Performance analysis and fine-tuning possibilities of DLR-based ice prevention method according to international project experiences

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Abstract— **Several challenges on the electric power network require the introduction of flexible and smart solutions in order to enhance the utilization of the existing infrastructure by also maintaining or even increasing the reliability of the system. Dynamic line rating (DLR) technology was developed for that purpose, of which basis is the thermal state monitoring of the phase conductors. Based on DLR methodology, the establishment of a complex power line management system is possible by using the same infrastructure as in case of a DLR system. One of these subsystems is the ice management module, which is established in order to reduce the risk of power lines icing.**

The aim of this paper is to present the development process of ice management subsystem at the Budapest University of Technology and Economics (BME). Moreover, the operation of BME's ice prediction model is also investigated via case studies.

Keywords— ***dynamic line rating, DLR, ice prediction, ice prevention, overhead line, system approach***

I. INTRODUCTION

During the operation of the electricity network, system operators have to cope with different technological and economic challenges on all voltage levels. These challenges originate from the increasing load demand of the consumers, the aging network, the more and more often appearing extreme weather conditions and the optimization requirements of operational, maintenance and investment costs. Basically, dynamic line rating (DLR) technology was developed to deal with these engineering and economic requirements, by utilizing power lines in a more liberal way than before with the so-called static line rating transmission capacity allocation method. The essence of the DLR technology is that it continuously monitors the environmental conditions along the power line corridor and the line load at the same time, on which based the thermal equilibrium of the phase conductors can be modelled with mathematical and physical approaches. In this way, the actual ampere capacity (ampacity) of the line can be calculated, which means the complete thermal utilization of the conductors in practice. On the other hand, if weather forecast is also available as an input parameter of the DLR system, the transmission capacity of the line can be determined in ahead for a few hours or days. [1]

The requirements on the input side of the DLR methodology allows the development of a complex line management system with a widespread of functionality based on DLR technology. As the results of the research and development activities discussed in [2],[3], a complex line management system had been developed, which includes the functionality of ice prediction and prevention subsystem. BME's (Budapest University of Technology and Economics) ice prediction system has been developed in order to forecast and prevent the most severe ice sleeves on the phase conductors of overhead lines, therefore it is able to distinguish three different ice types. In order to increase the reliability of the DLR-based ice prediction system, BME's model has been extended with the conductor temperature forecast module. With this extension, the number of false warnings can be decreased, as the model investigates if the conductor temperature falls below the threshold temperature, that favourable for ice accretion on the phase conductors.

BME HVL's participation in different international pilot projects – that are aiming the flexibility and reliability increment of electricity power network – offers the possibility to investigate ice prediction model working in field operational circumstances. The aim of this paper is twofold. Firstly, the extension of BME's DLR-based ice prediction model with conductor temperature forecasting method and its physical background are presented. Then, a performance analysis is performed, which investigates the overall reliability of the proposed and extended ice prediction and anti-icing subsystem by including international project experiences from FLEXITRANSTORE [4] and FARCROSS [5] projects.

II. ICE PREDICTION ON POWER LINES

By investigating the international literature, it can be stated that the most severe risk during power lines' icing is caused by glaze, wet snow and hard rime in order. These ice types can cause such an extent of extra mechanical load on the conductors, that can lead to permanent elongation of the conductors, or even the mechanical break of the conductors, insulators and towers. [6]-[12] Therefore, BME's ice prediction model is developed in order to forecast these ice types, thereby subserve the prevention against such an extreme weather conditions.

A. *Characterization of ice types*

Ice layer formation on power line conductors can be divided into two main groups, namely in-cloud icing and precipitation icing. The former type is accreted from suspended, supercooled water droplets, while in the latter case the snowflakes or raindrops are freezing and adhering to the conductor. In-cloud icing can cause soft-rime, hard rime and glaze caused by supercooled cloud droplets, while the precipitation icing can result to wet snow, dry snow and freezing rain caused glaze.

In the case of glaze icing, the colliding water droplets don’t freeze immediately after the mechanical impact, thus shaping a water surface layer that then freezes. The glaze ice layer has the highest density of atmospheric ice types and also characterized by the strongest adhesion coefficient. The resulting layer of ice is hard, well-bonded and mostly homogeneous in appearance, while its density is varying between 700 and 900 kg/m^3. Generally, the ambient temperature during glaze icing is in the range of [-3; 0] °C, while the wind speed is between 1 and 20 m/s. [6]-[12]

In Mediterranean countries with low elevation, wet snow icing represents the highest risk on power lines’ icing. Wet snow layer can from during snowing conditions with ambient temperature in the range of [-0.5; 2] °C and independently from wind speed. Ice layer from wet snow only poses risk to the conductors, if the precipitation amount exceeds 10 mm during the icing event. The adhesion coefficient of such an ice type is week in case of ambient temperature above 0 °C, while it might turn into very strong, if the air temperature drops below freezing point after the formation. In terms of density, the wet snow sleeve is varying in wide range, however it can reach up to 850 kg/m^3. [6]-[12]

Hard rime may be accreted on the conductors as the results of collision of supercooled water droplets in the air layer around the wires, that then freezes on the conductors. Hard rime can occur at an ambient temperature in the range of [-8; -2] °C and wind speed between 5 and 10 m/s. The density of the hard rime ice layer is varying between 300 and 700 kg/m^3. The direction of hard rime formation concurs with the wind direction, while its adhesion coefficient is relatively high. [6]-[12]

B. *Weather-based ice prediction with decision tree*

Primarily, the ice type is defined by the environmental parameters, on which based a decision-tree algorithm is developed to identify the ice type in case of an expected icing event. These parameters are the ambient temperature, relative humidity, precipitation rate, and wind speed, while wind direction are also required in order the track the accretion process.

The summarization of favourable environmental conditions for ice formation in the case of the three most sever ice types on overhead lines are outlined in II. A., on which based BME’s decision-tree algorithm is established. The schematic of the weather-based ice prediction model is shown in Fig. 1.

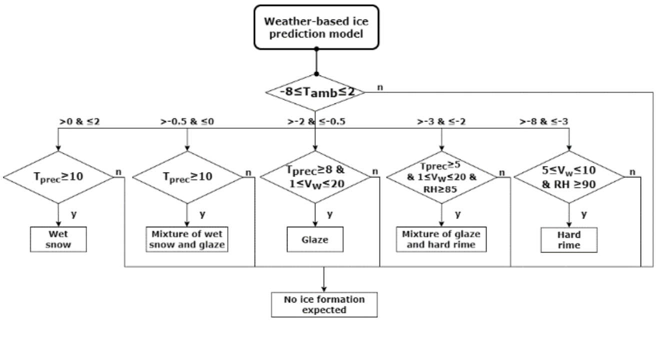

Fig. 1 Schematic of weather-based ice prediction model

The weather-based decision-tree algorithm takes into account the T_{amb} [°C] ambient temperature, T_{prec} [mm] total precipitation amount during the icing event, V_w [m/s] wind velocity and RH [%] relative humidity parameters in order to determine the expected ice type.

Accordingly, the output of the algorithm can be one of the following values:

- No ice formation expected,
- Wet snow,
- Mixture of wet snow and glaze,
- Glaze,
- Mixture of glaze and hard rime,
- Hard rime.

III. DLR-BASED ICE MANAGEMENT SYSTEM

Although, weather-based ice prediction algorithm can be established by only considering the output of weather forecast models, it doesn’t take into account if the temperature of the phase conductors falls below the threshold value that favourable for ice formation. Therefore, it can cause false warnings in these cases.

On the other hand, in the case of icing event, dynamic line rating calculation methodology is able to determine the anti-icing current in advance, or the de-icing current during the ice accretion process in this way offering two different Joule-heating based methods for decreasing the risk of power lines’ icing.

A. *Extension possibilities of weather-based ice prediction*

In the operation practice of transmission lines, generation schedule should be determined in order to predict power flows in the transmission system. The forecasted time range can vary depending on the role of the transmission line (cross-border or internal line), and also on the given TSO’s practice (generation schedule is generally planned a few hours ahead, day-ahead or for the obsessed day).

Dynamic line rating technology is not only an effective method for calculating the transmission capacity of the power lines. By knowing the line load in advance combined with weather forecast, the thermal state of the phase conductors also can be predicted. For this purpose, the fixed point of (1) should be solved in an iterative way.

$$P_J(T,I) + P_S - P_c(T) - P_r(T) - P_e(T) = \varepsilon \cong 0 \quad (1)$$

where P_J [W/m] is the Joule-heating caused by the line load, P_S [W/m] is the heating effect of global radiation, P_c [W/m] is the convective cooling effect of wind, P_r [W/m] is the radiative cooling effect and P_e [W/m] is the evaporative cooling of precipitation. Contrarily to the widely used international DLR models by Cigre [13] and IEEE [14], (1) is an extended equation, which deals with the evaporative cooling of precipitation [15], [16].

In this way, the conductor temperature can be determined in advance, thus, the threshold limit regarding the surface temperature of the conductor also can be investigated. Since ice layer can be formulated on conductors only if their temperature does not exceed 2 °C [17], the false warnings of the weather-based ice prediction model can be significantly reduced with this extension.

The schematic of BME’s ice prediction model with this extension is shown in Fig. 2.

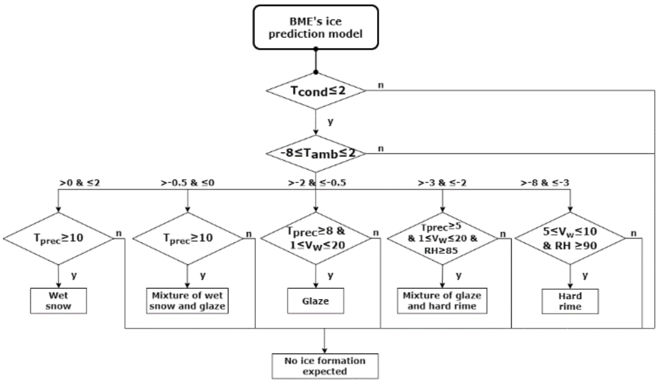

Fig. 2 BME’s decision-tree model for ice prediction on power line conductors

B. *Ice accretion process on phase conductors*

The structure of the ice layer accretes on the phase conductors and therefore the adhesion and mass of the ice deposit can differ significantly by distinguishing different ice types. The physical parameters that influence ice formation process are precipitation rate and its nature, the velocity of snowflakes or water droplets, collision efficiency, sticking efficiency, accretion efficiency and mass concentration.

Based on the predicted ice type with BME’s ice prediction model, further parameters of the expected ice layer can be determined by applying international models for the ice accretion process. For this purpose, the same parameter list is required, that is already used during the DLR system implementation, therefore ice prediction model can be effectively integrated into the DLR systems. In this way, the surplus mechanical mass caused by the ice deposit, and its radius are also determined according to the ice type.

Ice layer as the results of freezing rain precipitation is called glaze. In order to monitor the ice formation process during a freezing rain event, Pytlak et al. model [18] can be applied, which provides ice thickness depending on precipitation amount and perpendicular wind speed during the icing event. Furthermore, the mass of the ice layer can be calculated by knowing the conductor radius, the ice thickness and the density of glaze.

Wet snow is able to form on the conductors, when the total precipitation amount exceeds 10 mm in case of a snowing icing event with ambient temperature slightly above freezing point. Lacavalla et al. model [19]-[22] calculates the ice sleeve diameter and the mechanical ice load on the conductor reliant to the precipitation intensity, wind velocity and the angle between wind direction and conductor.

Hard rime can be accreted on the phase conductor from in-cloud icing, when the supercooled water droplets collide in the air around the wires, then freeze on its surface. The mechanical ice load on the conductor and the sleeve diameter can be calculated with Shao et al. model [23] depending on the ambient temperature and effective wind speed.

C. *Treatment of power line icing with DLR-based thermal methods*

In case of anti-icing and de-icing techniques passive methods, active coatings and devices, mechanical techniques and thermal approaches can be distinguished. The essence of a dynamic line rating system, that it constantly monitors the thermal state of the phase conductors, therefore, it can be applied effectively against power lines icing.

In case of anti-icing techniques, preventive steps are made against ice deposition. From thermal approaches point of view, it means that a preventive heating current should be applied in case of an expected icing event, in this way avoiding the ice formation process. Generally, anti-icing strategy requires minor interventions than de-icing. In case of anti-icing, the line load should be increased to reach conductor temperature the 2 °C threshold limit. Another advantage of this technique from operation point of view, that it can be reconciled with generation schedule planning, which means a solution that is easier to put into practice at system operation level.

On the other hand, de-icing techniques are applied against icing events, when the ice formation have already started. Generally, the ice layer can be considered as a thermal insulator layer around the conductors, thus requiring more dissipated heat in order to melt the ice sleeve. In case of de-icing, it is already worth to mention, that the de-icing current is depending on the melting time which correlates with the speed of ice formation process for successful application of de-icing. Therefore, in case of extreme icing conditions, the required de-icing current may exceed, the power line’s static line rating, accordingly, DLR technology should be applied to calculate the permissible magnitude of de-icing current.

D. *Realization of DLR-based ice management system*

TABLE I. Input Parameters Required for DLR-based Ice Management System Modules

Monitored parameter / ice management module	**Line load [A]**	**Ambient temperature [°C]**	**Wind speed [m/s] and direction [°]**	**Precipitation rate [mm/h]**	**Relative humidity [%]**
BME’s DLR model	X	X	X	X	X
BME’s ice prediction model	X	X	X	X	X
Glaze accretion model			X	X	
Wet snow accretion model			X	X	
Hard rime accretion model		X	X		
Anti-icing model		X	X	X	X
De-icing model		X	X	X	X

Based on the thermal monitoring of phase conductors, dynamic line rating (DLR) technique can be applied effectively to deal with power lines' icing also from the prediction phase to the de-icing process. TABLE I. summarizes the required input parameters for the DLR system and also for the DLR-based ice management system, which shows that BME's ice management system can be a functional extension of BME's DLR system, as it requires the same input parameter set.

By investigating the operation of BME's DLR-based ice management system, it firstly determines the conductor temperature based on the weather forecast and the generation schedule for the forecasted time period. Then, if the conductor temperature is favourable for ice formation, BME's decision-tree based ice prediction model determines the expected ice type during the icing event. On this based, the appropriate ice accretion model calculates the mass and thickness of the given ice layer. If the expected ice type is a mixture of two different ice layers, both accretion models have been called, from which the worst-case scenario is considered as system output. By inspecting the time period of the icing event, BME's DLR model calculates the anti-icing or the de-icing current. In the latter case, the dynamic thermal limit of the line is considered, if extreme weather conditions and rapid melting demand it. The flow chart of BME's DLR-based ice management system is shown in Fig. 3.

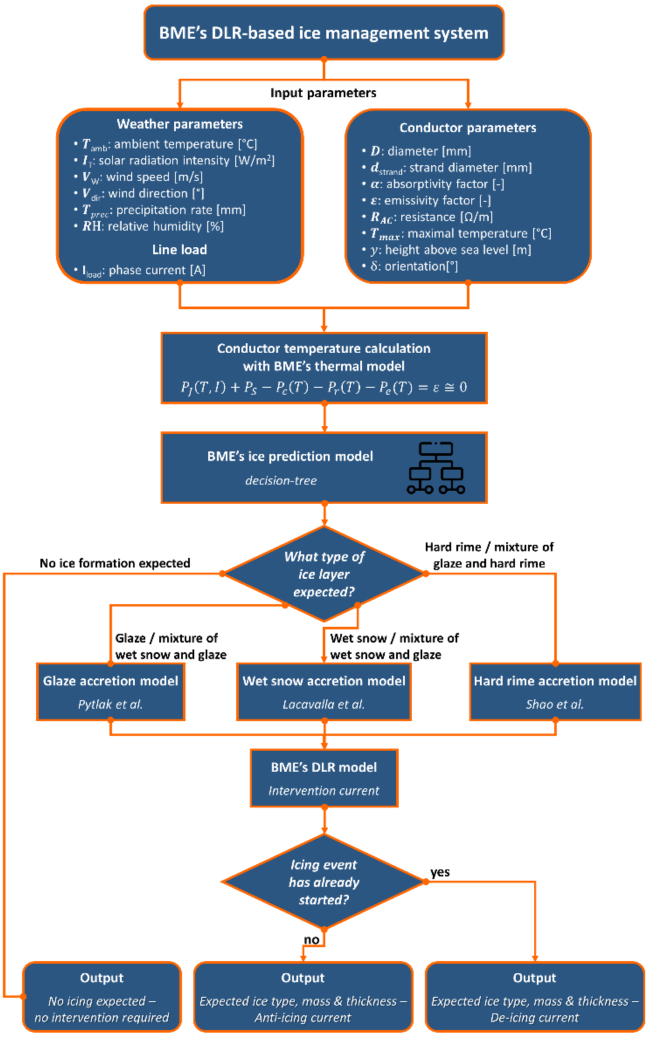

Fig. 3 Flow chart of BME's DLR-based ice management system

IV. CASE STUDIES AND INTERNATIONAL PROJECT EXPERIENCES

BME's weather-based ice prediction method and DLR-based ice management system have already been implemented at different TSO's side in the framework of FLEXITRANSTORE and FARCROSS projects. As FLEXITRANSTORE project started earlier, these project experiences only contain the results of weather-based ice-prediction model, which first outcomes are presented in [24] and [25]. For FARCROSS project, this model has been extended with the conductor temperature prediction module based on generation schedule and weather forecast, therefore offering a more reliable system with less false warnings.

A. *Operation of conductor temperature prediction module*

The operation of conductor temperature prediction module is presented on a 220 kV, single circuit Central-European line. The power line runs through a mountainous area; therefore, the environmental conditions are generally favourable for ice formation The line equipped with a 360/57 mm^2 ACSR conductor in a single bundle configuration.

Weather forecast is available for several forecast points along the line route, while two different type of line monitoring sensors and a weather station have been installed in the same span in the northern part of the line. For validation purposes, the closest weather forecast point to the measuring equipment is chosen to investigate possible icing events, which means a few hundred meters distance in practice.

According to the weather forecast, hard rime formation was possible on the line on 24-25 January 2022. The weather conditions and the expected ice formation based on only weather forecast is shown in Fig. 4.

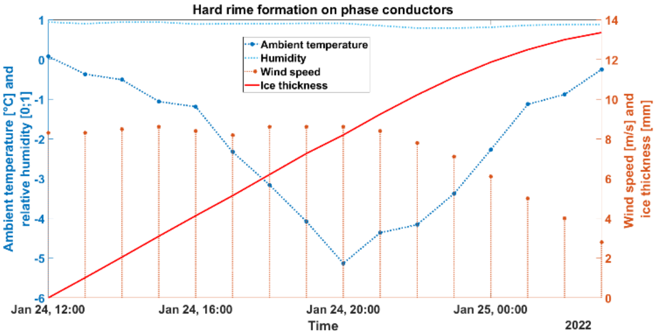

Fig. 4 Hard rime formation process based on only weather forecast

According to Fig. 4, an ice layer from hard rime is expected with 13.5 mm thickness and 1.2 kg/m mass on the phase conductors. During the expected icing event, the mean value of the ambient temperature was -2.1 °C, the total precipitation amount was 1.1 mm, and the mean value of the humidity was 88%.

By taking into account also the expected line load from generation schedule, there were two time periods, when the conductor temperature didn't reach the threshold limit of 2 °C, which is shown in Fig. 5.

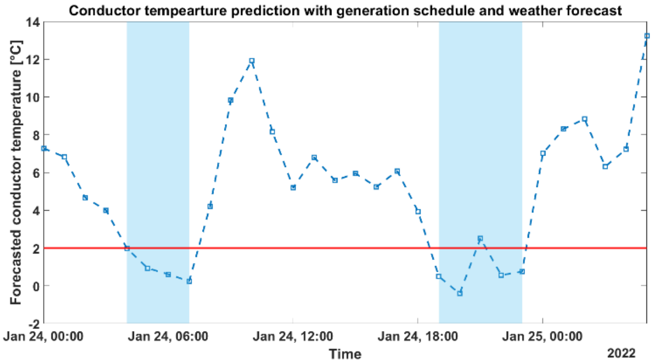

Fig. 5 Conductor temperature prediction with BME's DLR model in the case of a possible icing event

The first time period was between 04:00 and 07:00, where the mean value of the ambient temperature was -1.1 °C, the total precipitation amount was 1.2 mm, and the mean value of the humidity was 91.5%. According to the ice type classification, the ambient temperature was too high for in cloud icing, while the total amount of precipitation was too low for precipitation icing in this period, accordingly, ice deposition wasn't able to form.

During the second time interval between 19:00 and 23:00, the conductor temperature also fell under 2 °C. During this, the mean air temperature value was -4.2 °C, the total amount of precipitation was 0.2 mm, while the mean value of the relative humidity was 84%. Accordingly, in cloud icing risk was insignificant due to the relatively low humidity and time period for rime accretion.

By comparing the reliability of the weather-based ice prediction model with the extended ice prediction system, it can be stated, that the false alarms can be reduced by taking into account the forecasted conductor temperature.

On the other hand, the uncertainty of generation schedule and in this way the conductor temperature prediction also should be investigated from reliability point of view. For this purpose, the correlation between the load forecast from generation schedule and the actual measured current from the SCADA system for the same day was compared. The correlation coefficient was 92.1%, while the root mean square error (RMSE) was 38.6 A, while the mean line load was 487.4 A on this day. Accordingly, the maximal error with worst-case sum of error propagation at the 2 °C conductor temperature threshold limit is 49%, which means a high relative uncertainty, however the absolute uncertainty is only ±1 °C. In order to increase the operational safety of ice prediction system, this absolute error can be considered by setting the threshold limit of ice formation to 3 °C instead of 2 °C.

B. *Ice detection with weather-based ice prediction system*

In the case of FLEXITRANSTORE project, there were some minor icing events that were identified successfully with the weather-based ice prediction model. One of these was occurred on 6 January 2021, where the ambient temperature varied around freezing point, while precipitation fell smaller to a greater extent almost throughout the whole day. The expected ice formation process is shown in Fig. 6.

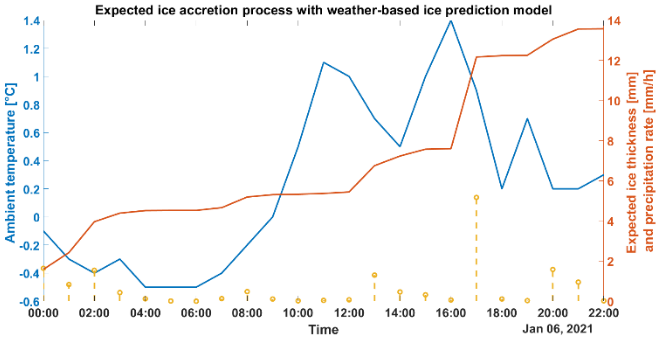

Fig. 6 Expected wet snow accretion

The real field state can be examined by using field images provided by line monitoring sensors.

Fig. 7 Real field state on 6 January 2021

Fig. 7 shows a slight layer of snow on the topside of the conductor, tower structure and jumpers. However, the real ice type looks more like dry snow, the icing event was recognized by BME's model.

C. *Performance analysis of BME's ice prediction system*

The summary of BME's ice prediction system results in 3 demo sites at different countries are presented here from international DLR projects, namely FLEXITRANSTORE and FARCROSS. In the former case, as generation schedule is not available (demo site #1), only the weather-based ice prediction model is running, while in the latter case BME's whole DLR-based ice management system is implemented at the other two demo sites (demo site #2 & demo site #3).

TABLE II. IDENTIFIED ICING EVENTS WITH BME'S ICE PREDICTION MODELS

Icing event / demo site	**No. of predicted icing events**		**No. of icing events in realty**
	Weather based model	**Extended model**	
demo site #1	5	-	2
demo site #2	0	0	0
demo site #3	4	0	0

TABLE II. presents, that there were some false warnings at demo site #1, because of the lack of generation schedule, although the icing event that de facto occurred had been identified.

No icing event was predicted for demo site #2, which is in accordance with the Mediterranean climate of the country. On the other hand, the extension of weather-based ice prediction model with conductor temperature forecast gives an opportunity for the fine-tuning of the system by reducing the number of false warnings. In these cases, however the environmental conditions are favourable for ice deposition on the phase conductors, the conductor temperature does not allow the adhesion of water droplets or snowflakes to the conductor surface. This model correction be observed at demo site #3.

V. CONCLUSIONS

Nowadays several challenges are occurring during the operation of electric transmission system, that which system operators have to cope with. For the enhanced utilization of the transmission network and protection against extreme weather conditions, Budapest University of Technology and Economics have been developed a power line management system on dynamic line rating basis.

One module of the power line management system is the DLR-based ice management unit. The ice management system uses the same input parameters as required for the DLR calculation methodology. By investigating these input variables, the possibility of an icing event can be determined. BME's model is able to distinguish three different ice types in case of an expected icing event, namely glaze, wet snow and hard rime. The system also anticipates the ice radius and its mass depending on the ice type; thus, the effective risk of the ice accretion procedure can be determined. For this purposes, international models are used. Then, the current required for thermal intervention is calculated, which can be anti-icing current or de-icing current conditional to the beginning of the icing event.

Case studies are also presented in this paper, that shows how the model is able to identify icing events. Moreover, the extension of DLR-based ice management system with conductor temperature prediction seems to be an efficient method to reduce the number of false alarms.

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