Ice Monitoring at Austrian Power Grid Status and Outlook

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Abstract— **Austrian Power Grid (APG), the main TSO of Austria, started a research project on ice monitoring on conductors of overhead lines (OHL), because ice can compromise security of supply and can damage the structure of towers. To monitor such events, an ice-sensor was developed together with the company micca and the Graz University of Technology. The main focus was to find a method to detect the beginning of icing as early as possible. Hence countermeasures can be set up more easily, e.g. de-icing or increase the awareness. After two years of successful operation, the functionality of the sensor, especially the ability to detect ice at a very early stage, is verified. APG plans to install more ice sensors with special attention on areas known for frequent icing, but also remote and alpine areas. An early identification of potential future problems with regard to climate change, changes in icing load amounts and/or frequency of events are also a target of research.**

Keywords— ***Overhead line, Monitoring, Icing, thickness of ice, early detection of ice, Transmission System Operator***

I. Introduction

Icing on conductors of overhead lines (OHL) is a well-known issue. This paper describes the approach of APG together with the Graz University of technology and the company micca regarding this topic. First off the transmission grid and the operating experience of APG with ice-monitoring is depicted. The following chapters present the development of the soft- and hardware of the ice-sensors and the. At the end an outlook of the future plans regarding ice-monitoring will be given.

II. Status of Ice Monitoring at APG

A. Topology of APGs OHL Grid

The transmission grid of APG has 3.432 km of line-route length with 12.000 towers, 64 substations and has voltage-levels of 110/220/380 kV. The main power-generation is located around the Danube river and in the eastern part of Austria. Most of the strong and steadily growing wind-generation is situated in the east. Areas with high power consumption are found in the north and east. The western part of Austria is dominated by the Alps, where the big pumped-storage hydroelectricity power plants can be found. Therefore many OHLs are located in alpine terrain.

B. Design Criteria for OHLs at APG

Principally OHLs at APG are designed to withstand the expected iceloads they are exposed to. The design parameters for iceloads are defined in standards and can be complemented by the experience of service operation considering local topographic- and environmental conditions. There are four

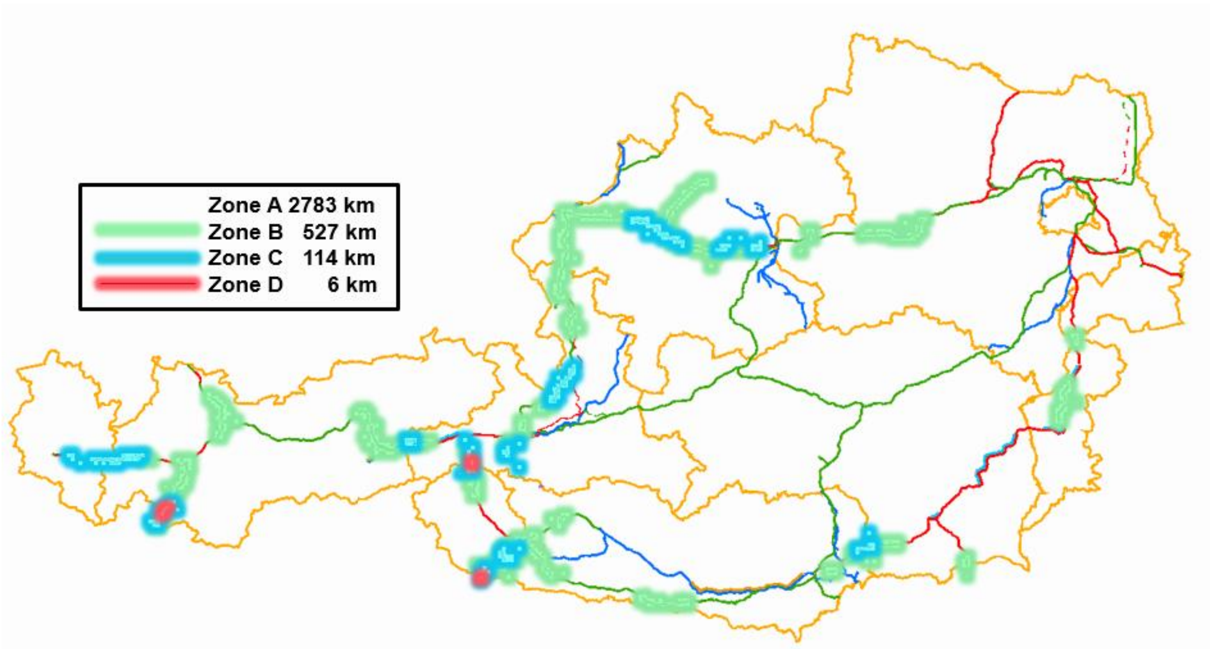

Figure 1: Iceload zones at APG´s grid

levels for standard- and exceptional iceloads defined by APG. The following list shows the values for "exceptional iceloads" per meter (sub)conductor, here given for 380kV OHL.

- Zone A: 5 kg/m
- Zone B: 7,5 kg/m
- Zone C: 10 kg/m
- Zone D: >10 kg/m

The "exceptional iceloads" depend on the voltage level. Zone A is the minimum requirement for every OHL at APG. From there on the levels rank up to zone D, which is unlimited for areas with potential extreme weather conditions, such as high mountain passes. Therefore APG only seldom has to deal with problems that are caused by icing. Figure 1 gives an overview of the iceload zones at APG.

C. Motivation for Ice Monitoring

The two main reasons for ice monitoring at APG are security of supply and person safety.

Icing can affect security of supply by reducing internal clearances, causing flashovers when ice-sleeves are dropping down from a single phase, triggering the conductor to jump up and thus getting too close to other phases or by initiating damages to structure of towers that demand an instantaneous shutoff or repair work. Especially earth wire peaks can get damaged more often by unequal ice load, as they are not heated by resistive losses of the loadflow. On rare occasions a thin ice-film in combination with high wind speed can lead to galloping, which causes high stress to all components of an OHL.

Person safety can be affected by dropping of ice-sleeves to the ground. This can endanger pedestrians or person driving with cars. Figure 2 shows an example of such a situation at a well-known icing hotspot in Austria.

Another issue is damage to foreign property caused by ice pieces (e.g. glass-houses, parked cars, roofs).

Some cases are known were the dropping of ice-sleeves on or from busbars in substations induced short circuits.

D. Current Ice Monitoring at APG

There are some known geographic areas in APG's grid with frequent icing events. Currently two lines respectively areas are monitored. One line is a 110 kV-line close to Vienna, where a neighbour, living in a critical area, has agreed by contract to inform APG about icing events. The other line is a double circuit 220 kV line with single conductors in Upper Austria close to the Danube river, which is monitored by ice-sensors. There is one sensor on each circuit of the duble circuit line. These sensors have the ability to detect icing in its earliest stage – a thickness of 1 mm ice can be measured. Additionally the base-station of the system is connected to a weather station on the nearest OHL tower, to have a plausibility check of the measured respectively computed ice-values.

Figure 2: Ice marks on the ground caused by dropped ice-sleeves

If a certain threshold of ice on the conductor is reached, the grid control center will be automatically informed by the system. It is therefore possible to set countermeasures, e.g. de-icing by changing the local grid topology to increase the electric current on the line and thus warm up the conductors.

It is not always possible to implement these measures or the effect is not strong enough to prevent icing. In this case APG personnel on site gets instructed to monitor the OHL.

In the worst case the line must be switched off and the ice has to be knocked off manually. As it is very likely, that the structure of a tower in such conditions is iced too, the climbing of the tower becomes very dangerous and thus should be the very last option. Additionally streets and areas below the OHL have to be monitored and secured from persons and traffic. This is very important, as remote controlled activities like de-icing can cause legal issues, regarding the responsibility in case that the de-icing causes big chunks of ice to drop down and potentially hit people or foreign property. Hence the approach of APG is to already react at the beginning of icing.

E. Experience and Detected Icing-Events of the ice-sensor monitored OHL

After two years of successful operation, the functionality of the sensor, especially the ability to detect ice at a very early stage, is verified. Historical data of the ice-sensor-system is stored on servers at APG and can be accessed over a web platform, which offers the options to directly examine time series with a simple dashboard or to download the data for further detailed computation. The analysis of the gathered data with a time resolution of 2 minutes shows following findings:

- Most icing events were monitored in January, there was no ice from April to September
- 25 % of the time in the winter months (October-March) there was ice on the OHL
- 90 % of continuous icing events lasted shorter than 7 hours one circuit of the line, and 10 hours for the other one. The longest continuous icing events lasted 26 respectively 54 hours.
- 90 % of icing events were observed between -5°C and +4°C with most events monitored at a mean value slightly below 0°C, following approximately a Gaussian distribution.
- Ice accretion of more than 10 mm was observed 12 % of the time relative to all icing events, see Figure 3.
- Ice dropping of more than 10 mm occurred 63 times, the value is the sum of both circuits
- There is an indication with relatively low significance, that wind speeds from 3-5 m/s stimulate ice accretion and wind speeds from 8-12 m/s decrease ice accretion
- 90 % of the time the difference between the two monitored circuits was below 7 mm

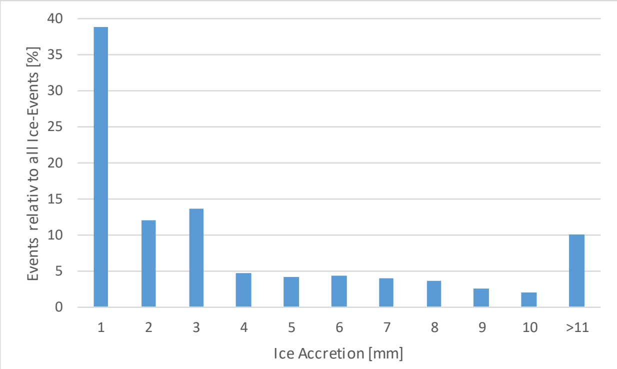

Figure 3: Ice accretion relative to all ice-events

Experience shows that de-icing by increasing the load flow is necessary 1-2 times a year and OHL. Since the introduction of the ice-monitoring sensors no further measures have been needed to de-ice OHLs (e.g. manual knock off).

III. Development of The Ice Monitoring System

F. Development and Testing of the Software Algorithm

Ice formation and accretion and the subsequent growth of a thick layer of ice on a power line cannot be reliably detected by measuring the coupling capacitance C_X between two electrodes that are galvanically isolated from the environment (see **Fehler! Verweisquelle konnte nicht gefunden werden.**), because in rain or pollution together with high humidity a capacitance C comparable to ice can be measured. A more complex electrode topology and sophisticated algorithms are necessary to distinguish ice formation and ice accretion from effects caused by humidity films or water. Figure 5 shows a framework that starts from a dry, clean sensor and in a first step can distinguish between a wet sensor and ice formation with the help of a suitable electrode topology and smart algorithms. If ice formation and accretion is reliably detected, the system switches to the ice thickness measurement state. For this, the electrodes must be further away from each other, as the electric field must penetrate deeper into the ice than during ice formation in order to measure thicker ice.

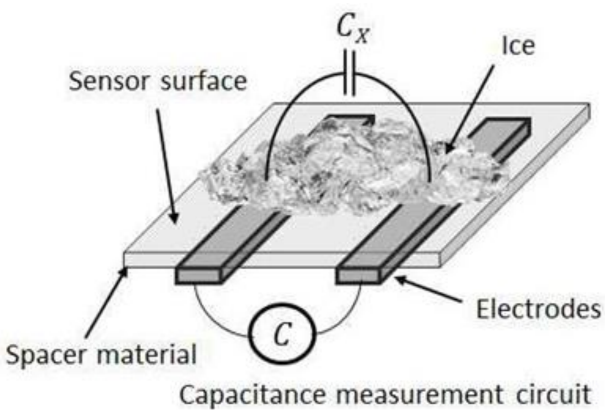

Figure 4: A spacer material and galvanic isolation protects the measuring electrodes of a capacitive sensor from the environment. Ice on the sensor surface influences the measuring Capacitance C_X between the electrodes [1].

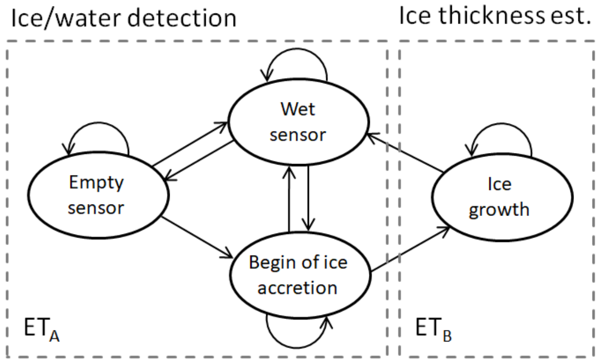

Figure 5: State transition model for the ice estimation framework [1].

If the algorithm has detected "Wet sensor" instead of "Beginning of ice accretion", it remains in this state until either the sensor dries (Empty sensor) or "Ice growth" is detected.

The state "Ice growth" can only be abandoned by melting ice or breaking down ice. In both cases, the algorithm branches to the "Begin of ice accretion "or "Wet sensor" and from there either to the "Empty sensor" or to the "Beginning of ice accretion ".

For the actual decision to perform a state transition, the concept of hidden Markov models is applied [2]. A probability measure obtained from additional information such as a temperature measurement defines the transition between the states. The assignment of these transition probabilities should be based on physical knowledge of the icing process, taking into account additional information such as meteorological data.

The distinction between ice formation (dielectric constant $\varepsilon_{r\ ice} = 3 \ldots 3.6$) and water (dielectric constant $\varepsilon_{r\ wat} = 60 \ldots 80$) is not trivial: air humidity on a cold power line can freeze into ice crystals or condense into tiny raindrops. Furthermore, the dielectric constants ε_r given only applies to clean water and ice. Furthermore, contamination significantly increases the conductivity of the water or ice and can lead to misinterpretations.

Ice formation, condensation and contamination are stochastic and spatially distributed processes on the measuring electrodes. The algorithm is thus based on statistical signal processing. The problem of pollution can be mitigated by synchronous rectification and four quadrant demodulation, but not completely eliminated, since the processes described are spatially distributed stochastic processes.

To estimate the ice thickness in the "Begin of ice accretion" state of the state transition scheme shown in Figure 5, a model-based estimator derived from the Bayes Law is used. With this formulation, the ice thickness can be estimated by means of an optimization problem, i.e. maximizing the likelihood function.

A further feature of the algorithm used is the consideration of the time course of the measurement signals. For example, condensing water or rain on the electrode surfaces must cause a greater variance of the measurement signal than, for example, the growth of a thin layer of ice.

Figure 6 shows the results for the estimation of the ice thickness of a capacitive ice sensor for overhead power lines with the presented algorithm in a climate chamber. The sensor

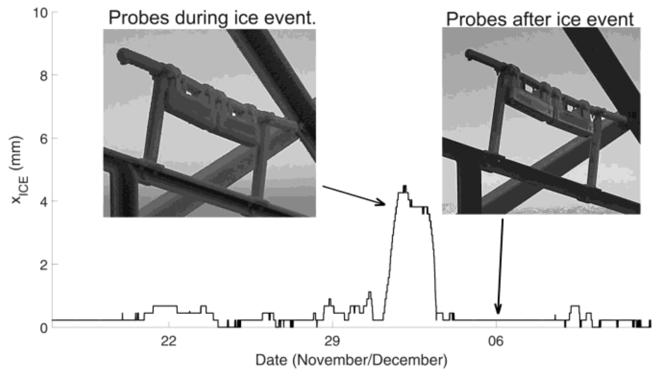

Figure 6: Measured ice thickness on a power line wire during a field experiment (November to December). The pictures show the sensor during and after the ice event [1].

consists of a ceramic composite material that holds the electrodes. The ceramic composite material seals the electrodes against moisture. The sensor surface is coated to prevent contamination and improve cleaning in rainy weather.

Figure 6 shows an extract from a field test of two ice sensors in which the estimated ice thickness over a period of several days including a significant ice event is illustrated by the photos taken during and after the ice event. The two photos, the data from the weather station and the personnel on the test site confirm the ice measurement results. The two-year duration of the field experiment also made it possible to investigate the long-term behaviour of the probes. During fair weather periods, which could be identified from the data of the weather station, the sensor readings were compared. No drift could be detected in the corresponding data, which proves that no contamination effects occurred in the two

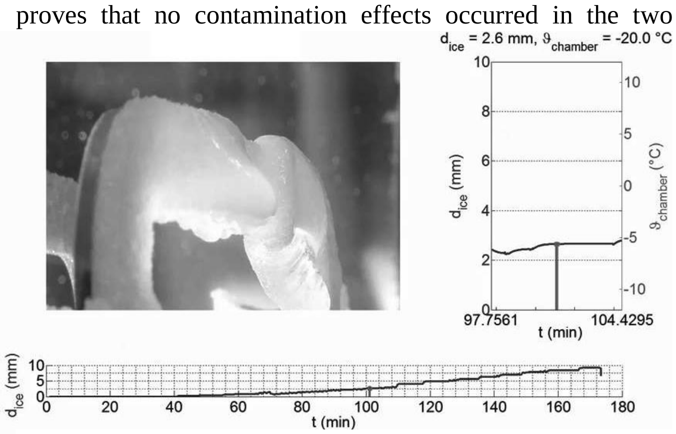

Figure 7: Experiment on ice estimation in a climate chamber. The small diagram to the right of the picture shows the trend of ice thickness and temperature in the chamber. The diagram below shows the estimated ice thickness for the whole experiment [1].

sensors over the test period of 2 years.

G. Ice Accretion Measurement:

The overall monitoring system is structured in three parts:

- Sensors on site on the conductors
- Multichannel datalogger and long haul communication
- Data platform

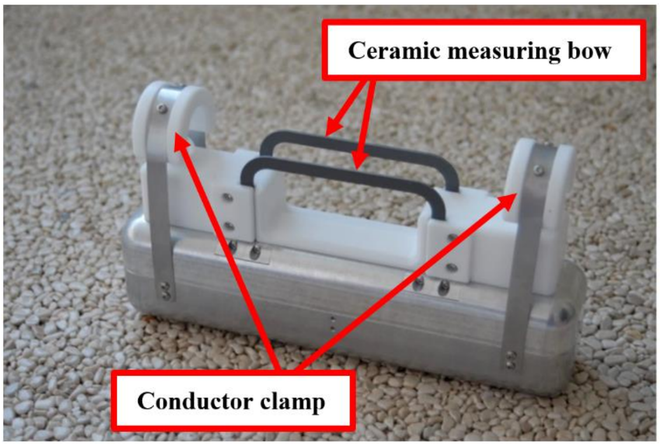

Figure 8: Ice sensor with ceramic measuring bow

The task was to integrate the ice measurement in the already existing concept used by the company's dynamic line rating (DLR)-sensors. Thus the application method to the conductor as well as the energy supply (LiIon battery in the sensor body) of the sensor corresponds with the existent system and used components of that monitoring system. The ice sensor is pictured in Figure 8**Fehler! Verweisquelle konnte nicht gefunden werden.**.

Physical measurement is done by two ceramic bows (one on each side of the conductor), whereat each one contains 1 exciter and 4 responding measuring channels. The obtained capacity measurement values are then send to a base station, which is mounted to the structure of a neighbouring tower and from there send to a server via GSM. At the server the values get computed and can be obtained over an online platform. The given results on the platform are:

- Ice Thickness
- Probability of icing
- Confidentiality of thickness information

The calculation method itself is based on relatively diminutive changes in capacitance and doesn't rely on absolute values. Water (melting ice layers, rain and drying water) can be clearly distinguished from solid ice. For additionally verification the algorithm uses the line temperature.

The minimum measuring time is set to 1 minute as ice can arise within short periods under certain meteorological conditions (humidity, wind, temperatures around 0° C).

Mandatory for trustable results is the repeatability of measurements. Therefore each individual sensor has to pass a calibration procedure using a climate chamber, see Figure 9. The default values have to be very stable and are used as reference values in the algorithm.

The most challenging part of the development path was to achieve the required stability of these reference values. Thus the sensor bow attachment to the sensor body has to be absolutely dense and water proof. To use silicon as a sealing is not possible as this material ages significantly over time and loses impermeability. It took quite a long time to qualify the right sealing material. To bond the wires between the bow and the datalogger, hand crafting is required. The procedure is comparable with handmade soldering on SMT components.

The achieved results in the field trial and more important in reference installations gave evidence of the reliability and confidentiality of the system.

Figure 9: Ice sensor test in an icetunnel, University of Quebec, Chicoutimi

In a further development step it is foreseeable that the used method will also give indication of ice quality based on the liquid water content. If this further step will be followed is determined by the acceptance in the market.

IV. Conclusion and Future Outlook

APG has a very positive experience with the monitoring system that was established in 2017. Based on the successful operation in the last years, APG plans to install more ice sensors with special attention on areas known for frequent icing, but also in remote and alpine areas, where by now only sparse information about the local icing characteristics exists. An early detection of possible future problems with regard to climate change, possible changes in icing load amounts and/or frequencies of ice events are also targets of the research efforts by APG. The knowledge gattered by a denser monitoring of icing within APGs grid can potentially be used to revise the design criteria's for OHL in certain areas or to adapt de-icing measures for specific OHLs.

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