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On-line Monitoring of Vibration and Strain Measurement in Pillar's Legs of Transmission Line for Estimation of Tensile Force in Conductor

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SUMMARY

Modern electric transmission systems provide additional data about conductor conditions under different weather conditions as temperature and sag of conductor. Except direct measurement on high voltage conductor, nowadays the indirect measurement technique is possible to apply in pillar's legs of transmission line. Results of strain measurement in pillar's legs of transmission line shows correlation between weather conditions, temperature of air and temperature of conductor vs. length of conductor, sag and change of tensile force in conductor. The study is dealing with change of deformation in legs of pillars. The boundary conditions are obtained by experimental measurement of strain in legs and geometrical measurement of all three conductors between two pillars. The performed study shows that online monitoring of change strain can be connected with change of geometry of conductors and consequently the change of tensile force in conductor. The change of tensile force in conductor can be caused by additional weight or temperature change. The measurement of natural frequencies shows that natural frequencies depends on temperature of pillar and tensile forces in conductors.

KEYWORDS

Overhead power line, Tower, Strain measurement, Vibration measurement.

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INTRODUCTION

The study developed a hypothetical model for monitoring the strain changes of tower's legs of overhead lines in relation to changes in sag. The boundary conditions are obtained by experimental measurement of strain in legs of tower. No. 111 of profile's size L140x140x14 and geometrical measurement of catenary of all three conductors in the span between the towers No. 111 and 112 on the overhead line 220 kV Obersielach-Podlog (Austria). The study is based on measurements and consists of two parts, namely:

-study of dependence on change in horizontal force from the conductor's sag, which can be a consequence of temperature changes or additional weight of the conductor, and - study of change of elastic strain in legs of the overhead line tower due to changes in horizontal force or in vertical load on the conductor.

The pilot results of the study showed that by monitoring the change in strain of towers above the foundations, it is possible to detect changes of forces in the conductor, which can be a consequence of changes in sag, either due to mechanical factors influencing the conductor (for example additional weight) or due to temperature changes. To verity the model and to transfer it from the hypothetical model, it is necessary to carry out additional measurements of the catenary at different temperatures of the conductor and also carry out continuous monitoring of strain in support angles of the tower and/or parameters on the conductor.

MEASUREMENTS OF STRAIN ON TOWER AND CONDUCTOR'S SAG

The study shows measurement of eigen frequencies and strain on support No. 111. The sag of the conductor between towers No. 111 and 112 was also measured on the route RTP Podlog - RTP Obersielach (Austria) on the 220 kV overhead power line at constant sustained current and practically unchanged meteorological conditions. On the basis of these measurements, the boundary conditions were set as a first step in the aforementioned research intended to assess the sag/temperature/tensile stress in the overhead power line conductors on the basis of diagnostics of mechanical properties of the tension support. It is an indirect approach where the strain in tower is actually measured and the tension in conductors is determined on its basis.

Three strain meters (strain gauges in longitudinal and transversal direction), accelerometers and tower support temperature gauges were attached in the lower support scheme. Meteorological conditions were measured with a mobile meteorological station by the company ARTES d.o.o. from Velenje. Wind was changing direction with the speed from 0.02 to 5.12 m/s (mean 1.08 m/s). Air temperature at the time of measurements was +4.42 °C. Average relative humidity 51.3 % at average air pressure 0.973 bars. The measured analogue signals were electronically supported and recorded with a computer. On the day of the measurements, the 220 kV power line was loaded only with a 160 A current, which did not cause any significant temperature load on the conductors. Layout of strain gauges for one half of the Wheatstone bridge for all 4 legs consisting of structural steel angels 140x140x14 at the height of 1600 mm is shown on Figure 1and is defined according to the geographical position where the individual tower support leg is standing.

Figure 2 shows the control penetrometer for fast checking. The accelerometers are used for measurement of vibration in both directions, as is shown in Fig. 3. The gauges, amplifiers are connected to the computer. Computer program for automatically capturing and recording data was applied, as shown in Fig. 4. Vibration measurements, which have been detected with accelerometers, are carried out for the frequency range up to 50 Hz. The excitation of tower in order to measure eigen frequencies was carried out with a steel hammer rum covered with two accelerometers. Measurements of eigen frequencies were repeated four times. The results have been subjected to frequency analysis, on the basis of which it was established that the first eigen frequency lies in the range between 5-6 Hz, as is shown in Fig. 5. Frequency analysis is based on Fourier's analysis of oscillations with regard to time, where the repeated iteration procedures eliminate the noises and random impulses on the basis of comparison between all 4 measurements of structure's vibration response. The power line has been under a constant current of 160A and the meteorological conditions were also stable, so there has been without changes on temperature in the conductor. We were also not able to detect any significant changes in strain with the use of strain gauges. For these reasons, we decided to take strain measurements in the legs of the tower by forced oscillation of the tower, in which there has been a strain change that the measuring system was able to detect. The results were obtained in a 10-minute long interval and are shown in figure 6. It is evident from Fig. 7 that due to the change of tractive-horizontal force, the character and amount of strain in the tower leg usual for bracket bending is changed. Namely, one side comes to pressure and the other one to tension with characteristic mean value, which corresponds to the amount of voltage variations due to horizontal force on the tower brackets. Other couples have shown minor deviations, which corresponds to dynamic behaviour in the neutral zone. Because of the potential oscillation in pressure and tension, all the channels were placed in the area 50% of the entire measuring range.

Complete measuring range (100 %) was defined as 1mm/m or "1 milistrain". From the measured values it can reasonably be assumed that the strain of SG1 reached 1% of the measuring range in pressure, and on SG6 0.5 % in tension, which, according to calibration of the strain gauges, amounts to a change in pressure of -2.1 MPa and 1.05 MPa change in tension.

Figure 1: Layout of strain gauges on the south-east tower leg

Figure 2: The control penetrometer was placed on the south-eastern leg

Figure 3: Layout of accelerometers in both directions in relation to the plane of the profile

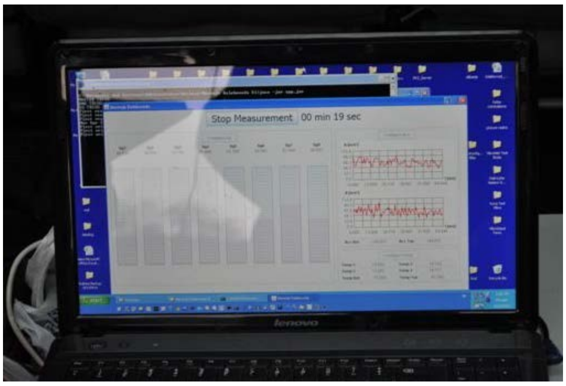


Figure 4: Mobile measuring station with computer and program for capturing and recording the measurement results

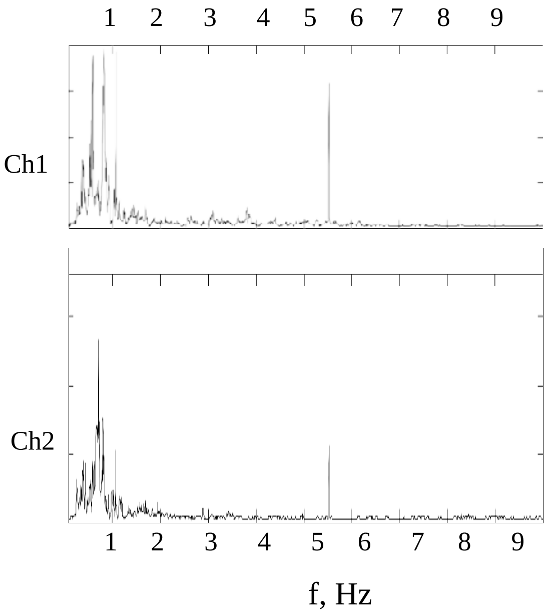


Figure 5: Acceleration measurements and determination of tower eigen frequency 5.5 Hz

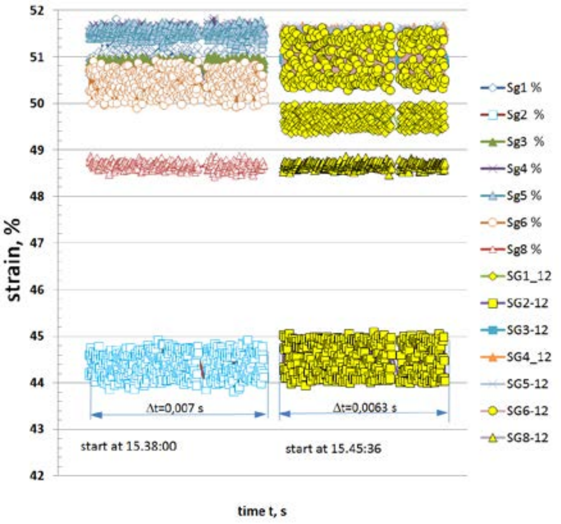


Figure 6: Strain measurements with two strain gauges per each profile leg

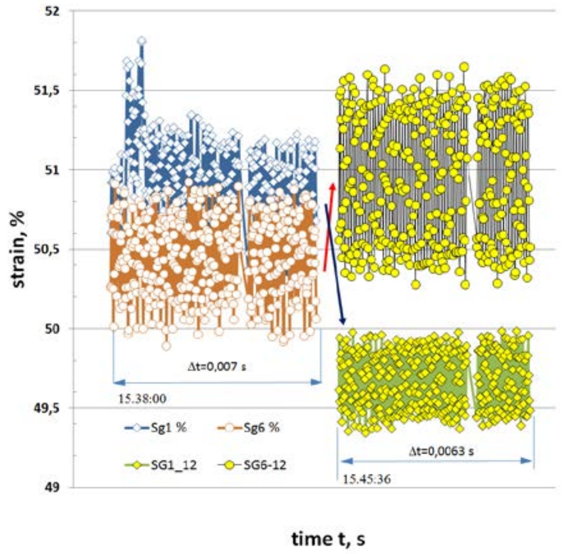


Figure 7: Strain measurements in two diagonal legs of the tower in a 7-minute interval (at–gain of 1 mm/m=100% of measuring range)

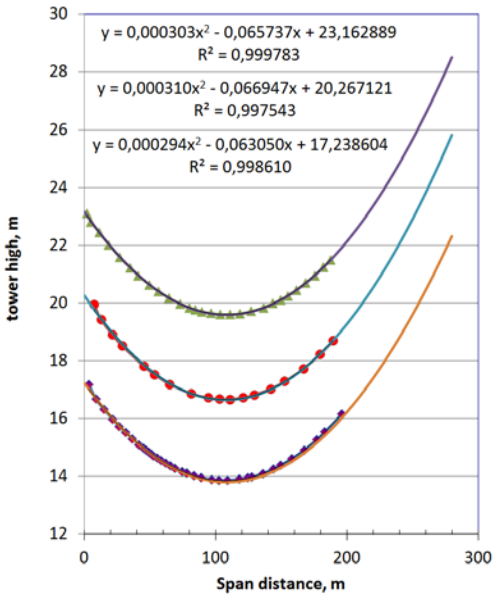


Figure 8: Measurement of catenary of all three conductors on the span between the towers

Next to strain measurement, we also carried out sag measurements of all three conductors between the towers No. 111 and 112 with a measuring station Leica TS30. The results of the measurements are shown in Fig. 8. It is evident from Fig. 8 that the catenary corresponds to a parabola. High correlation compliance (R>0.99) defines the parameters of the parabola.

The conductor was at a temperature T=+5.3°C. Due to difference in altitude between towers No. 111 and No. 112, the peak point of all three conductors is closer to tower No. 111. Due to difference in altitude, the values of horizontal forces at the point where the conductor is suspended on the insulator are also different. As the temperature elongations change the length of the conductor, the peak point with the biggest sag will also move in the horizontal direction. Boundary conditions of the conductor that were realized during the assembly of the conductor are based on the measured catenary. The measured values are shown in table 1. Meaning of individual parameters in table 1 is shown schematically in Fig. 9. L_1 and L_2 are the lengths of the conductor from the suspension point on the insulating material to the lowest peak point from the left side L_1 and right side L_2, w_1 and w_2 are rectilinear horizontal distances from the suspension point on the insulator to the lowest peak points from the left side w_1 and right side w_2, f_1 and f_2 are sags from left side f_1 and right side f_2. L is the total length of conductor, and w is the entire span between suspension points.

Table 1: Geometric parameters of catenary with typical geometrical points

	Conductor 1	Conductor 2	Conductor 3
L_1, m	105.628	103.959	109.184
w_1, m	105.56	103.86	109.11
f_1, m	3.56	3.61	3.42
L_2, m	176.62	179.40	171.11
w_2, m	174.35	176.04	170.80
f_2, m	8.91	9.17	8.51
L, m	280.25	280.35	280.29
w, m	279.91	279.90	279.91

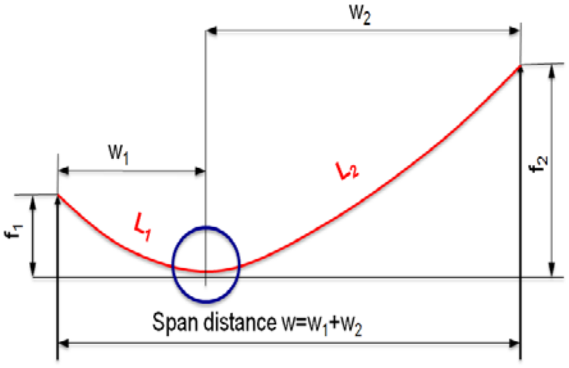


Figure 9: Typical geometric parameters of the conductor catenary across the span

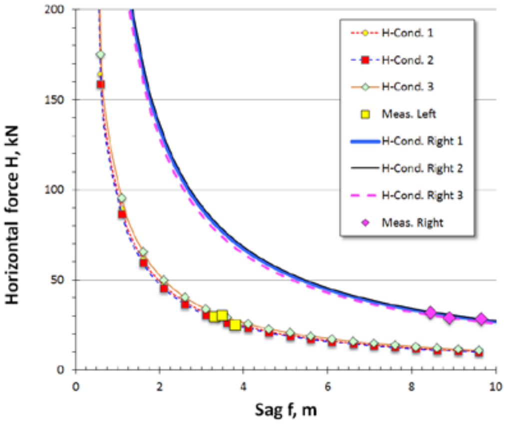


Figure 10: Horizontal force H vs. sag f for theoretical and experimental data

THE CHANGE IN HORIZONTAL FORCE AND SAG TO TOWER STRAIN

In them model, the sag f_1/w_1value was normalized to the horizontal distance between the anchor points and the point of maximum sag f_1/w_1. Hence we obtain the normalized conductor length L1/w1 by using the standard parabolic equation of catenary with correction factor k to take into account deviation from the ideal catenary.

$$\frac{L_1}{w_1} = \frac{k \cdot sh\left(\frac{4f_1}{w_1}\right)}{\frac{4f_1}{w_1}} \tag{1}$$

The force in the conductor changes with length according to Eq. (2)

$$a = \frac{H}{q \cdot g} = \frac{w_1^2}{2 \cdot f_1} \qquad [m] \tag{2}$$

Where a is the parabola parameter in meters, H is the force in Newtons, q=1,8 kg/m is the mass per unit length and g=9,81 m/s^2 is gravity acceleration. By using measured sag values and knowing the conductor weight (per unit length) we obtain the dependence of the force H and the sag of both sides of the span distance. The values of H as a function of sag *f* for theoretical and experimental data are show in Fig. 10. The measured data points lie on the curves obtained with our model.

The model for calculating changes in horizontal force in dependence on the measured strain in the tower's legs was made considering the strength adjustment of leg profiles L140x140x14. Layout of legs of tower No. 111 is schematically shown in Figure 11. Geometrical characteristics of the profiles to which the strain gauges were attached were used for the calculation. In calculating the bending moment M, a simplification is considered, namely that the changes in forces ΔH in all three conductors will be approximately the same, but each will have its own distance from the tower base, as can be seen in Fig. 8.

$$\begin{aligned} \Delta M &= \Delta H \cdot (l_1 + l_2 + l_3) \quad [Nmm] \\ l_1 &= 20500\, mm, \\ l_2 &= 23500\, mm, \\ l_3 &= 26500\, mm \end{aligned} \tag{3}$$

Table 2: Calculated values of horizontal forces and sag for both, left and right side

	Conductor 1	Conductor 2	Conductor 3
H_1,kN	29.75	25.08	30.15
f_1, m	3.56	3.61	3.42
H_2,kN	28.95	28.34	31.80
f_2, m	8.91	9.17	8.15

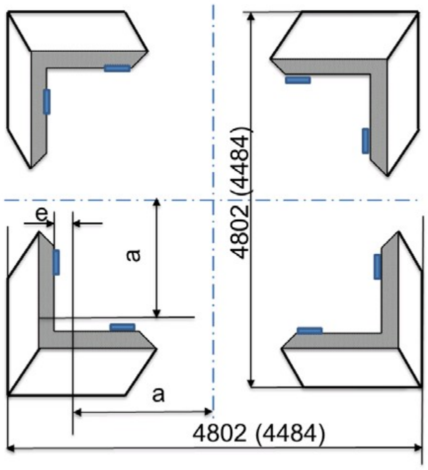


Figure 11: Scheme of base profiles layout

The change in tension Δσ is determined by the change of the bending moment based on strength low

$$\Delta\sigma = \frac{\Delta M\left(\frac{s_2}{2} - t\right)}{I_u} \quad \left[\frac{N}{mm^2}\right] \qquad (4)$$

Where s_2 is the smaller distance between the two extremities of the profile s_2= 4484 mm, t=14 mm is the thickness of flange and I_u= 692.10^4 mm^4 is the total moment of inertia, which is as follows according to the Steiner's rule:

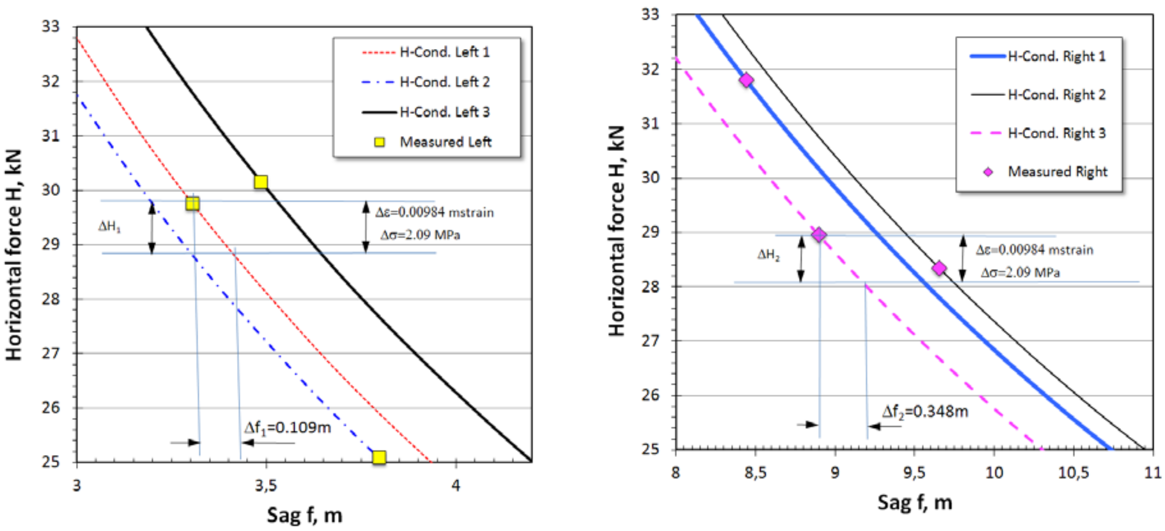
$$I_u = 4\cdot(I_x + a^2\cdot A) = 7{,}216\cdot 10^{10} \quad \left[mm^4\right] \qquad (5)$$

a=2201.8 mm is the distance from the tower centre to the individual centre of gravity of the profile in the height of strain gauges and A=3720 mm^2 is the surface of cross-section of profile L140x140x14, as is shown in Fig. 11.

By taking into account the Hooke's law on elastic dependency between strain and tension, we get

$$\Delta\sigma = \Delta\varepsilon\cdot E = \frac{\Delta M\left(\frac{s_2}{2} - t\right)}{I_u} \quad \left[\frac{N}{mm^2} = MPa\right] \qquad (6)$$

Where Δε is the change in strain that was measured with strain gauge and E is the elasticity module (210 GPa for steel).



a) Left side

b) Right side

Figure 12: Change in horizontal force in dependence on the change in conductor sag

The dependency between the change in horizontal force ΔH and the measured strain Δε in the tower's leg has been obtained by inserting the equation (3) into the equation (6)

$$\Delta H = \frac{2 \cdot \Delta\varepsilon \cdot E \cdot I_u}{(s_2 - 2t) \cdot (l_1 + l_2 + l_3)} \; [N] \tag{7}$$

The result of 964.8N for average change in horizontal force in individual conductor has been obtained by taking into account the measured change in strain Δε in tower's legs.

It is possible to show the influence of the change in horizontal force on the sag of the conductor in the field of the measured sag of the conductor between towers No.111 and No. 112, by taking into account the equation (2). The figure shows that at average change in horizontal force ΔH=964.8 N, the sag changes for Δf_1= 109 mm on the left side and for Δf_2= 348 mm on the right side.

CONCLUSIONS

Within the study, we carried out measurements of strain behaviour of tower's legs under the influence of horizontal force change. We carried out experimental strain measurements on legs of tower No. 111 L140x140x14 and geometrical measurements of catenary of all three conductors on the span between the towers No. 111 and 112 on the path substation Podlog and substation Obersielach (Austria) on the overhead line 220 kV. The measurements have shown that the form of the catenary can approximate the parabola equation for the most part.

For conversion of geometry and catenary forces, the conductor is split to left and right side, namely from the suspension point on the insulator to the lowest point which corresponds with the maximum point of sag. For each side of the conductor, we used the measured parameters from table 1. We carried out strength adjustment of the bending moment and of bending elastic strain in the legs of the overhead power line tower due to changes in horizontal force or in vertical load on the conductor.

The pilot results of the study showed that by monitoring the change in strain of towers above the foundations, it is possible to detect changes of forces in the conductor, which can be a consequence of changes in sag. To verity the model and to transfer it from the hypothetical model it is necessary to carry out additional measurements of the catenary at different temperatures of the conductor and also carry out continuous monitoring of strain in tower's legs and/or parameters on the conductor.

BIBLIOGRAPHY

[1] CIGRE Brochure no. 498 "Guide for Application of Direct Real-Time Monitoring Systems, Paris, 2012

[2] CIGRE Brochure no. 425 "Increasing Capacity of Overhead Transmission Lines: Needs and solutions, Paris, 2010

[3] McGuinness Sean, Doyle Ray: *Rating System Implementation & Analysis*, DLR Condition Monitoring, Sept. 2011

[4] Real time Ampacity Monitoring with Ampacimon^{TM}, Version 0.1, University of Liege, Department of Electricity, Electronics and Computer Sciences, Belgium, Dec. 2008

[5] N.Gubeljak, K.Bakic, F.Jakl, A.Veg, J. Predan: "*An Attempt to OHL Conductor Dynamic Line Rating by Strain-Vibration Detection of Tower*", International Symposium CIGRE Best Practice in Transmission and Distribution in a Changing Environment, Auckland, New Zealand, September 16-17, 2013