Monitoring Icing on Overhead Power Lines: Challenges and Preventive Measures

V. Lovrenčić, PhD

N. Gubelják, PhD

The development of technology has spurred after the catastrophic icing event when large numbers of low, medium and high voltage overhead power lines (OHL) collapsed particularly in Slovenia in the beginning of 2014. Development and financial incentives for the construction of the DEMO were obtained from European development funds, the Horizon 2020 project called "FLEXITRANSTORE". The DEMO was constructed on OHL 110 kV Kleče -Logatec single circuit overhead line equipped with ACSR 240/40 mm^2 conductors. On the OHL two devices OTLM (On-line transmission line monitoring) SMART and one weather station were installed on two towers. The OTLM SMART software was updated with inclination measurement and with new software features for determining additional mechanical load of conductors due to ice or wet snow. Additional mechanical load is determined based on the difference between measured angle and mathematically determined angle by model. The combination and synchronization between algorithms, weather service and measuring equipment is the key of successful operation. EU H2020 financed project “FLEXITRANSTORE” was launched by the end of 2017 to develop a cross-country co-operation, with objective to improve anti-icing and de-icing solutions. A test equipment was installed to demonstrate the capabilities of this new technologies on the DSO grid of Electro Ljubljana (ELJ). This paper will present the positive experience and results from BME and C&G, partners of DEMO, after the first winter 2018/2019 after polygon was established.

1. INTRODUCTION OF PROJECT FLEXITRANSTORE

Project HORIZON 2020 »FLEXITRANSTORE« (21.7 M Euro) [1] has begun on the 1st of November 2017 and will lasts for 4 years. 27 project partners with 8 demonstrations in 6 countries will provide new results in several topics including Dynamic Line Rating (DLR). The main objectives are to demonstrate sensor technology for power system operators to effectively handle and prevent sudden and often fatal failures, especially during icing weather conditions, to increase system security and reliability by reducing icing phenomena and to facilitate cross-border power exchanges by the implementation of the described systems [2].

2. CATASTROPHIC ICE STORM IN SLOVENIA IN 2014

After the catastrophic icing event in Slovenia at the beginning of 2014, when large numbers of low, medium and high voltage overhead power lines (OHL) collapsed particularly in the western part of Slovenia, a sophisticated development was initiated regarding advanced ice monitoring. Several hundred thousand of customers in this area of Slovenia have been out of electrical power supply for several days. The complete reconstruction of the damaged OHL network lasted several months. Distribution System Operators (DSOs) and Transmission System Operator (TSO) were forced to use provisional solutions at all levels of tension. The single important high voltage OHL has been successfully put into service using Emergency Restoration Systems (ERS). In the last thirty years, in the Slovenian transmission and high voltage distribution, there were more than forty breakdowns on different transmission lines from 110 kV to 400 kV [3,4]. Especially disastrous were the consequences on the line between the transformers in the vicinity of Ljubljana and Divača, where 220 kV and 400 kV transmission lines were destroyed. The additional load of the ice also broke the towers and tore the wires [3,4]. The ice storm of February 2014 paralysed Slovenia, with damage to overhead lines of all voltages, including voltage (LV), medium voltage (MV) and high voltage (HV). The consequences were catastrophic, and more than 250,000 people were left without electricity for several days. Whole cities were without electricity. After a few days of complete darkness, aggregates were turned on, and the restoration of LV and MV lines as well as some 110 kV OHLs started, with the help of emergency restoration towers [3,4]. On Fig. 1 is detail of glaze ice on a conductor on the OHL 110 kV Cerkno – Idrija (TSO, ELES).

Fig. 1 Glaze ice on a conductor on the OHL 110 kV Cerkno – Idrija (TSO, ELES) [3].

Around midday Friday, January 31st, the snow turned to rain in most parts of Slovenia. It was snowing in the north-western part of the country. On Saturday, February 1st, the weather conditions worsened in most parts of Slovenia, where the temperatures were around -3ºC. Slovenia was covered in ice. At around 5.30 p.m., the OHL 220 kV Kleče–Divača failed, and an hour later the so did the OHL 400 kV Beričevo–Divača (Fig. 2) [3].

Fig. 2 Typical image of a 400 kV OHL tower after catastrophic icing storm (TSO, ELES) [3].

3. ICE DETECTION SYSTEM OF OTLM SMART

As technology advances, we will be able to collect, analysed and predict very large databases in the field of meteorology and electrical engineering. The ability of processing mentioned data, combined with know-how results in the capacity to operate power lines at their thermal limits during different ambient parameters. This technology, called Dynamic Line Rating (DLR) – is not only a great way to increase the transmission capacity of a certain OHL, but can also be effectively used to prevent, or even solve icing-related issues. Higher currents result in higher Joule-heats, that consequently heat the conductors. If limits can be reached or approached, icing can be prevented. If prevention is not possible, the detection and removal of the ice layer is necessary. The proper handling of this icing issues requires advanced algorithms (expert systems) and reliable measuring equipment. In order to the determine available capacity of electrical high voltage transmission lines, the distributor needs results about safety clearance and temperature of conductors. Therefore, the OTLM SMART software unit was updated with inclination angle measurement “inclinometer” and with new software features for determination of additional mechanical load of conductors due to ice or wet snow. Determination of additional mechanical load based on difference between measured angle and mathematically determined angle by model. Since angle of conductor is usually small (less than 10°) the measurement of conductor angle is challenging. In order to overcome the problem of accurate angle measurement the new expert system has been developed. The newly developed expert system is based on the statistical analysis of collected data of on-line measurement in the long time period with a specific time interval of 10 min. The set of data at each temperature of the conductor includes the air temperature, humidity, current (A) and the conductor angle at the attachment point of the OTLM SMART device. All measurements of the conductor’s angles are statistically analysed at belonging temperature of the conductor in order to determine the mean value and statistical range at 99,97 % of probability. This is statistical relevant parameters, without any additional mechanical load of the conductor, are considered as initial statistical data. From the current set measurement, the expert system calculates new statistic parameters. Each new measured value of the angle is considered as a new added value in statistical analysis. The Expert system compares both set, initial statistical data and new statistical data with additional value. The range of probability distribution overlapping provides the probability of ice on the conductor. The statistical analysis contributes to a better quality of compared values and provides higher reliability to measured values. The combination and synchronization between algorithms, weather service and measuring equipment is the key to the successful operation.

3.1 Development of OTLM SMART line monitoring sensor

The severe ice storm was observed in Slovenia in 2014, indicates the demand for new safety measures during overhead lines operations. For this purpose, one of the additional safety precautions was to inspect the overhead lines when received information from national weather service that ice storm is possible in the given region. Based on this forecast information the TSO should check if ice storm is affected by the overhead line or not. Unfortunately, some overhead lines are located high in the hills and approach is nearly impossible in case of snowy winter time. These facts encourage the manufacturer to build a camera into OTLM SMART line monitoring sensor (Fig. 4), which can be used for monitoring overhead lines and to check the ice status on overhead line conductors [5].

Fig. 4 Installation of OTLM SMART on the conductor & integrated camera [5].

3.2 OTLM SMART's ice detection function

The thermal monitoring of OHL in a transmission grid is possible with various technologies on different power levels. The choice depends on the requests given by the transmission system operators. The sag and the conductor temperature are two key parameters which define the ampacity of the OHL. The conductor temperature is defined by thermodynamic equilibrium where the heat input equals heat losses. The conductor is heated by the solar radiation and by the heating effect of flowing current (I^2R). The technical brochures CIGRE are of great help with the development of the application for determining ice formation on conductors [6-15]. At the time of development and understanding thermal rating calculations of overhead lines we used excellent literature CIGRE [10-15]. The conductor temperature can be measured in one spot or continuously all over the length of the line. The spot method is cheaper but the device has to be carefully placed on the OHL. It should be mounted on the bottom conductor, on the part of the line which passes through the area where the landscape changes sharply and a line is shielded from the wind by various natural or manmade barriers. In complex terrain, the number of measurement points should be greater than in flat woodless areas. The ampacity was calculated by using the newest CIGRE formula (TB 601) [15]. Considering conductor temperature and ambient weather conditions the real-time sag and safety height are calculated by using a mathematical model [15]. A mathematical model has been developed for sag and horizontal force calculation. The model was developed as a computer application. The model includes installation conditions and conductor characteristics and determines the interdependence between conductor sag and horizontal force for actual conductor temperatures. The computer application is an integral part of OTLM SMART software. The developed mathematical model includes mechanical and physical characteristics of the conductor, conductor weight and sag size for the calculation of internal forces. Combining measurements of conductor geometry and sag at several conductor temperatures with software is using for calibration of the sag and angle function. Ensuring conformity is crucial for the implementation of the function ICE-ALARM since a continued growth of discrepancy between the measured and calculated angle in ambient conditions is a sign of glaze ice on the conductor [16-19]. 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 tower collapse. 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. 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.

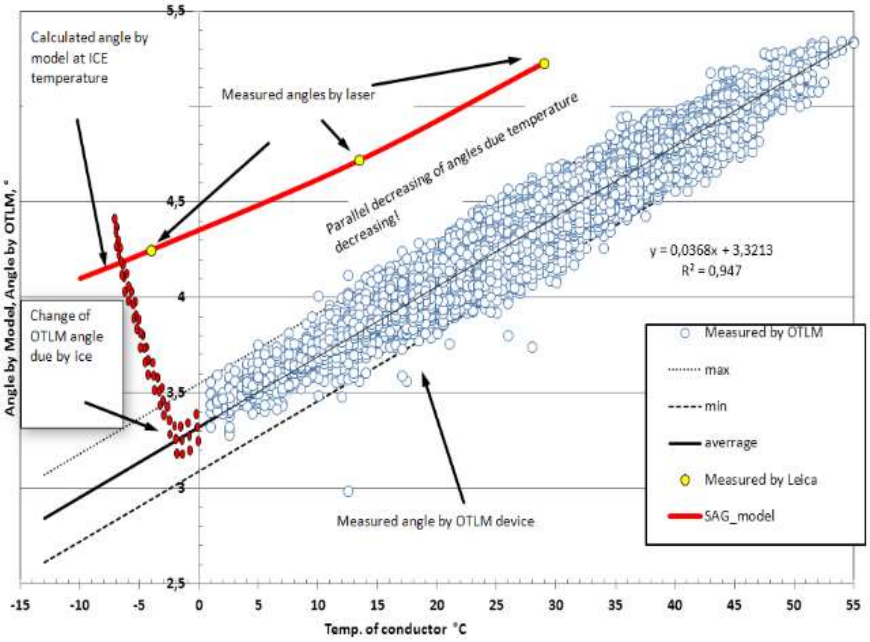

Fig. 5 Real state of a phase conductor [16-19].

Fig. 5 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 present the expected behaviour of the conductor and/or a change in the angle due to the build-up of the ice on the conductor. The continuous red line represents the angle of inclination depending on temperature according to the mathematical model. If an angle significantly increases in the meteorologically favourable ice 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.

4. BME’S ICE PREDICTION MODEL

Besides the geometry of the conductor, local environmental conditions, such as rainfall, ambient temperature, humidity, wind speed and direction, also play an important role in the formation of ice layer on the surface of the conductors. These parameters determine the structural properties of the resulting ice layer and thus its properties. Based on these environmental factors, three types of ice can be distinguished, which can cause high mechanical extra load to the conductors through high-adhesion and density. These three ice types are wet snow, glaze and hard rime. BME’s ice type determining system is established to predict the expected ice type based on environmental parameters, on which based the ice layer diameter and extent of extra mechanical load can be calculated according to the actual ice type. The algorithm takes into account the ambient temperature, precipitation type and intensity, relative humidity and also the temperature of the conductors in order to determine the expected ice type. The results of the system can be the following: wet snow, mixture of wet snow and glaze, glaze, mixture of glaze and hard rime, hard rime or ice formation is not expected. Ice can only shape when conductor temperature below 2 °C, but due to the uncertainty of the conductor temperature calculation model and the deviation of line monitoring devices, this threshold value was set to 3 °C in the model, which appears as a safety factor while it can be also increase the number of false alarms [20]. The structure of the ice layer deposited on the overhead line conductors largely depends on the type of precipitation, which through several parameters - water droplet / snowflake velocity and mass concentration, collision efficiency, adhesion factor, deposition factor - influences the forming ice layer.

In this way, the ice layer will be accreted differently for different types of ice, so the calculation of the thickness of the resulting ice sleeve and the consideration of the extra mechanical load caused by it should be calculated in different ways depending on the type of ice. BME's ice determining system use Lacavalla et al. model [21], [22] for wet snow calculation, Pytlak et al. model [23] for glaze computation and Shao et al. model [24] for hard rime estimation.

5. CASE STUDIES

To illustrate the operation of the two-level icing model, some case studies are presented here. Although, there was a "green winter", which means there was no considerable icing, only some snowing events occurred, nevertheless the operation of the model can be showed through these snowing events. Case studies was made for Kleče -Logatec 110 kV single circuit transmission line equipped with 240/40 mm2 ACSR conductors [25].

5.1 20 November 2018

BME's model predicted wet snow and glaze ice types based on weather forecast for different grid points. The expected ice thickness was 5 to 6 mm for glaze and 10 to 14 mm for wet snow. Fig. 6 shows the accretion of glaze ice depending on precipitation intensity. On the other hand, as Fig. 7 shows the image captured by OTLM device, there is a slight ice layer can be seen on the bottom of the wire [25].

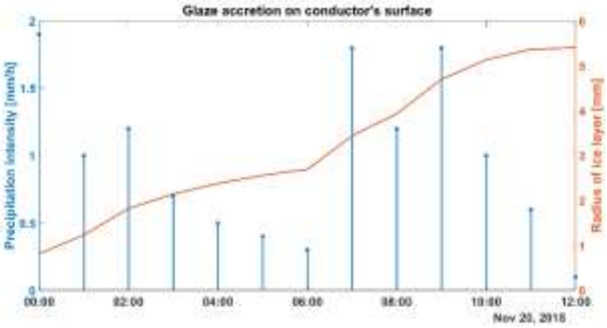

Fig. 6 Glaze accretion according BME's model

Fig. 7 Real state of a phase conductor

5.2 18 January 2019

A mixed type of ice from wet snow and glaze was anticipated according to BME's ice prediction model with a thickness between 9 to 12 mm for the different forecast grid points. The expected ice formation is shown in Fig. 8. The real field conditions are shown in Fig. 9, where a huge snow deposit can be seen front of the camera, and a layer of ice on the tower [25].

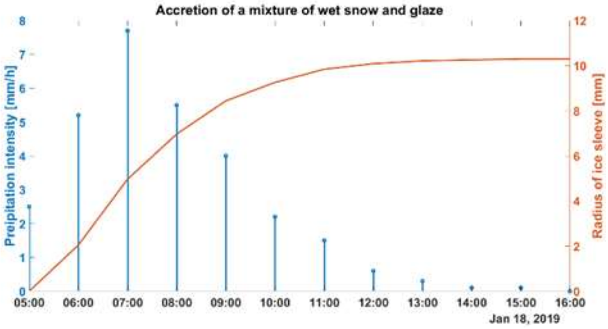

Fig. 8 Glaze accretion according BME's model

Fig. 90 Real state of a phase conductor

5.3 Summary of case studies

The operation of the model was investigated in 2018-19 winter time, when only slight ice formed on the conductors mostly form wet snow. BME's ice prediction model forecasted properly the ice formation, while the quantitative estimation should be fine-tuned, when significant ice sleeves will occur. On the other hand, OTLM device offers an appropriate solution for real-time monitoring of the conductors, which can be the basis to the intervention for system operators [25].

6. CONCLUSIONS

According to FLEXITRANSTORE's project this paper presented the development of a two-level ice prediction and detection model for high voltage overhead lines. The first level is a weather-based system, which aims to predict the possibility of different ice types – wet snow, glaze, hard rime – accretion on conductors. The model is able to calculate the radius of the ice sleeve and its mechanical extra load based on the accreting ice layer's type. On the second level a computer algorithm was developed for 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. 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. Furthermore, OTLM sensor is able to monitor the actual state of the conductors with its camera. The essence of the two-level system is the prediction opportunity combined with the real-time monitoring function. System operators get a forecast of the seriousness of the icing event in this way, while the intervention can be made according to the danger factor, therefore the number of unnecessary interventions can be reduced.

ACKNOWLEDGMENTS

Authors acknowledge the Slovenian Research Agency for founding members of research program P2-0137 Numerical and Experimental Analysis of Nonlinear Mechanical Systems.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774407.

BIBLIOGRAPHY

[1] FLEXITRANSTORE, European Union's Horizon 2020 project, http://www.flexitranstore.eu/The-project.
[2] FLEXITRANSTORE, European Union's Horizon 2020 project, http://www.flexitranstore.eu/Demo-3.
[3] V. Lovrenčić, V. Leva, R. Maruša, N. Zima and P. Ogrizek, "Experiences in the use of emergency restoration towers for repairment of collapsed 110 kV overhead power lines during the icing rain in Slovenia", 12th Symposium HRO CIGRE, Šibenik, Croatia, November 2015.
[4] V. Lovrenčić and T. Pungartnik, "Application of emergency restoration towers for repairment of collapsed overhead power lines during the icing rain in the utility Elektro Ljubljana", 5th (11th) Symposium HO CIRED, Osijek, Croatia, May 2016.
[5] W. Troppauer, V. Lovrenčič, N. Gubeljak, B. Nemeth, M. Kovač, G. Gocsei, U. Krisper, "Advanced monitoring of icing and prevention against icing on overhead power lines", IWAIS 2019, 18th International Workshop on Atmospheric Icing of Structures, June 23 -28, Reykjavik, Iceland.
[6] Working Group 06 CIGRE, Task Force 01. "Guidelines for field measurement of ice loadings on overhead line conductors" (Cigré Technical Brochure No. 179), 2001.
[7] Working Group SC B2.16 CIGRE. "Guidelines for Meteorological icing models, statistical methods and topographical effects" (Cigré Technical Brochure No. 291), 2006.
[8] 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.

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

[10] Working group 22 CIGRE, “Thermal behaviour of overhead conductors”, (Cigré Technical Brochure No. 207), 2002.

[11] CIGRE, “Conductors for the uprating of overhead lines”, (Cigré Technical Brochure No. 244), 2004.

[12] Working group B2 CIGRE, “Guide for selection of weather parameters for bare overhead conductor ratings”, (Cigré Technical Brochure No. 299), 2006.

[13] Working group, Task Force B2.12.3 CIGRE, “Sag-Tension Calculation Methods for Overhead Lines”, (Cigré Technical Brochure No. 324), 2007.

[14] Working group B2.36, CIGRE, “Guide for Application of Direct Real-Time Monitoring Systems”, (Cigré Technical Brochure No. 498), 2012.

[15] Working group B2.43 CIGRE, TB 601, “Guide for Thermal Rating Calculations of Overhead Lines”, (Cigré Technical Brochure No. 601), 2014.

[16] V. Lovrenčić, N. Gubeljak, B. Banić, A. Ivec, D. Kozjek, M. Jarc “On-line monitoring for direct determination of horizontal forces vs. temperature and incline angle of transmission conductor” (11th Symposium on power system management HRO-CIGRE, Opatija, Croatia, November 2014).

[17] 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),” DEMSEE'15 10th International Conference on Deregulated Electricity Market Issues in South Eastern Europe, Budapest, Hungary, September 2015.

[18] N. Gubeljak, B. Banič, V. Lovrenčić, M. Kovač, S. Nikolovski ”Preventing transmission line damage caused by with smart on-line conductor monitoring” (Proceedings of 2016 International Conference on Smart Systems and Technologies, (SST), Osijek, Croatia, October 12-14, 2016).

[19] N. Gubeljak, V. Lovrenčić, B. Banić, M. Pinterič, M. Jarc, “Application of an Ice-Alarm in the OTLM System”, First South-East European CIGRE conference, Portorož 2016.

[20] D. Szabó, “Development of Dynamic Line Rating system” MSc Thesis, Budapest University of Technology and Economics, Budapest, 2019.

[21] Lacavalla, Matteo & Marcacci, Pietro & Frigerio, Antonella. (2015). Forecasting and monitoring wet-snow sleeve on overhead power lines in Italy. 78-83. 10.1109/EESMS.2015.7175856.

[22] Matteo Lacavalla, Paolo Bonelli, Gilberto Mariani, Pietro Marcacci, Giuseppe Stella: The WOLF System: Forecasting Wet-Snow Loads on Power Lines in Italy, 14th International Workshop on Atmospheric Icing of Structure, May 8 May 13, 2011, Chongqing

[23] Pawel Pytlak, Petr Musilek, Edward Lozowski, Dan Arnold: Evolutionary Optimization of an Ice Accretion Forecasting System, Monthly Weather Review July 2010 138(7):2913

[24] Shao, J & J Laux, S & J Trainor, B & E W Pettifer, R. (2003). Nowcasts of temperature and ice on overhead railway transmission wires. Meteorological Applications. 10. 123 - 133. 10.1017/S1350482703002044.

[25] D. Szabó, B. Németh, G. Göcsei, V. Lovrenčić, N. Gubeljak, U. Krisper and M. Kovač, “Icing Analysis Of Kleče-Logatec Transmission Line With Two-Level Icing Model”, 21st International Symposium on High Voltage Engineering, Budapest, Hungary, August 26-30, 2019.