P24

# Application of an Ice-Alarm in the OTLM System

**N. GUBELJAK[1], V. LOVRENČIĆ[2], B. BANIĆ[3], M. PINTERIČ[4], A. IVEC[5], M. JARC[5]**
**[1]-Universtiy of Maribor, Faculty of Mechanical Engineering, Smetanova 17, Slovenia**
**[2]- C&G d.o.o. Ljubljana, Slovenia; C&G d.o.o. Pula, Croatia**
**[3]-High School "1. Gimnazija" Varaždin, Croatia**
**[4]- University of Maribor, Faculty of Civil Engineering, Smetanova 17, Slovenia**
**[5]- C&G d.o.o. Ljubljana, Slovenia**

## SUMMARY

The developed system for Overhead Transmission Line Monitoring (OTLM) monitors the temperature and the conductor angle of inclination in order to maximise the utilization of the transmission line. Additionally, the measured temperature and the angle can be used by software application to detect conductor elongation by ice overload or a fallen tree. The mathematical relationship between the tensile force in the conductor and the sag is crucial for the calculation of the conductor elongation and the final length of the conductor over the constant span distance. The conductor elongation increases the deflection and the angle of inclination at the position of OTLM device. The reliability of ice thickness calculation depends on the reliability of temperature and angle measurements. The ice thickness on the conductor depends also on weather conditions and the temperature of the conductor. The difference between environment temperature and temperature of the conductor depends mainly on transmission current. In the framework of the OTLM-ICE application the operator of the transmission network can monitor the change in the sag and clearance of the conductor subjected to ice overloading. The operator can optimize and determine the suitable current of the transmission line in order to prevent damage in the early phase of freezing rain.

## KEYWORDS

Overhead Transmission Line Monitoring, Ice, Alarm, Sag of Conductor, Tensile Force in Conductor

**nenad.gubeljak@um.si**

## INTRODUCTION

Overhead high-voltage transmission systems are sensitive to weather and temperature conditions. The geometry of the conductor's catenary has to be continuously monitored in all weather conditions on separate sections of the route where sagging and reduction of conductor clearance could exceed the prescribed safety limit. These weather conditions include high summer temperatures and high currents and low winter temperatures in cases of ice build-up and/or additional loading. Besides monitoring the geometry of the catenary curve it is necessary to monitor a change in the tensile forces in the conductor. Direct and indirect techniques for the determination of sagging and tensile forces in the conductor have been developed worldwide on the basis of the measurements of the conductor temperature and meteorological conditions on a route and/or span width or tension field. [1-5].

Even before the fatal collapse of overhead power line pylons caused by ice in February 2014, as shown in Figure1, the company C&G ordered the development of a computer application of a mathematical model from the Institute of Mechanics, Faculty of Mechanical Engineering in the University of Maribor. A mathematical model for the calculation of the geometry of the catenary curve of the conductor and tensile strength in the conductor has been developed as a basis for the continuous monitoring of the temperature and the conductor angle of inclination at the position of the OTLM (Overhead Temperature Line Monitoring) device [6-9].

The paper presents the concept of the application and the relation between the geometry and load parameters on the catenary curve when ice or heavy snow builds up and the estimated effect of the current increase on the melting of ice as a tool for the prevention of pylon collapse.

**Figure 1: An icy shell on a DV 110 kV phase-conductor of Cerkno –Idrija transmission line**

## EXPERIMENTAL DETERMINATION OF LOADING CHARACTERISTICS OF CONDUCTOR

A conductor is a quasi-statically loaded self-supporting element, where a tensile force changes depending on the oscillating temperatures and mechanical loading. Due to the complex design of the conductor it is necessary to determine the behaviour of the conductor during the cyclic tensile loading and the stable elastic constant, which is applied to determine a change in the force depending on the elongation. Figure 2 shows the method of clamping the conductor with the installed device measuring elongation-extensometer. Each time, a cyclical loading has been performed up to the tensile force of 20 kN with the tensile speed of 1 mm/min. After the complete relaxation, the hydraulic activator returned to the initial position, as shown in Figure 3. A permanent deformation increased every cycle and stabilized only after the 10th cycle. A deformation measurement by extensometer was carried out simultaneously. The results of the measurements in Figure 4 show that the conductor contracts in the first cycle and stretches only after the second and subsequent cycles. It is interesting that each time the conductor is loaded by 20 kN, a successive relaxation follows the same curve as the previous loading, but the following loading cycle begins by a displacement of the new permanent deformation – initial position. Such behaviour has to be included in the model in case that building-up of ice and/or wet snow causes different conductor sag than the one before the activity of the ice and/or wet snow. This means that the initial position of the angle changes when such high tensile forces are active. Figure 4 also shows that there is no change in the slope (elastic constant) of the function in case of a low number of recorded data and tensile speed of 50 mm/min, and that it practically amounts to 26.447 kN/strain all the time.

**Figure 2: Tensile testing of the conductor in a laboratory**

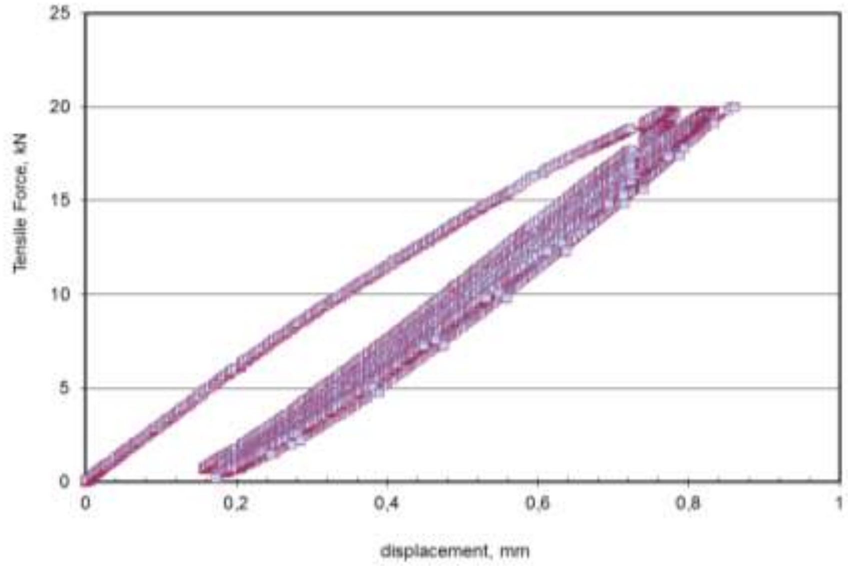


**Figure 3: Tensile characteristics of the conductor with a multiple cyclic loading**

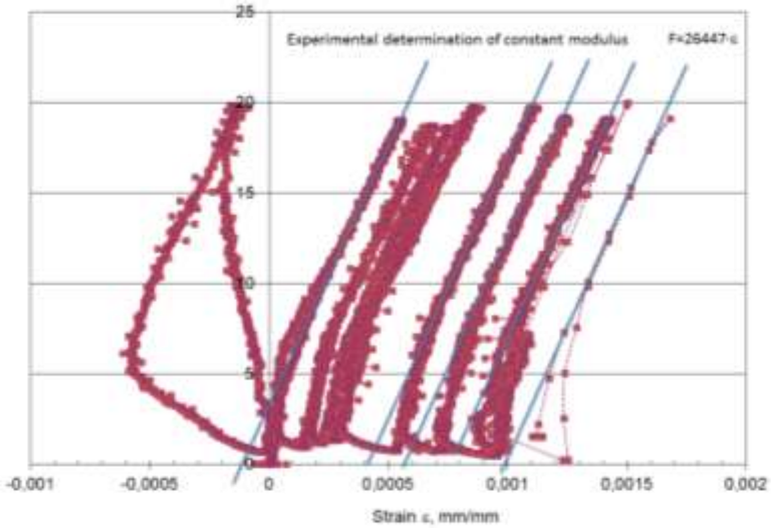


**Figure 4: Experimental determination of the elastic constant of the AlFe (ACSR) 240/40 mm$^2$ conductor**

## DESCRIPTION OF THE MODEL

The mathematical model takes into account the mechanical properties and physical characteristics of the conductor as well as its own conductor mass, length and the length of span between two pylons. A snapshot of the actual condition of the conductor measured at different temperatures has to be made for the accurate monitoring of geometrical changes in the catenary curve of the conductor. This presents a limiting condition for the further development of the application. The computer application for the selected section of the route of the high-voltage overhead power line was made on the basis of the presented concept. A part of the conductor between pylons SM23 and SM24 on 2 x 110 kV overhead power line Dravograd – Slovenj Gradec was selected. OTLM devices with the installed devices measuring angles – inclinometers are mounted onto two conductors on the SM 23 pylon. A weather station with the solar cell power supply is also mounted on the SM23 pylon, as shown in Figure 5.

The actual geometry of the catenary curve is evident from the laser measurements and presented in form of coordinate points in the local x-y plane system, as shown in Figure 6. The mathematical model calculates the parameters of the catenary curve in the local x-y coordinate system that is placed directly under the support point on the bracket of the pylon foundation, based on the laser measurements taken in the global coordinate system (μ–ξ–η) that is placed on the location of the measuring instrument, as shown in Figure 6.

**Figure 5: Standard configuration of the OTLM system – weather station and 2 x OTLM**

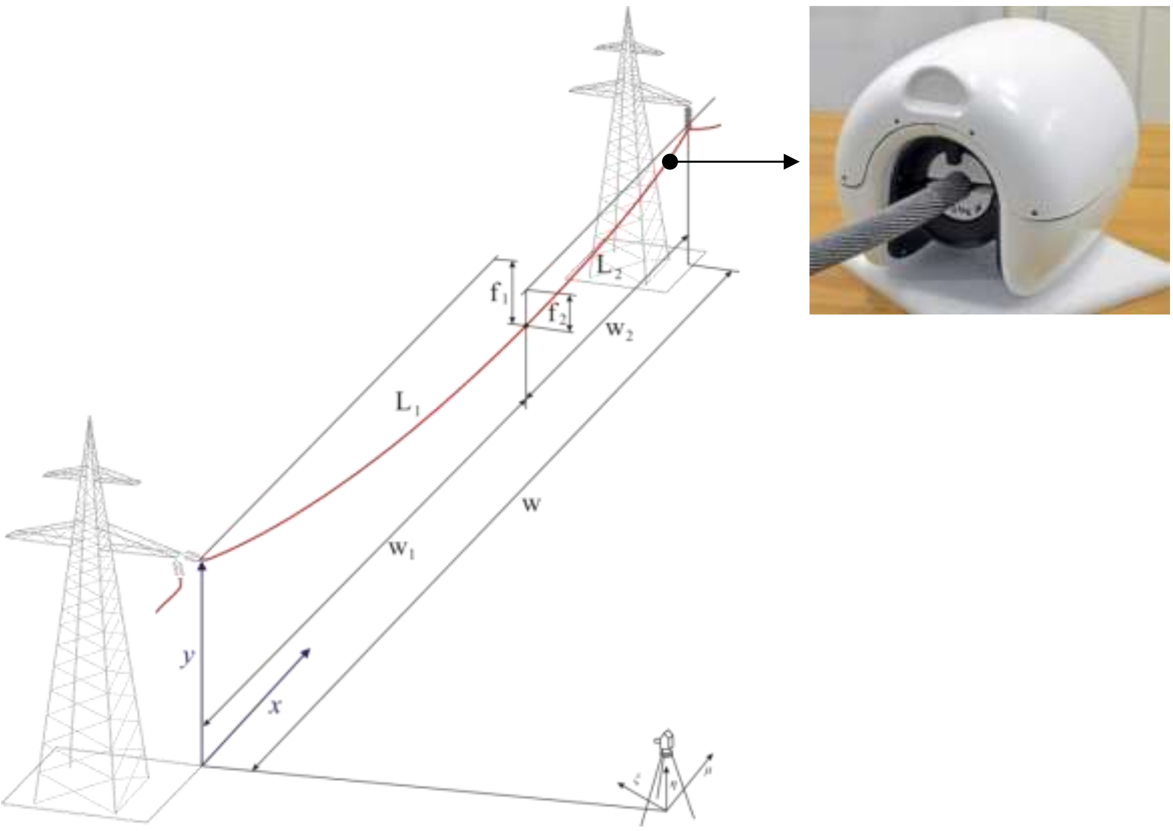


**Figure 6: Orientation of the global (μ–ξ–η) and local x-y coordinate systems**

The model as the computer application takes into account the geometry of the catenary curve after the conductor mounting, depending on the temperature of the conductor, where a laser measurement of the geometry of the catenary curve was made. The sag and thus the geometry of the catenary's conductor change according to the tensile force relationship by changing the meteorological conditions and the temperature of the conductor. The mathematical model re-calculates the new geometry of the catenary and the tensile force depending on the changes in temperature, while the measured angle of the inclination of the conductor at the position of OTLM device serves as the control value. The model is based on the independent treatment of the catenary curve of the conductor from the place of clamping on the bracket and/or insulator to the lowest point and/or place of the maximum sag for each side, as presented schematically in Figure 6.

The entering of the characteristic points into the computer application using the input screen is presented in Figure 7. The input screen is divided into three tabs, where the first one includes geometrical characteristics of the catenary curve of the conductor. The first tab of the screen contains the data already entered with the characteristic points for the measurements taken in February 2015, such as $T_1$ as a support point of the conductor to the insulator on the pylon SM23, $T_2$ as the lowest point of the conductor and $T_3$ as the support point of the conductor on the insulator on the SM24 pylon. The central tab contains the position of the OTLM device and the value of the angle of inclination that is calculated by measuring the position of the point before and after the presence of OTLM device. The data about the conductor (AlFe and/or ACSR 240/40) and the conductor temperature T= - 4 °C at which the measurements have been made are entered in the third tab "Conductor parameters". It is also necessary to enter the calibration parameters a0 and a1. The calibration parameters a0 and a1 have been obtained on the basis of the correlation between the actually measured angle of the inclination and the angle given by the mathematical model for the conductor [6]. The calibration parameters include deviations of the model from the actual behaviour of the conductor through the temperature interval measured. Deviations are a result of the conductor condition such as ageing and the history of loading that has not been recorded. In the literature Prof. Milan Vidmar, Ph. D. has previously taken into account these unknowns of the constructive elongation as a non-elastic elongation.

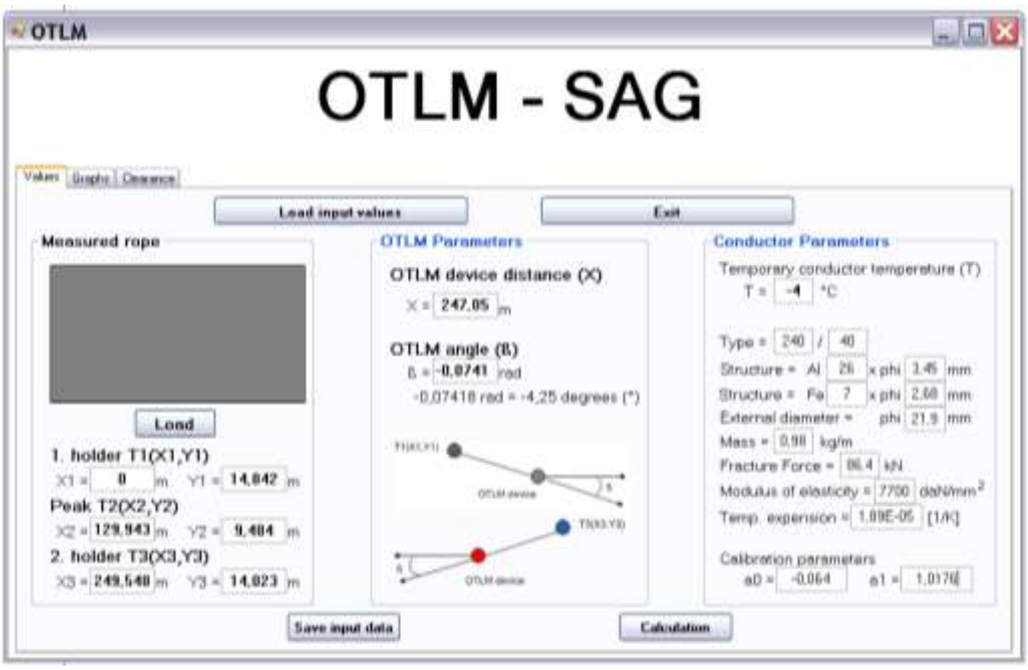


**Figure 7: Entering of catenary curve data at the conductor temperature of - 4 °C**

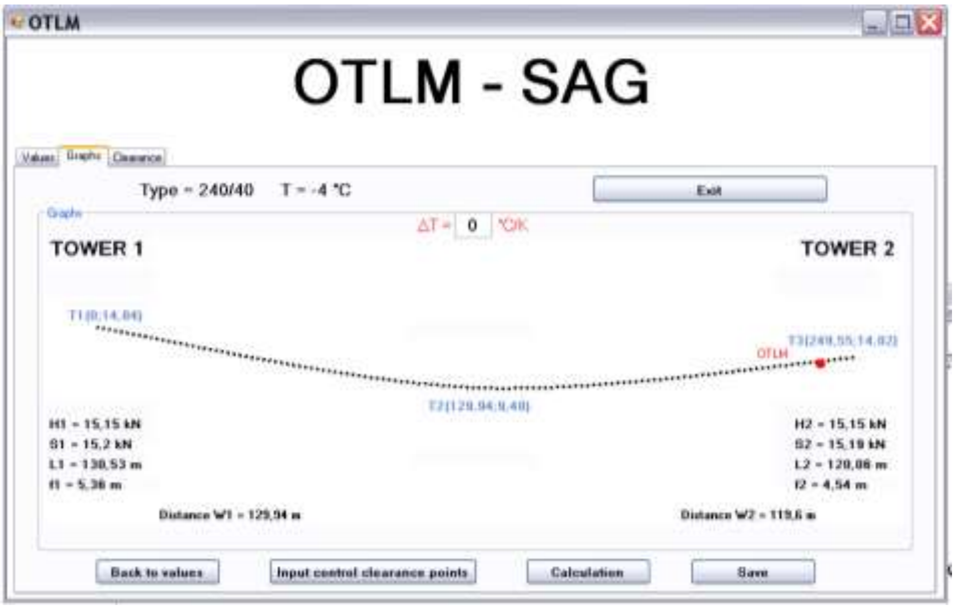


**Figure 8: The basic calculation of tensile forces and the sag before the iterative calculation**

Figure 8 presents the calculated values of tensile axial and horizontal forces in the conductor at the temperature of measurement, T= - 4 °C, along with the entered characteristic points of the catenary curve. The computer algorithm initially makes a separate calculation for the left and right sides of the conductor from the lowest sag point. The computer algorithm prepares an iterative calculation for an arbitrary (or the same) temperature up to the common matching of the sag point. The results are presented in Figure 9. The criterion is the matching of the sag point smaller than half the thickness of the conductor, i.e. it is below 12 mm. In this case the difference is 5.38 mm. The computer algorithm now calculates the angle of inclination of the catenary curve at the position of the OTLM device, the angle of the tensile force in the support point of the conductor and the insulator on the bracket. The values obtained represent the initial state at - 4 °C without any additional load and/or ice.


**Figure 9: Calculated parameters of the catenary curve and axial tensile forces in the conductor at the temperature of freezing rain without the ice load**

The parameters of the catenary curve at the temperature of the freezing rain represent the initial state of the activation of the ICE-ALARM computer algorithm. If favourable conditions for the formation of ice appear during the continuous monitoring of the conductor condition and condition on the route in the surroundings of the meteorological station then it is possible to estimate the amount of additional loading and the ice thickness on the basis of the change in the angle of inclination and by knowing the tension-deformation behaviour of the conductor at increased loading. Figure 10 shows the change in the angle in accordance with the model and the angle measured by the inclinometer. White circles present actual average angles as a function of average temperature of conductor measured in the time interval of 30 s. Red circles presents the expected behaviour of the conductor and/or a change in the angle due to the build-up of the ice on the conductor.

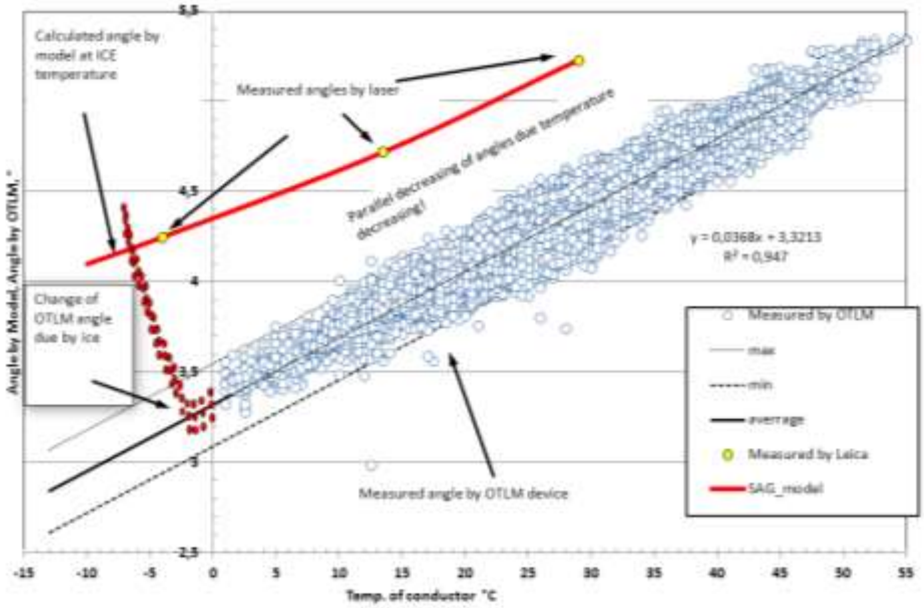


**Figure 10: Change in an angle at the OTLM device position depending on temperature**

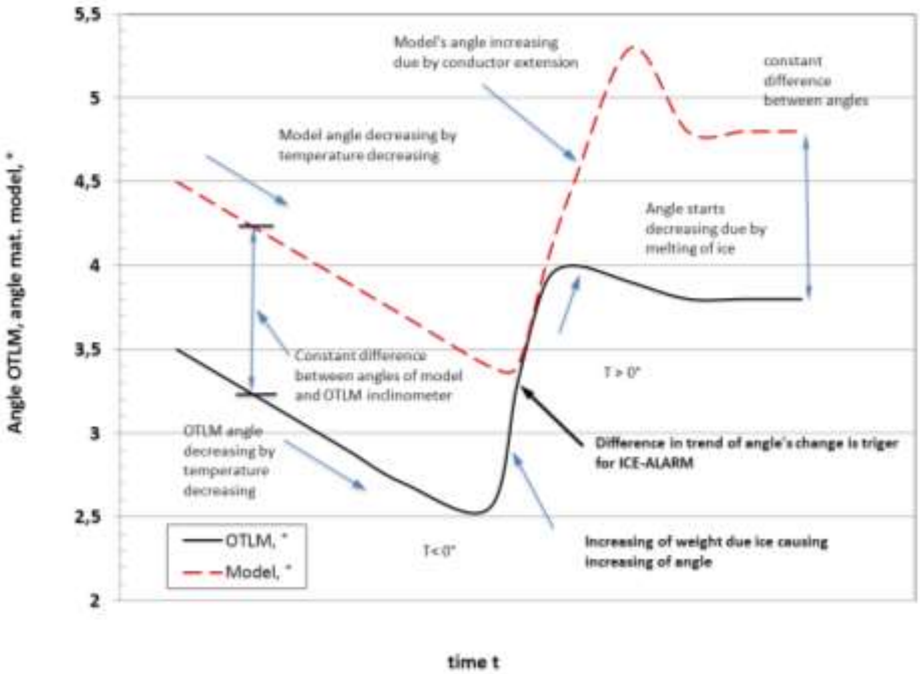


**Figure 11: Change in an angle of inclination during the activation of ICE-ALARM and melting of ice**

The continuous line in Figure 10 represents the angle of inclination depending on temperature according to the mathematical model. At the temperature of the freezing rain – 4 °C the angle is the same, as shown in Figure 9. If an angle significantly increases in the meteorologically favourable conditions and the temperature inversion and if the calculated angle significantly differs from the angle measured by inclinometer, the application informs the operator that ice has built up on the conductor.

Figure 11 shows the expected change in the angle at the position of the OTLM device according to the model and the angle measured through the time interval during the detection of ice build-up on the conductor. The reliability of the ice build-up measurement depends on the accuracy of angle measurement of +/- 0.25° and causes a time lag during the beginning of ice build-up and the beginning of the ICE-ALARM activation. The application is activated only after the measured change in angle of inclination is larger than the statistical error of an angle measurement. ICE-ALARM warns the operator that an increase in the current is required. The larger current gradually increases the temperature of the conductor, but the ice can still build up, elongating the conductor and consequently increasing the angle of inclination. Based on the characteristic of the elastic and constant elongation of the AlFe (ACSR) 240/40 conductor recorded in the laboratory, it is possible to determine and monitor the elongation. The model (red hatched line in Figure 11) monitors the elongation of the conductor and re-calculates the change in the angle, accordingly. At the moment, when the ice thickness begins to decrease (the highest value on the continuous line in Figure 11), the angle measured by the inclinometer in the OTLM device also starts reducing. When all of the ice has melted, a new geometry of the catenary curve and/or new sag of the conductor and new initial position before the new build-up of the ice are obtained, as it has been simulated by a laboratory testing of the conductor.

Parameters of the catenary curve were monitored in the adequately long time period and under various weather conditions and currents in order to develop a mathematical model in form of the mathematical algorithm that determines the expected geometry of the catenary curve and the conductor angle of inclination at the position of the OTLM device. When discrepancy between the measured and the expected angle of inclination outside the tolerance interval of deviations is observed, the algorithm for the re-calculation of the change in the catenary curve is started due to the additional ice load causing an elongation of the conductor on the span. The elongation corresponds to the additional tensile force calculated in accordance with the model. Tensile testing of the conductor was necessary to determine the dependence of the tensile force to the elongation.

Figure 12 shows an increase in the force during the ice build-up depending on the g factor and the angle on the location of the OTLM device. The initial value of the force equals the initial tensile strain in Figure 9, and amounts to 15.25 kN on one side and to 15.24 kN on the other one, at the initial angle of 4.25° at the position of the OTLM device. The increase is possible only up to critical fracture strength of the tensile force of the conductor, which amounts to 86.4 kN. In case of the presented span it corresponds to the gravity factor of $9.2 \cdot g$ and an increase in the angle by 4.56° and/or to 8.24°, as shown in Figure 12.

Figure 13 presents the sag increase due to the angle of inclination increase at the conductor temperature of -4 °C. It is evident from the diagram that the sag depends linearly on the measured angle by the inclinometer in the OTLM device. It is also evident that the sag increases by approximately 1.1 m per one degree change of the angle for the presented span.

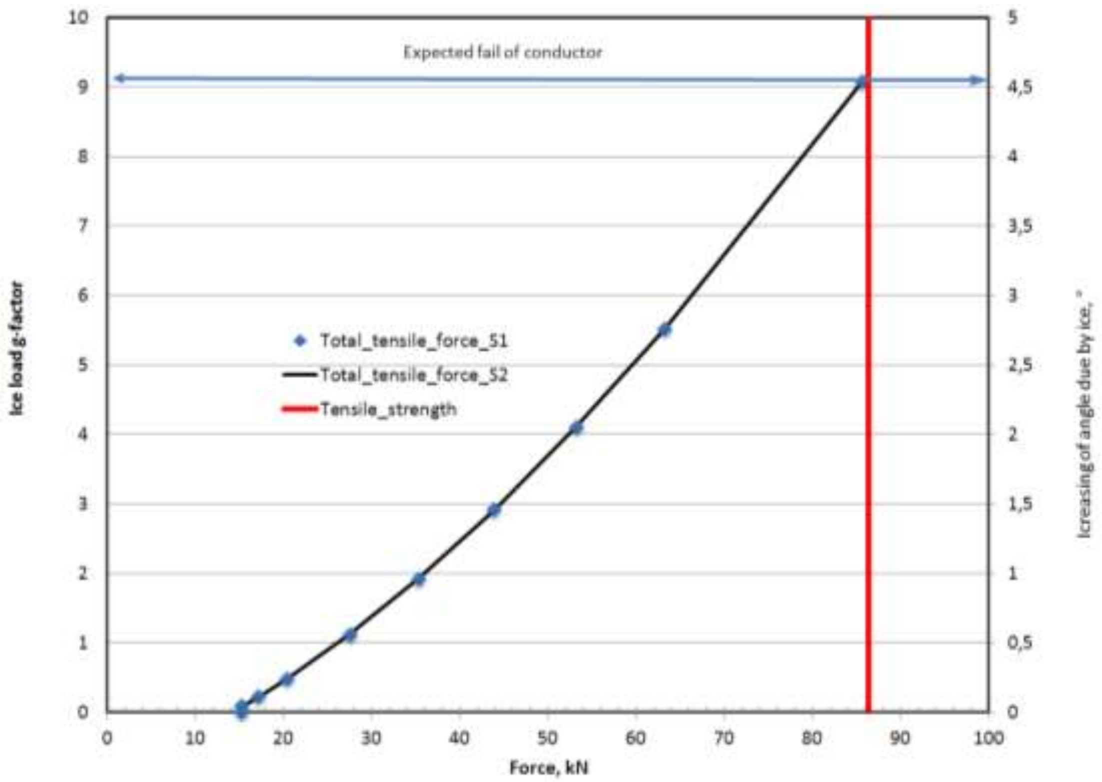


**Figure 12: The relation between force, g factor and the angle of inclination at the location of the OTLM device**

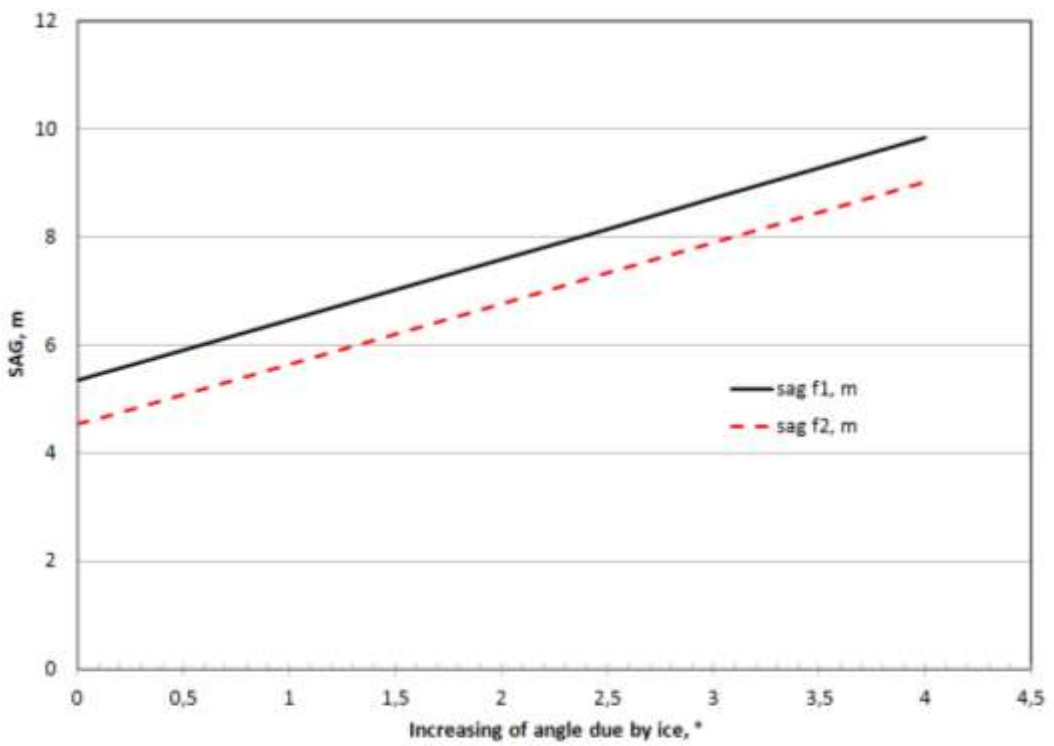


**Figure 13: The sag as a function of the angle increase due to ice build-up**

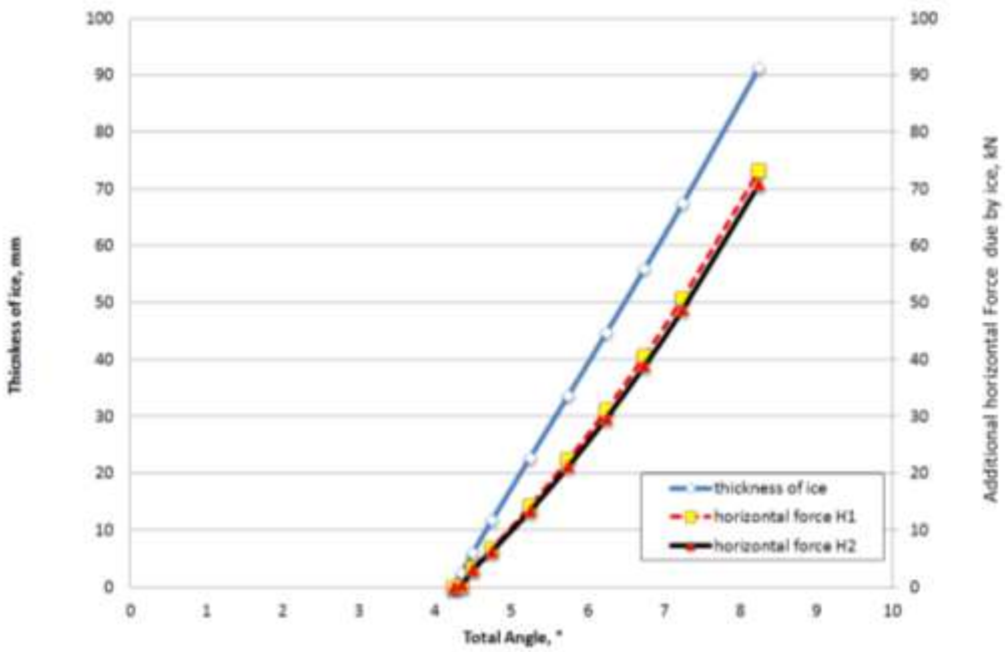


**Figure 14: The relation between ice thickness, the angle of inclination and horizontal forces**

Figure 14 presents the relations between the total angle of inclination, additional tensile strain in the conductor and ice thickness. The angle to ice thickness dependence is linear, as evident in Figure 14, while the increase in horizontal (shear) strength up to the destruction force of 86.4 kN is exponential.

## CURRENT AND ICE THICKNESS

In order to calculate the current necessary to remove the ice build-up, Joule heating, solar radiation, radiation of the conductor surface, convective heat transfer and melting of water have to be taken into account. Since Joule heating represents the dominant mechanism, convection and radiation shall be neglected in further calculations. Specific thermal capacity ($c_{Fe}$, $c_{Al}$, $c_i$) has to be considered for each separate material. The heat needed to heat the conductor and ice build-up from – 5 °C to 0 °C and the transformation of ice into liquid water is obtained by calculating mass of the steel core, conductor, Al-stripes and ice. The required current also depends on the temperature difference $\Delta T$ and on the time of heating $t$, which can be written by the following equation:

$$I = \sqrt{\frac{A}{t \cdot \rho}\left[A_{Fe} \cdot \rho_{Fe} \cdot c_{Fe} \cdot \Delta T + A_{Al} \cdot \rho_{Al} \cdot c_{Al} \cdot \Delta T + \rho_{\check{z}} \cdot \pi(\delta_i^2 + \delta_i \cdot d)\rho_i \cdot \left(q_i + c_i \cdot \Delta T\right)\right]} \qquad (1)$$

To obtain the equation (1) we also neglected the temperature dependence of metal resistivity and electrical conductivity of the ice. The current as a function of ice melting time for various thicknesses of ice on the Al/Fe (ACSR) 240/40 conductor observed is calculated from the equation (1), as shown in Figure 14.

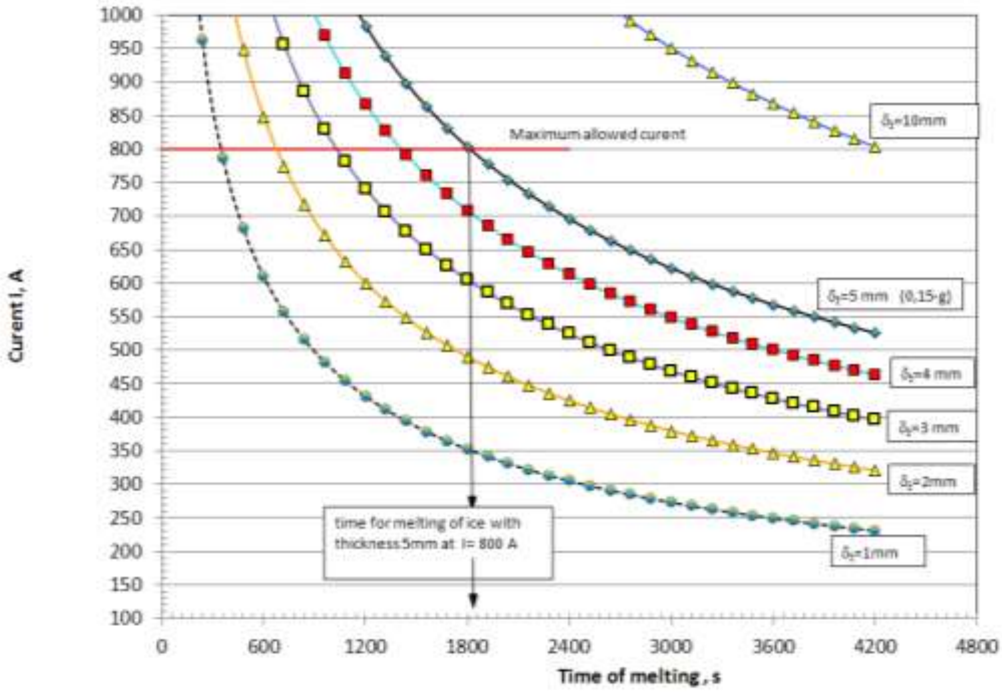


**Figure 15: Speed of ice melting depending on ice thickness and current**

Under the assumption that the ice build-up stopped at the time of a current increase, the time needed for ice melting can be graphically read from Fig. 15. A red line presents the result for the maximum current that is allowed by the HV equipment in the overhead power field (e.g. disconnector, break-switch, measuring transformers), i.e. 800 A. This line presents the shortest possible time for the elimination of the ice from the conductor by an increase in the current. In case of strong precipitation, when the quantity of freezing rain on the conductor is larger than the quantity of melted ice, the additional loading only increases and leads to the tearing of the conductor at a force of 86.4 kN and at an angle of incidence on the position of the OTLM device at 8.24°.

## CONCLUSION

The development of the ICE-ALARM application is based on the existing computer algorithm in the OTLM device. The developed computer algorithm is based on the mathematical model for a re-calculation of the sag and tensile strains in the conductor. It takes into account the actually measured form of the catenary curve of the conductor on the presented span at the conductor temperature measured by OTLM as the initial state. Based on the knowledge about the change in the sag of the catenary curve and the tensile forces dependence on the temperature of the conductor and monitored weather conditions, it is possible to determine the moment of activation the ICE-ALARM application. When ICE-ALARM is started, the required current for ice elimination is calculated. The current needed for heating the conductor and melting the known thickness of ice depends on the temperature difference $\Delta T$ and heating time $t$. The maximum thickness of ice at which the conductor fails is also determined. The angle on the position of the OTLM device under maximum thickness of ice is determined by the algorithm developed in this paper. The loading interval span is given and the prevention of damage caused by accumulation of ice or wet snow can be influenced by the current load.

## BIBLIOGRAPHY


[1] Working Group 06 CIGRE, Task Force 01. “Guidelines for field measurement of ice loadings on overhead line conductors” (Cigré Technical Brochure No. 179, 2001)

[2] Working Group SC B2.16 CIGRE. “Guidelines for Meteorological icing models, statistical methods and topographical effects” (Cigré Technical Brochure No. 291, 2006)

[3] Working Group SC B2.438 CIGRE. “Systems for prediction and monitoring of ice shedding, anti-icing and de-icing for power line conductors and ground wires” (Cigré Technical Brochure No.438, 2010)

[4] Working Group B2.44 CIGRE. “Coatings for protecting overhead power network equipment in winter conditions” (Cigré Technical Brochure No. 631 2015)

[5] M. Farzaneh “Atmospheric icing of power networks” (Dordrecht; London: Springer; 2008)

[6] V. Lovrenčič, M. Gabrovšek, M. Kovač, N. Gubeljak, Z. Šojat, Z. Klobas “The contribution of conductor temperature and sag monitoring to increased ampacities of overhead lines (OHLs)” (Periodica polytechnica, Electrical engineering and computer science, ISSN 2064-5260. [Print ed.], 2015, vol. 59, no. 3, pages 70-77)

[7] N. Gubeljak, M. Jarc, J. Predan, V. Lovrenčič, B. Banič, A. Ivec “Analiza spremembe kota in povesa v odvisnosti od temperature = Analysis of angle's change and sag's change regarding temperature” (Dvanajsta konferenca slovenskih elektroenergetikov, Portorož, 25.-27. maj 2015. [Ljubljana: Slovensko društvo elektroenergetikov CIGRÉ - CIRED, 2015], pages 1-13)

[8] N. Gubeljak, V. Lovrenčič, J. Predan, B. Banič, A. Ivec, M. Jarc “Razvoj aplikacije za pravnovremeno upozoravanje na nastanak leda na visokonaponskom vodiču dalekovoda = Development of application for on-line monitoring and alarm of ice on high voltage transmission system” (12. savjetovanje HRO CIGRÉ, 8.-11. studenoga 2015, Šibenik = 12th HRO CIGRÉ Session, November 8-11, 2015, Šibenik, Referati = Papers. Zagreb: Hrvatski ogranak CIGRÉ, 2015, 8 pages)

[9] V. Lovrenčič., B. Banič, D. Kojzek, N. Gubeljak, A. Ivec, M. Jarc “Monitoring za posredno određivanje promjene horizontalne sile u zavisnosti od promjene temperature i nagiba nadzemnog voda dalekovoda prijenosnog sustava”. (11. Simpozij o sustavu vođenja EES-a, Opatija, 10.-12. studenoga 2014 = 11th Symposium on Power System Management, Opatija, November 10-12, 2014. Zagreb: Hrvatski ogranak CIGRÉ, 2014, pages. 1-10)