ given by the following equation

$$EI_{\min} = n_a \cdot E_a \cdot \frac{\pi d_a^4}{64} + n_s \cdot E_s \cdot \frac{\pi d_s^4}{64} \quad (5)$$

where n_a is the number of aluminium wires, E_a is the aluminium Young's modulus, and d_a is the aluminium wire diameter. The other parameters n_s, E_s, and d_s are the same, but now regarding to the steel wires present in a multi-layer cable conductor.

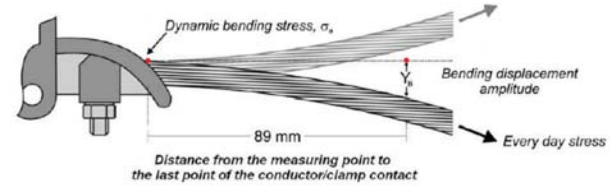

Figure 10. Schematic view of the conductor's clamp and the vibration amplitude measurement point.

3.4 Stockbridge dampers

Stockbridge dampers are the most widely used devices for aeolian vibration control. In general, they consist of two rigid masses connected to both ends of a messenger cable. A clamp ensures the connection between the damper and the conductor. This connection allows the transmission of displacements from the conductor to the damper (Fig. 11). The inertial masses attached to the messenger cable induce a cable bending, causing energy dissipation by friction due to the relative movements between the internal wires of the cable. Energy dissipation occurs in a frequency band close to their natural frequency, reaching maximum values when the Stockbridge is excited in that frequency range [3]. If the sum of the energy dissipated by the conductor and the Stockbridge damper is greater than the energy supplied by the wind, the conductor will vibrate with less amplitude and for less time.

However, to guarantee the system efficiency, it is essential that dampers are placed in the correct position along the cable, usually at the points of the cable with the largest amplitude of vibration and closest to the anchored points. Installing the Stockbridge dampers at incorrect positions can result in an increase in mechanical overload on the cable, which will lead to a reduced lifetime. Theoretically, a Stockbridge damper should be placed at a distance of λ/4 from the fixed point, as shown in Fig.12, where λ is the wavelength of the mode to be mitigated.

However, taking into account that the natural frequencies of the assembly damper-cable are different from the natural frequencies of the isolated cable, CIGRE recommends the damper installation at a distance [4]:

$$x = 0.85 \cdot \frac{\lambda}{2} \quad (6)$$

Where the wavelength is given by:

$$\lambda = \frac{1}{f_n} \cdot \sqrt{\frac{T}{m}} \quad (7)$$

In equation (7), f_n is the cable natural frequency in *Hz*, T is the tension force, expressed in *N*, and m is cable mass per unit of length, expressed in *kg/m*.

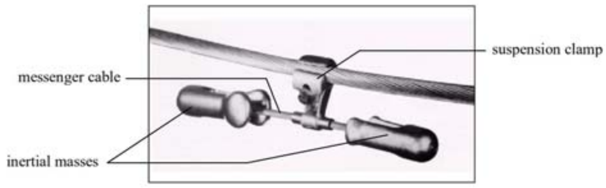

Figure 11. Stockbridge damper attached to the cable conductor [3].

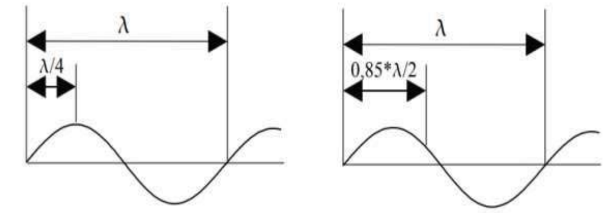

Figure 12. Theoretical and recommended distance of the Stockbridge installation.

The resonance phenomenon occurs when the wind excitation frequency (Strouhal frequency) approximates the natural frequency of the cable. Considering the Strouhal number equal to 0.185, which is the recommended number for the specific case of cables in overhead high-voltage transmission lines, critical wind frequency can be extracted from the expression

$$f = \frac{0.185 \cdot U}{D} \quad (8)$$

Where U is the wind velocity in *m/s*, and D is the diameter of the conductor, expressed in *m*.

3.5 VIBREC500 vibration recorder

As part of the assessment of aeolian vibrations on transmission line cables, devices used to measure vibration amplitudes and calculate the remaining lifetime are commonly used. In this work, the device VIBREC500-WT (Fig.13), manufactured in Switzerland, by Pfisterer Sefag was used to measure the aeolian vibrations, recording peak-to-peak amplitudes, vibration frequencies and temperature. The VIBREC weight is about 0.7 kg, including the battery, and has an autonomy of approximately one year, depending on the ambient temperature and the acquisition time interval. The device was developed for cables supported by suspension clamps. Therefore, they are usually installed next to these sections, and the measurement sensor is located at a distance of 89 mm from the clamp.

Figure 13. VIBREC500-WT device at suspension clamp.

Due to the necessity to manage the battery life and memory, the VIBREC500-WT does not continuously record data. The standard acquisition consists of storing 10 seconds of active-time data within 15 minutes of an idle interval, following the recommendation of CIGRÉ, which determines a minimum monitoring period of three months. Assuming that the device measures for three months, only approximately 24.8 hours of data would be recorded, which is equivalent to 0.3% of the period of one year. This low percentage is one of the main reasons for carrying out this work, which aims at characterising the quality of lifetime cable estimations based on such a short sampling period. Table 2 shows some VIBREC500-WT specifications.

Table 2. VIBREC500-WT data acquisition specifications

Active-time of acquisition	1 – 10s
Active-time + Idle-time	15s – 60min
Wind velocity	0 – 30m/s
Frequency range	0.2 – 200Hz
Amplitude of vibration	0 – 2mm

The VIBREC500-WT is also capable of calculating the remaining lifetime of the conductor with a software aid. The analysis performed by the software is following the most recent IEEE [4] and CIGRÉ [5] standards. Accordingly, the measured peak-to peak amplitudes are converted into bending stresses, using the Poffenberger – Swart equation (2).

Regarding cycle counting, the VIBREC500-WT manual states that the device automatically stores the number of half-cycles in a data matrix, and the software converts the data into a number of full-cycles.

The data are expressed through an S-N curve relating each block of stress to the number of cycles, and the damage at the conductor is determined using the Miner's rule using the expression

$$D = \sum_{i=1}^{m} \frac{n_i}{N_{fi}} \tag{9}$$

and the procedure shown in Fig.14. The S-N curve obtained with the recorded data is compared with the CIGRÉ's Safe Border Line [1], obtaining the final damage value, which is extrapolated to a one-year period.

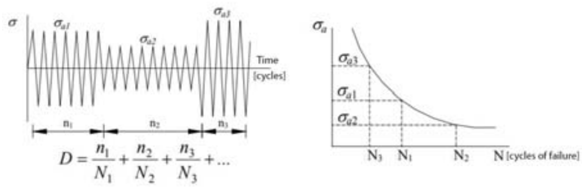

Figure 14. VIBREC500-WT device at suspension clamp.

Finally, the remaining lifetime is given by the following equation

$$V = \frac{1}{\sum D} \tag{10}$$

Where D is the accumulated damage and V is the remaining lifetime in *years*.

4 REMAINING LIFETIME ESTIMATION METHOD

As the objective of evaluating and comparing whether the signal acquisition time stipulated by VIBREC is sufficient to characterise the phenomenon of fatigue in conductor cables, the present work proposes a method of calculating the remaining lifetime due to fatigue using structural health monitoring data.

4.1 Periods of analysis

In order to use the same concepts and formulations employed by VIBREC500-WT, a micro-electrical mechanical accelerometer (MEM#3) has been installed close by the anchorage point to simulate the device position. This sensor measures the vertical accelerations of the cable (in-plane).

In possession of a relevant continuous monitoring database, two specific periods of analysis were considered. The first one was chosen before installing Stockbridge dampers and the second one after the installation, both with a three-month duration as recommended by CIGRÉ. Different weather conditions were also considered when choosing the period to take into account the effects of temperature variations. One interval was defined during three months in the summer without dampers, and another three months of data were collected in the winter with the dampers already installed. Fig.15 and Fig.16 show the 10-minutes wind mean velocity in both periods of analysis.

The calculations of the conductor lifetime were then made considering different record durations, starting in 5 s in every 15-minute period, and ending with the full 15-minute period.

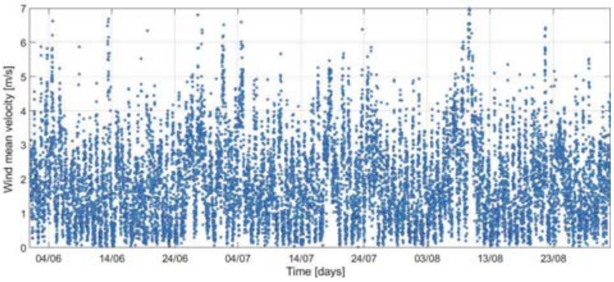

Figure 15. 10-minute mean wind velocity during summer.

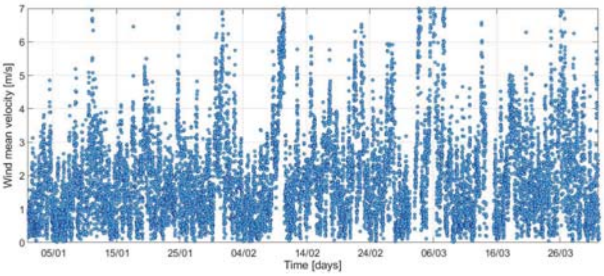

Figure 16. 10-minute mean wind velocity during winter.

4.2 *Processing of acceleration signals*

Before using the acceleration signals in the cables to calculate the fatigue lifetime, it is necessary to resort to data processing procedures. The algorithm developed collects the accelerometer signals and then analyses and remove the offsets, outliers and missing values.

Another important procedure that should be done is to filter the signal removing the frequency content out-of-range of wind vibrations. The wind-induced vibration frequencies can be determined using the equation (8) and the wind velocity range 0.5-7m/s for the cable BEAR-ACSR 325.

$$f = \frac{0.185 \cdot [0.5, 7]}{0.02345} \approx [4Hz, 60Hz] \qquad (11)$$

A Butterworth signal processing filter was designed to have a frequency response in the mentioned passband as flat as possible.

4.3 *Signal integration in the frequency domain*

The Poffenberger-Swart equation converts the cable amplitude of vibration into bending stress. This implies that the acceleration signals should be doubly integrated in the frequency domain to transform accelerations into velocities and afterwards velocities into displacements. It is necessary to be aware of the correct method to apply to integrate discrete signals in the frequency domain preventing the drift effect, which results in a corrupted signal. Table 3 shows the parameters used in the Poffenberger-Swart equation (2) considering the characteristics of the conductor under analysis.

Once the displacement signal is converted into a stress signal, the cycle counting Rainflow method is applied, and Miner's rule is used to determine the conductor's remaining lifetime.

Table 3. Poffenberger-Swart equation parameters

Aluminium Young's modulus, E_a	70000 MPa
Steel Young's modulus, E_s	200000 MPa
Aluminium wire diameter, d_a	3.35 mm
Steel wire diameter, d_s	3.35 mm
Number of aluminium wires, n_a	30
Number of steel wires, n_s	7
Conductor Bending Stiffness, EI_{min}	2.163x10^7 N/mm^2
Cable Tension, T	23320 N
Poffenberger-Swart constant, K	31.981 N/mm^3
Distance from LPC, x	89 mm

5 REMAINING LIFETIME ESTIMATION RESULTS

Several analyses have been performed using different acquisition times before and after the Stockbridge installation to estimate the remaining lifetime of the LMAT's conductor and assess the acquisition time used by VIBREC500-WT. Table 4 and Fig.17 show the results of these analyses.

Table 4. Lifetime estimations for LMAT's conductor

Acquisition time [s/15min]	Life [years]	
	Without dampers	With dampers
5	10.05	200
10	7.74	167
30	6.09	136
60	5.86	132
90	5.86	127
120	5.77	124
180	5.54	126
300	5.55	123
600	5.27	119

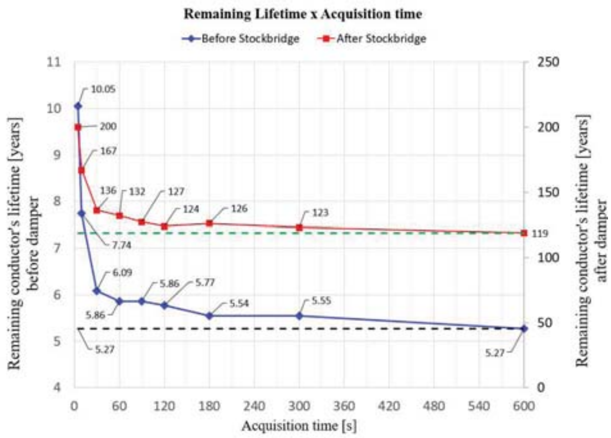

Figure 17. Remaining lifetime x Acquisition time.

Based on the analyses, the conductor's remaining lifetime tends to 5 years when increasing the time of acquisition in the cable without the Stockbridge damper. On the other hand, the cable analyses with dampers show a considerable increase in the conductor lifetime, which tends to 119 years. This occurs due to the energy dissipated by the dampers, reducing the amplitude of vibration and consequently reducing the stresses at the anchorage point. In Fig.17, it is possible to observe that the acquisition time of 10s for 15 minutes used by default in the VIBREC500-WT is not sufficient for a reasonable estimate of the lifetime, and even less for time intervals of less than 10s, as allowed in the device configuration. It can also be observed that the lifetime values obtained for the undamped and damped condition for the different periods of data analysis exhibit an asymptotic variation after a period of 60s/15min of data acquisition. Assuming the CICRÉ's recommendation of data acquisition using 10s/15min time, at the 3-month end, the amount of data analysed is 86400s compared to the 518400s using 60s/15min. As usual, the lifetime is expressed in years, and the data is extrapolated for this period. Considering the VIBREC500-WT period of acquisition, it represents 0.27% of a year. As stated before, this time is not enough to characterise the fatigue phenomenon due to aeolian vibrations. Considering the results obtained with this specific conductor, it is recommended to perform time domain analysis using at least 120s/15min for a reliable estimation of the remaining lifetime of a cable conductor, which represents 1036800s or 3.3% of a year. Fig.18 shows the accumulated damage curve compared with the CIGRÉ Safe Border Line for 120s of time acquisition without damper.

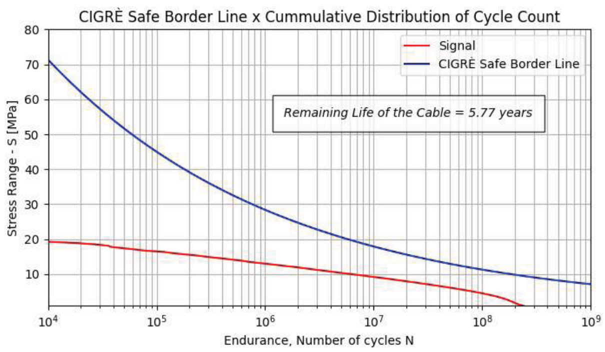

Figure 18. Accumulated damage x CIGRÈ Safe Border Line.

6 CONCLUSIONS

The installation of a monitoring system in a LMAT line allowed continuous observation through data collection and automatic analysis of the cable conductor's response with the main aim to assess the current recommendation of the data acquisition system of the aeolian vibrations measurement devices in overhead high-voltage transmission lines. The proposed method in this work allowed to estimate reliably the remaining lifetime of the cable due to fatigue before and after dampers installation, evidencing unconservativeness in the short-term monitoring using established sampling durations. Although further studies should be made to validate this conclusion, it is shown that the use of continuous monitoring acceleration can provide a good alternative to evaluate the remaining lifetime of a conductor if compared with the traditional methods.

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