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Advanced prevention against icing on high voltage power lines

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SUMMARY

Historical meteorological data indicates, that our weather is becoming more and more extreme. For the electrical utility operators (Distribution System Operators - DSOs and Transmission System Operators - TSOs), these changes arise in new operation challenges that need to be addressed. For example, frequent icing phenomenon affects all the components of the power line by a significant mechanical overload: it endangers the conductors, the insulators and the towers, as well. The result is often fatal and beside serious failures, it effects on operators' decisions. These not only endanger the reliability of electrical grids by the loss of a power line for weeks or even months, but in general, the safety in the surroundings of the power line. As technology advances, we will be able to collected, analyses 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 given line, 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, detection and removal of ice layer is necessary. The proper handling of this icing issues, requires advanced algorithms (expert systems) and reliable measuring equipment. The combination and synchronization between algorithms, weather service and measuring equipment is the key of the successful operation. An EU H2020 financed project called FLEXITRANSTORE has just been launched to develop a cross-country co-operation, with objective to improve anti-icing and de-icing solutions. To establish and analyse different solutions, the project includes several universities, TSOs and DSOs. To solve mentioned icing issues Budapest University of Technology and Economics' (BME) developed an advanced neural-network based algorithm which use OTLM system. It is planned to install and demonstrate the capabilities of this new technology on the DSOs grid (Electro Ljubljana - ELJ). Besides the introduction of DLR and icing, this paper also focuses on the preparation/organisation of co-operation between different companies and universities.

KEYWORDS

icing, de-icing, dynamic line rating, Flexitranstore, BME, C&G, OTLM, ELJ

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INTRODUCTION OF PROJECT FLEXITRANSTORE

21.7 M Euro project »Flexitranstore« 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 project itself aims to contribute to the evolution towards a pan-European transmission network with high flexibility and high interconnection levels. This will facilitate the transformation of the current energy production mix by hosting an increasing share of renewable energy sources. Novel smart grid technologies, control and storage methods and new market approaches will be developed, installed, demonstrated and tested introducing flexibility to the European power system [1].

Increasing the reliability of both the distribution and the transmission grid is essential, especially in cases of unpredictable or even extreme weather conditions. During the project, a novel Dynamic Line Rating (DLR) model is going to be developed and tested. DLR enables existing power lines to be used in the same way as lines with higher rated temperature of the conductors. A de-icing algorithm to be developed will integrate the advantages of several already established DLR systems with some additional parameters in an effort to increase accuracy. Given a more precise DLR algorithm the state of the conductors during the de-icing process can be followed online. During normal operational conditions DLR constitutes an effective way to increase the transfer capabilities of a power line. In case of extreme weather conditions de-icing can prevent serious failures.

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].

INCREASING TRANSMISSION CAPABILITIES – DYNAMIC LINE RATING

Today's energy consumption and energy demand is increasing. That is particularly true in case of electric power consumption. Although the transmission lines should operate at their designed voltage and ampacity, due to the increased demands, some of the lines are already operating on elevated temperatures. To resolve that issue, the capacity of the transmission network should be increased. Dynamic Line Rating is one of the most cost effective way to increase the transmission capacity of the already existing network. DLR is an operating method, which makes it possible to utilise better the network, based on real-time data and calculations.

The DLR system is based on different types of sensors, weather stations and weather forecast which provide the essential data for the system. Line monitoring sensors are complex electrical equipment which has to function reliably and properly on the conductor or near to the conductor. Therefore, these sensors have to be tested and fitted to operate in high voltage environment [3].

Having higher ampacity rates over a power line due to DLR, increased thermal stress occurs not only on the conductors, but on insulators, and on other pieces of equipment as well. Increased ampacity resulting in increased temperature of conductors brings about an increase in sag, thus electrical clearance might be violated with higher probability [4].

During DLR system implementation the first step is critical span analysis. In this phase of work all of the spans of the selected transmission line shall be examined by different aspects through calculations and simulations. Therefore, critical spans can be identified which firstly violate the regulations related to clearance, especially when the conductor operates near the designed maximal temperature or exceed this temperature even for a short period of time.

The longitudinal section of the whole overhead line has to be investigated, and critical spans shall be selected by the following criteria:

- Highest level differences between towers,

- Longest spans,
- Obstacles and terrain under the span.

The length of the span is a critical factor, because longer spans have higher sag in case of elevated temperatures. Level difference of the towers is also crucial, because in case of larger level differences the permitted sag is smaller than in case of smaller ones. Furthermore, obstacles and terrain under the span shall also be inspected.

These objects may violate clearance, because they may change after the construction of the line, too. As the result, design documentation may not take these effects into consideration (e.g. the growth of the vegetation or terrain changes due to landscaping). Figure 1 shows a part of an elevation profile of a transmission line, which is based on the above-mentioned three criteria.

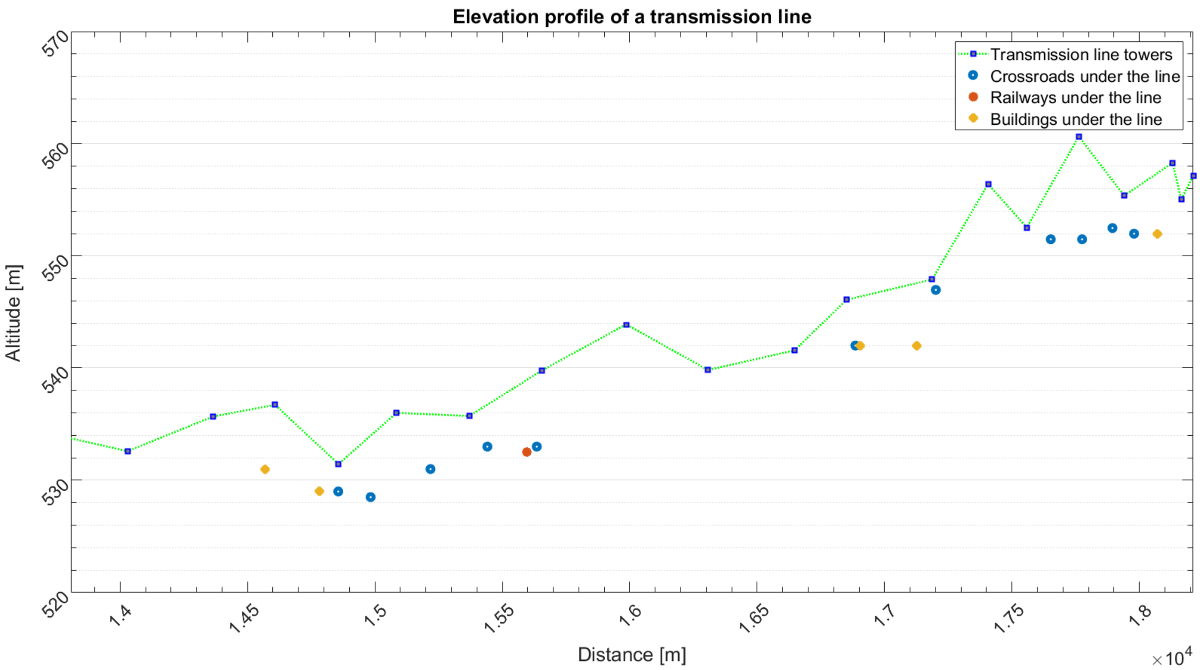

Figure 1 – Elevation profile of a transmission line (example)

To ensure that clearance regulations are not violated, critical spans shall be locally examined, and the sag of the line shall be calculated for higher temperatures than the designed to know which the thermal limit is, when the sag reach the clearance limit. In case of DLR, operating temperature might exceed the designed temperature for short time – e.g. during the use of short-time emergency rating – and the clearance regulations should be comply under all operating conditions. The transmission line sag calculations are usually carried out by modelling the sag as a parabola as it is shown in Figure 2.

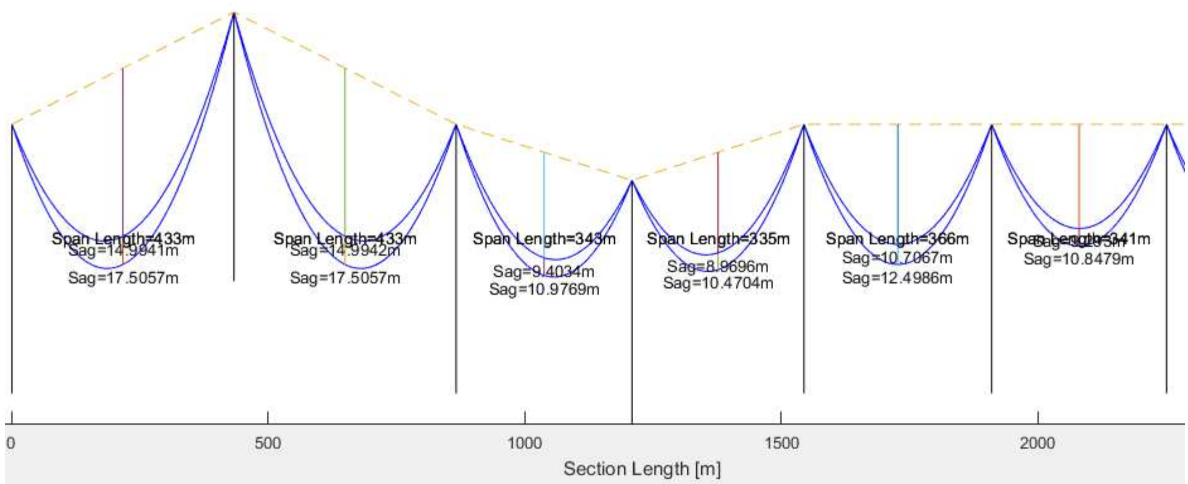

Figure 2 – Sag simulations for different conductor temperatures

BME'S WHITE-BOX AND BLACK-BOX MODELS FOR CALCULATION

Preliminary studies of wind

As several studies have shown in the past, the main cooling factor is the wind during the DLR calculations (both speed and direction).

It is common that a given direction characterizes the behaviour of the wind. This direction correlates with the strength of the wind, so the higher the wind speed is, the direction becomes closer to the dominant wind direction. Most of the studies agree that the wind speed above 5 m/s is worth to calculate with.

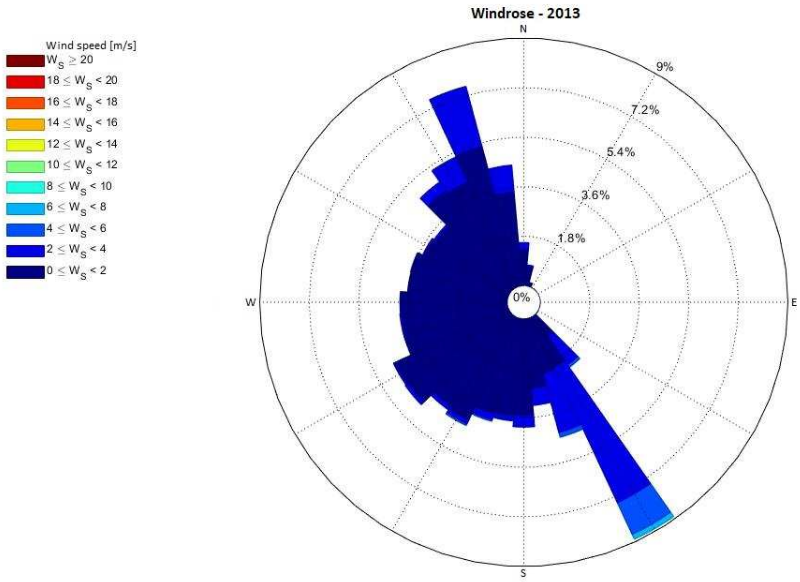

Figure 3 – Windrose (example)

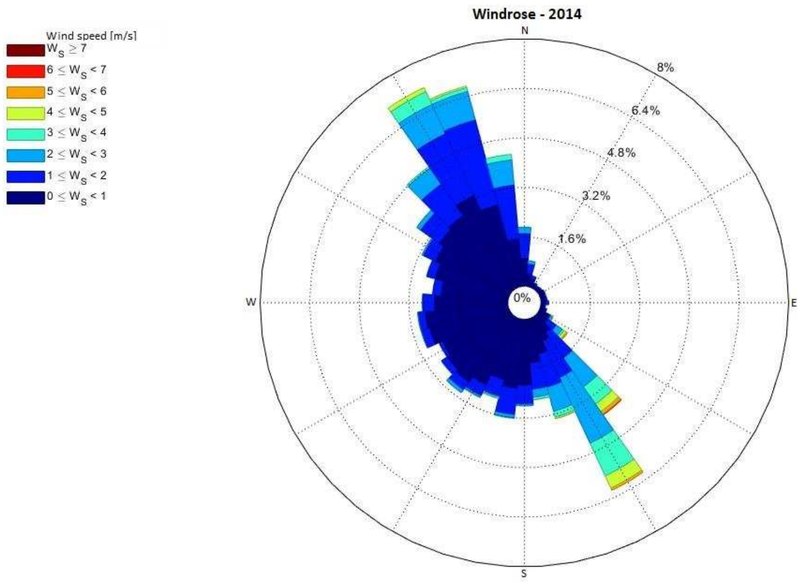

Figure 4 – Windrose (example)

Figure 4 and Figure 5 shows the windroses based on real meteorological data between 2013 and 2014. The diagrams justify the claim, that there is no characteristic win direction in case of low wind speeds – while wind speed ≤ 5m/s – thus the direction of the wind is fully stochastic. In case of higher wind speeds – while wins speed > 5 m/s – there is major direction which was south-southeast and north-northeast in this study. This study showed the wind direction cannot be accurately predicted in case of low wind speeds.

BME's extended white box model

In case of so-called »white-box« models, results of the calculations are based on equations taking the inputs as variables into consideration. An extended white box model was developed in the Budapest University of Technology and Economics (BME) based on the experiences gained during the analysis of archive weather data and the physical equations of the calculation methods. BME's extended white box model unites the international standards with the following new approaches:

- Takes into account the cooling effect of the precipitation
- Considering wind effect in different OHL sections
- Improved weather forecast processing

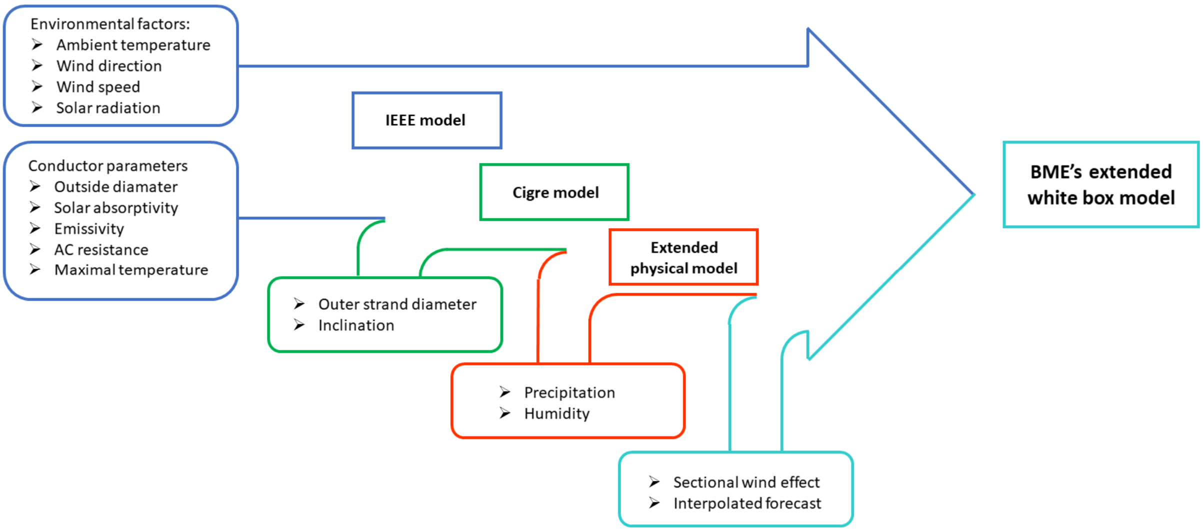

Figure 5 - Schema of BME's extended white box model

The extended physical model takes into consideration the cooling effect of the precipitation on the line, which is grant higher transmission capacity in case of rainy weather conditions. The stochastic behavior of the wind was corrected with the consideration of the wind in different OHL sections, thus the local thermal overloads of the conductor was eliminated. The improved weather forecast processing module increases the time resolution of the weather forecast with various interpolation methods.

BME's black box model

Currently there are two well-known algorithms to determine the ampacity of a given power line by the white-box model: CIGRE [5] and IEEE [6] methods. In general, CIGRE model takes more environmental factors into account than IEEE. In terms of »black-box« models, no equations are used. In the algorithm of BME, a novel approach has been developed and introduced based on the use of soft-computing methods (neural networks). Figure 6 shows the applicability of the neural network for DLR calculations:

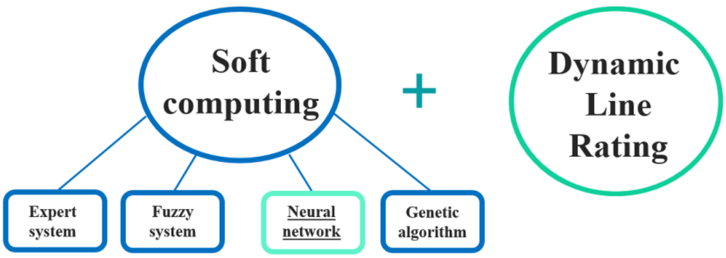

Figure 6 – Intelligent agents and DLR

The DLR model of the CIGRE and IEEE standards are empirical ones which means that there are some simplifications (cooling effect of the precipitation) in both of them. Moreover, there are special circumstances when these models provide different limit values for the current (e.g. when the wind speed is above 5 m/s). Due to this fact, it may be worthwhile investing new models based on different approaches. The examinations of the soft computing methods have shown that the use of neural network could be promising, because these kinds of networks are able to learn and handle complex data-sets. In BME's model, there are 2 main steps for the determination of the maximum current value: the calculation of the temperature of the line and the determination of the DLR value itself.

For the calculation of the temperature of the conductor, a neural network is applied. There are 4 inputs of the network, such as ambient temperature, wind speed, solar radiation, and the real-time current, while the output of the model is the temperature of the conductor. Running the simulations have shown, that a 4-layer, forward cascade neural network has the lowest error, where the number of the neurons are 4 in the input, 32 in the hidden and 1 in the output layer as it shown in Figure 7. Figure 8 illustrates the validation of the used neural network.

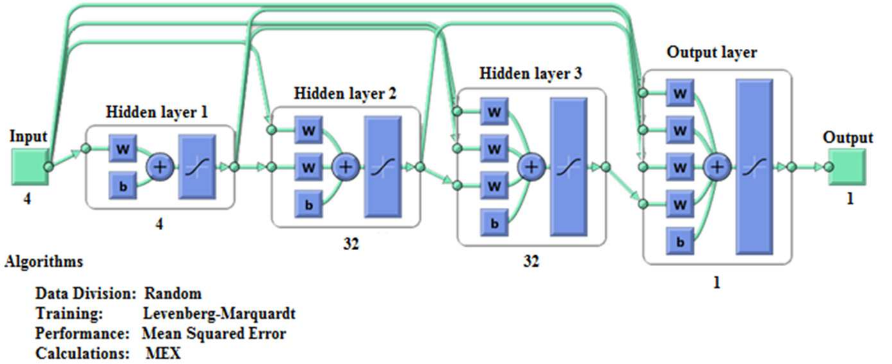

Figure 7 – The structure of the chosen neural network

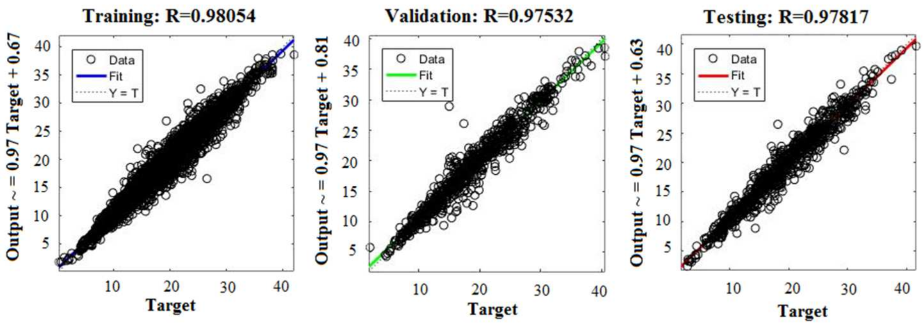

Figure 8 – The training, validation and test of the neural network

The average error of the network is about 2-3 °C, which is shown in Figure 9. This error is acceptable, because the average deviation of most sensors is ±2°C.

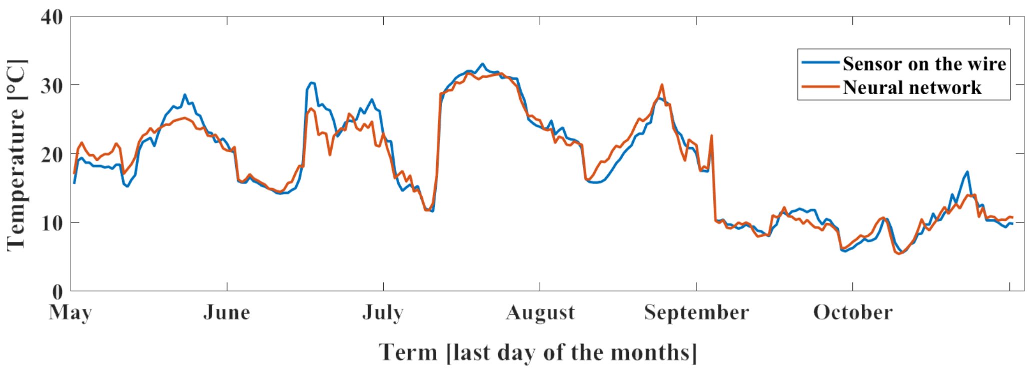

Figure 9 – The temperature of the wire as a function of time

As the line temperature is available, the DLR value can be calculated from a heat equation by determining the extra heat gained from the increased current of the grid as it shown in Figure 10. By using this calculation method, it is important to not exceed the temperature limit of the conductor.

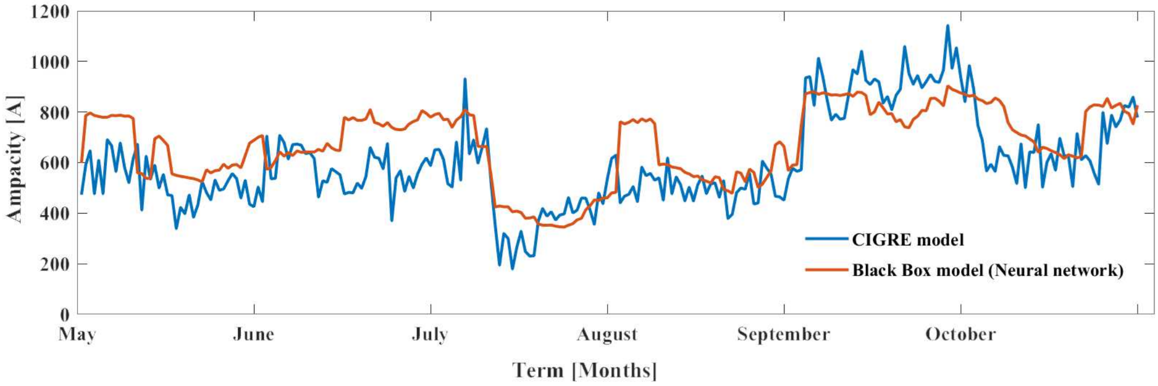

Figure 10 – DLR value of the last days of the 6 months as a function of time

The biggest advantage of the black box model is that temperature sensor for the validation of the results is installed on the line, while all the environmental parameters can be taken into account.

SPECIAL APPLICATIONS OF DLR: ANTI-ICING AND DE-ICING

Atmospheric icing may cause serious damage in infrastructures including power grid equipment, such as overhead line towers and power lines themselves. The increased mechanical load due to the ice accretion may even cause the power lines to collapse, which is not only dangerous to the environment, but may compromise the power grid's stability, as well.

The process of ice accretion can be separated to two main groups: dry growth and wet growth icing. During the first type, there is no precipitation. The humidity of air freezes onto the bare conductor in a more or less consistent thickness. The ambient temperature range – when this phenomenon may occur – is really wide. When the humidity is high enough, and the wind speed is significant, as well, hard rime develops from around 0 ℃ to -8 ℃. When temperature is between -8 ℃ to -20 ℃ and of course, there is sufficient humidity, soft rime sticks to the surface.

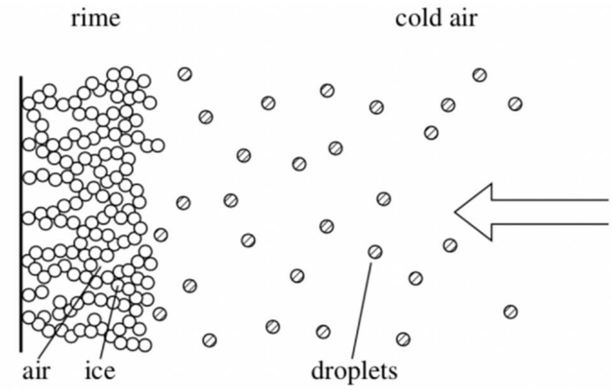

Figure 11 – Dry growth [5]

As for the wet growth, the ice accreting by supercooled water droplets hitting the conductor's surface (called freezing rain) or from wet snow sticking to the conductor. In both cases, the temperature is around 0 ℃. These two types may inflict notable mechanical load in a short period of time.

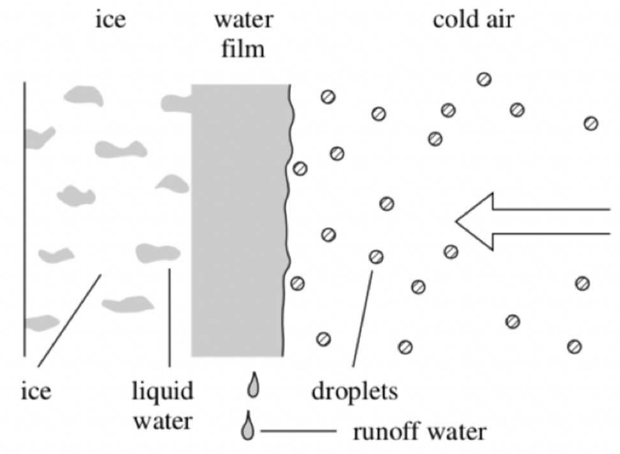

Figure 12 – Wet growth [5]

DLR is an effective technique not only for ampacity calculation, but to use increased and controlled currents for anti-icing and de-icing purposes, as well. In order to prevent or at least predict events with serious consequences, several models [6], [7] were created or updated to calculate ice growth properly, especially on cylindrical shape because of the application. The icing process has a lot of external influences which are hard to describe and even a small inaccuracy during modelling, measuring, or calculating may cause completely different results in prediction [5]. If the accreted ice's weight is high enough to cause damage, then some de-icing methods need to be performed on the power line. There are several techniques [8] for this application, but with improper implementation, the melting attempt itself can endanger the stability of the power grid.

In order to prevent mentioned icing the mathematical model has been developed for sag and horizontal force calculation. The model was developed as a computer application. 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 software. The catenary represents a starting condition for monitoring conductor behaviour on the span between two towers. Temperature of conductor, ambient conditions and the electrical line current cause changes in conductor length and consequently a change in catenary geometry. The developed mathematical model includes mechanical and physical characteristics of the conductor, conductor weight and sag size for the calculation of internal forces. Based on optical-laser sag measurements, a calibration curve was developed between the sag/angle/temperature/tensile force in the OHL conductor, which applies to normal working conditions or operational load [8]. This enables us to estimate the change in catenary form in a wider temperature range.

The measurement of conductor catenary on different conductor temperatures and ambient temperature shows an excellent correlation between measured sags in the field and the sags that were determined with a mathematical model "OTLM-SAG". It confirms that the data can be used as an alarm when the critical sag are reached. The described application offers the user real-time monitoring and it helps a safe operation of the chosen OHL.

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.

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.

The parameters of the catenary curve at the temperature of the wet growth 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 13 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.

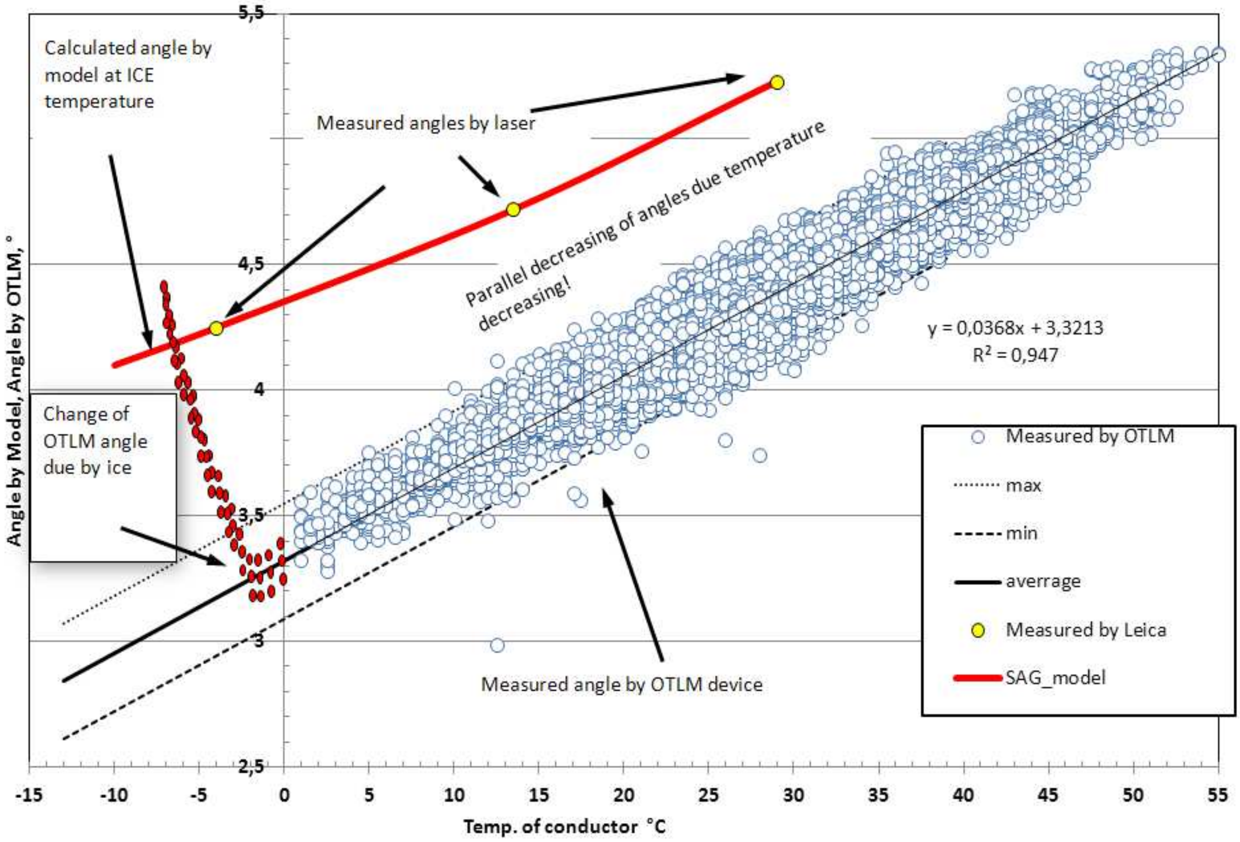

Figure 13 – Change in an angle at the OTLM device position depending on temperature

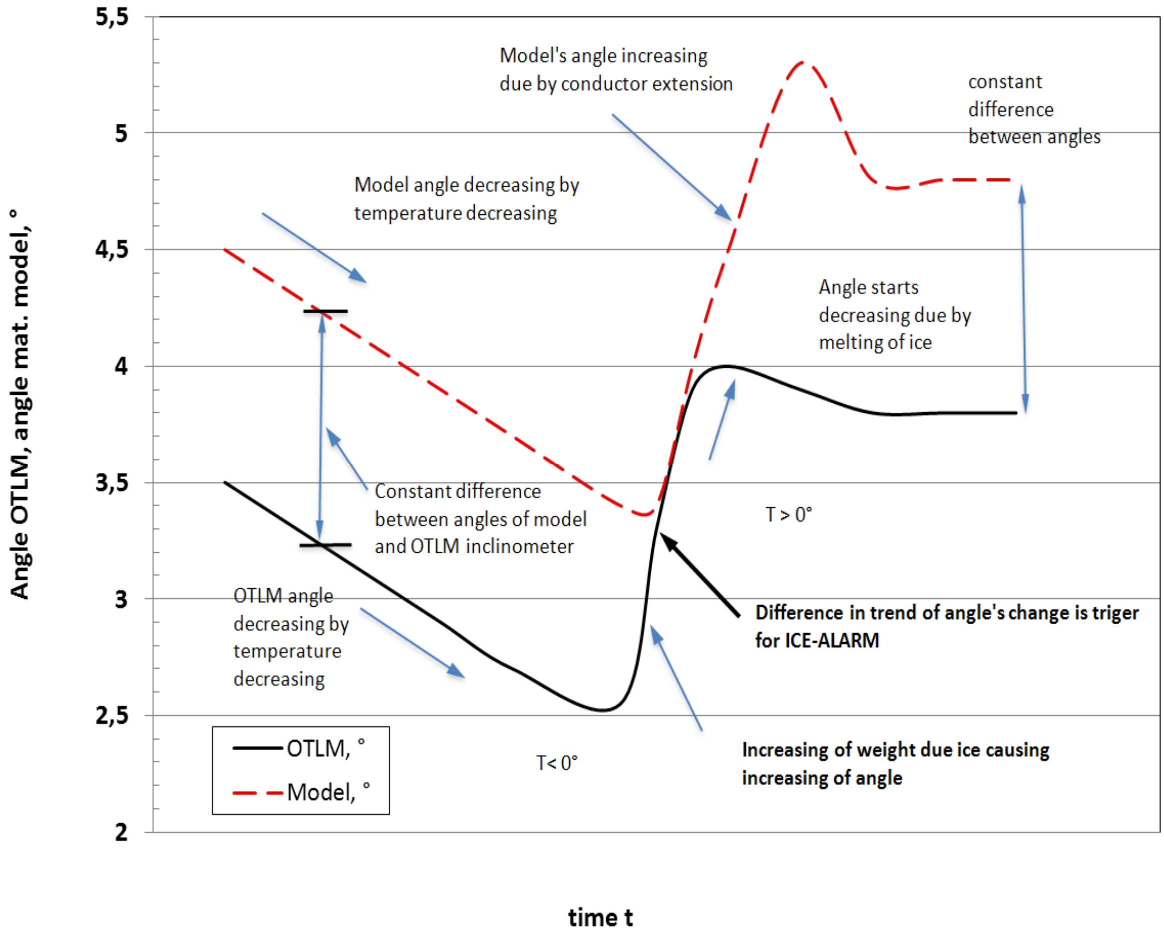

Figure 14 – Change in an angle of inclination during the activation of ICE-ALARM and melting of ice

The continuous line in Figure 13 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 13. 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 14 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 Al-Fe (ACSR) 240/40 conductor recorded in the laboratory, it is possible to determine and monitor the elongation [9]. The model (red hatched line in Figure 14) 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 14), 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 a 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, as determined DLR concept. 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 15 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, while the increase in horizontal (shear) strength up to the destruction force of 86.4 kN is exponential.

Figure 15 shows also 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 15, 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·g and an increase in the angle by 4.56° and/or to 8.24°, as shown in Figure 15.

Figure 15 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 15, while the increase in horizontal (shear) strength up to the destruction force of 86.4 kN is exponential.

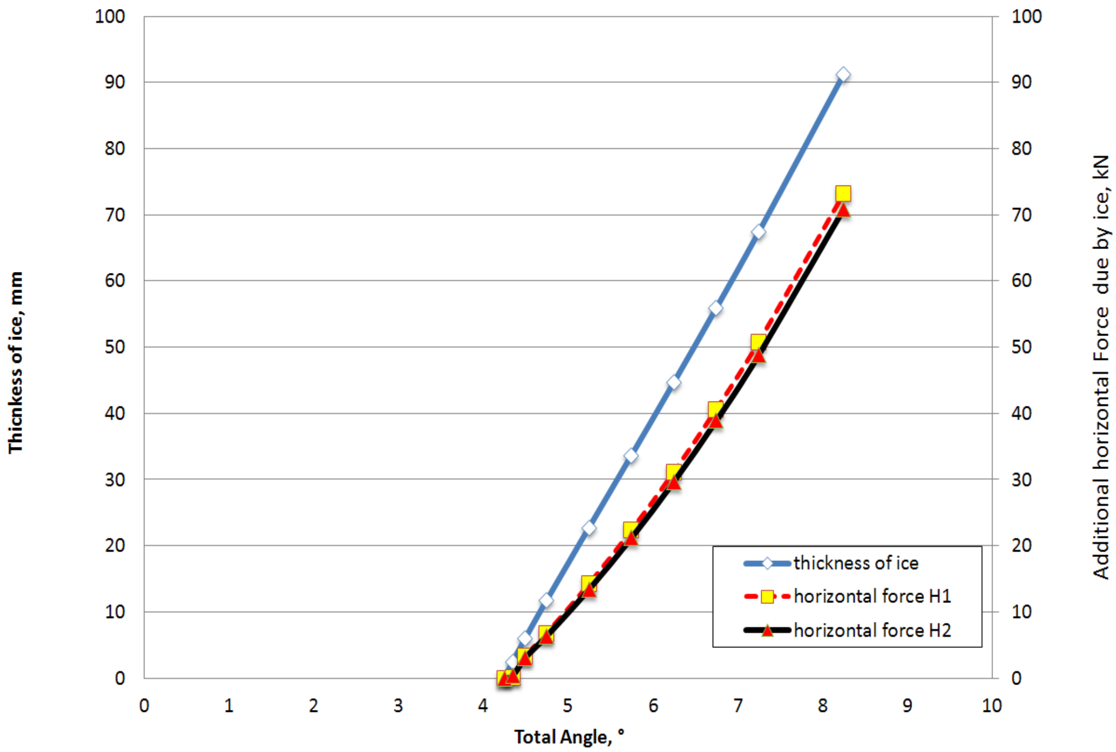

Figure 15 – The relation between ice thickness, the angle of inclination and horizontal forces

CONCLUSIONS

DLR is a novel, effective and promising technique not only to increase transmission capabilities, but in some cases (like extreme weather conditions), precise control of ampacity allows its use for anti-icing and de-icing purposes.

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

In the framework of project Flexitranstore, there is a great opportunity for the development of these applications through the test of several DRL sensors from different manufacturers. From the results, not only the precision of sensors, but efficiency of the algorithms will be seen clearly.

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