Monitoring, measurements and mitigation for wet snow accretion on overhead conductors

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Abstract— **The accretion of wet snow sleeves on overhead conductors represents the main cause of electric outages to be faced by TSO and DSO in Italy. RSE has developed a weather forecast system named Wet-snow Overload aLert and Forecast (WOLF) able to provide, 72-hours ahead, the snow loads on the entire HV grid together with the estimation of anti-icing currents in the expected weather conditions. Furthermore, an experimental activity for monitoring wet snow accretion on conductors is underway at the test site Wet-snow Ice Laboratory Detection (WILD), realized by RSE. The station allows to fine-tune the accretion model parameterization and to verify the thermal anti-icing model in wet snow conditions. Liquid Water Content (LWC) measurements of wet snow have been collected. LWC data are useful to estimate the growth limits and the shedding conditions of sleeves. A comparison among conductors coated with different ice-phobic materials is in progress. Ice-phobic coatings for conductors may contribute to alleviate the threat for the overhead lines and different stakeholders have shown interest on the matter, with special reference to TERNA (the Italian TSO). Some experiments are being carried out involving also conductor's manufacturers. This experimentation is an important test to get a selection of ice-phobic coating to be applied for testing on operative HV lines, in areas exposed to wet-snow risk. In Veneto region, in collaboration with the TSO, three spans of ground wire treated with different coatings have been installed on the 132 kV line, and their performances have been assessed qualitatively. The ongoing experimental activities are also aimed at measuring the snow sleeve load on MV spans in collaboration with the DSO e-distribuzione. Three sites with different climatic situations have been chosen to monitor the snow load on different diameters of MV conductors. The purpose is threefold: i. to validate an accretion model on a real span, ii. to compare the accretion among conductors of various diameter, iii. to integrate real time sleeve measurements with the system WOLF. All the snow load measurements will be useful to validate the accretion model employed for the revision of the Italian ice map of the NNA (CEI-EN-50341-2-13) for the mechanical design of power lines.**

Keywords— ***wet snow accretion, wet snow forecast system, anti-icing current, ice-phobic coatings, resilience***

I. INTRODUCTION

The interaction between extreme meteorological phenomena and the electric system is a relevant issue for the Operators. Severe weather events are responsible of prolonged electric blackouts for the users, but also the high costs of reimbursement for the energy not supplied and the restoration costs of the infrastructures are not negligible.

Among these phenomena, wet snowfalls events are increasing in Italy [1] causing the formation of snow sleeves over conductors (Fig. 1), thus representing the main criticality for the transmission and distribution network. As an example, in February 2012, 125,000 users were affected by power outages during an important wet snowfall in central Italy. Subsequently, an escalation of similar events culminated on January 2017 with a heavy snowfall on Abruzzo and Marche regions, with an accumulation at ground of up to 3m and sleeve loads over conductors of 15 kg/m in areas where the design criteria did not exceed 5 kg/m at most. During this event, a peak of over 300,000 users without energy for more than 8 hours and a Loss Of Load (LOL) of 843 MWh took place, giving rise a reimbursement estimated by the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) in 40M€ [2].

Electric operators are aware that to safely manage the power grid during adverse weather conditions, it is not possible to focus only on the robustness of the line, but it is necessary to predict events and to use both active and passive mitigation strategies that maximize the resilience of the electrical system.

Fig. 1 - sleeve formation over MV conductor

RSE is addressing the issue of extreme snowfall events through specific monitoring and experimental activities in order to develop innovative forecasting and alert systems, evaluating the most appropriate mitigation solutions for the transmission and distribution network.

II. EXPERIMENTAL ACTIVITIES AT THE WILD STATION

Since 2013 an automated monitoring station named WILD [3] is operating in the Western Alps of Italy at 950 m asl. The WILD station is the unique one in Italy devoted to the study of the wet-snow effects over conductors. The WILD capability to aggregate unconventional totally ice-free weather measurements, accretion data and web-camera pictures during the wet-snow events, constitutes a platform for studying and developing active and passive solutions to mitigate the sleeve formation on conductors. Some of these experiences are presented below.

A. Monitoring of wet snow accretion

A quantitative monitoring over a 3m length ACSR ø31.5mm conductor placed in slow rotation is available, as requested from the standard ISO12494 [4]. The conductor is continuously weighted by load cells, and a pair of ultrasonic sensors provide the thickness of the sleeve accretion, as shown in Fig. 2.

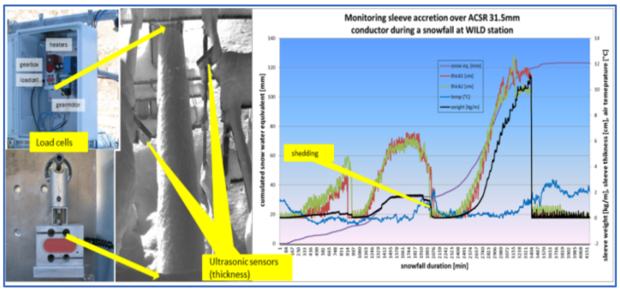

Fig. 2- monitoring sleeve accretion over an ACSR ø31.5mm conductor

This experience, together with meteorological measurements and snowflakes falling speed coming from a disdrometer, allowed to fine-tune the accretion model parameters [5][6][7] employed in the forecast system Wet-snow Overload aLert and Forecast (WOLF), developed by RSE [8].

B. Monitoring and validation of the anti-icing thermal model

Different thermal models to estimate the temperature of a conductor subject to the Joule effect are available. However, in snowfall conditions, and as preventive method to avoid sleeve formations, the heat necessary to melt the flakes should be considered. The thermal model proposed by Shurig and Frick [9] has been used and modified by adding the thermal contribution to maintain the conductor free from snow accretion, and the heat balance equation in steady state and snow conditions is given by (1):

$$P_j + P_s = P_r + P_c + P_w \quad (1)$$

where P_j is the Joule heating due to current flow, P_s is the solar radiation heating (negligible), P_r is the radiative cooling, P_c is the loss for convective cooling and P_w is the cooling term due to the snow heat of fusion. An automatic low voltage circuit, able to maintain the skin conductors temperature at 1°C, 1.5°C and 2°C as shown in Fig. 3(left), allowed to analyse the power supplied for each conductor depending on the meteorological variables gathered by the station. From the tests, it was noticed that a skin temperature close to 1.5°C is optimal and not expensive in terms of energy, while 1°C seems critical to prevent snow formations. It was possible to isolate the term P_w as function of the Water Equivalent Snow Rate (wesr) and formulate the equation (2):

$$P_w[W/cm^2] = 0.0022 * \ln(wesr) + 0.0039 \quad (2)$$

where P_w is expressed for surface unit. The anti-icing current can be expressed as:

$$AI = 5.6 * \sqrt{\frac{(P_r + P_c + P_w - P_s) * 10^4 * D}{R_T}} \quad (3)$$

where:

- D is the diameter of conductor (m)
- R_T is the resistance (Ohm/km at T=0°C)

As an example, referring to Fig. 3 (red circles for AI current and power), for a conductor ACSR ø31.5mm at T_a 0°C (i.e. 2-m air temperature), wesr 5mm/h, T_{surf} 1.5°C and wind speed 5m/s, 500A or 13W/m of Joule power are required to keep the conductor ice-free.

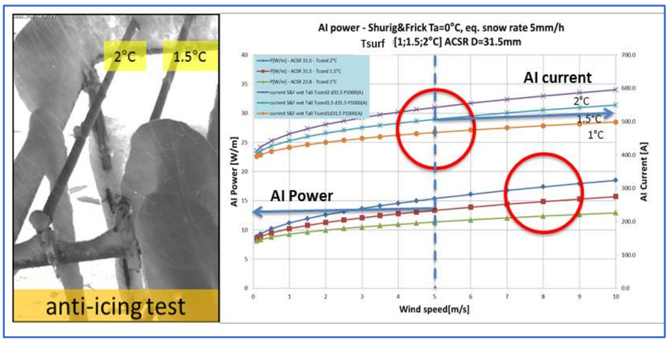

Fig. 3 – anti-icing outdoor test (left), anti-icing power and current curve for different skin temperature ($T_{surf=}$1°C,1.5°C,2°C) at 5mm/h of wesr and function of wind speed (right)

The anti-icing thermal model has been inserted in the system WOLF, in order to provide the Electric Operators with anti-icing current to support the use of active mitigation strategies.

C. Monitoring and performance evaluations of ice-phobic coatings for conductors

During the winter season the station hosts a comparison among different conductors treated with ice-phobic coatings developed at the RSE's laboratories, coming from commercial solutions or from conductor's manufacturers. The purpose is to assign the most promising treatments to an experimentation on operational lines. The comparison involves up to six 15 m spans and four slots hosting some specimens of ACSR ø31.5mm conductor. The conductors are installed on a slow rotating systems, able to turn them around every 30'. The complete setup for the last winter campaign is shown in Fig. 4 and Fig. 5.

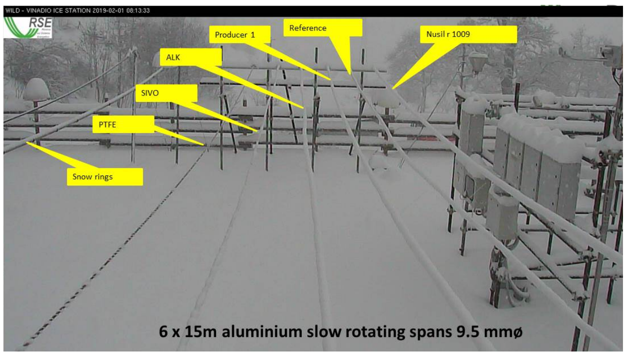

Fig. 4 - test of ACSR coated spans and snow rings

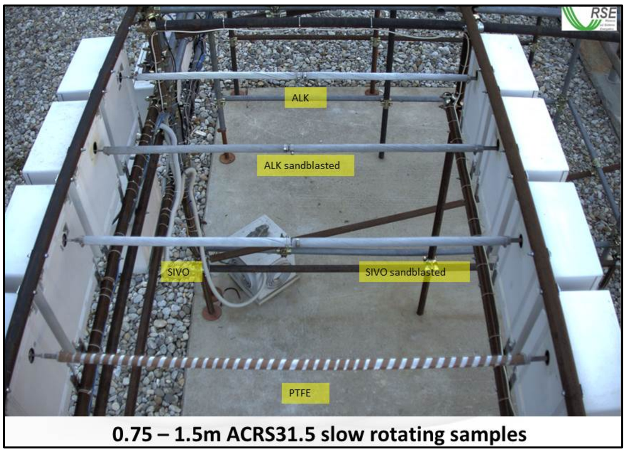

Fig. 5 - test of ACSR 31.5 mm coated specimens

Table I summarizes the surface coatings tested during the last winter campaign and the specimens type.

TABLE I. SAMPLES DEPLOYMENT FOR THE LAST WINTER CAMPAIGN AT VINADIO SITE

Progr.	*Type*	*Coating*
1	*15m span ø9.5mm*	*Reference*
2	*15m span ø9.5mm*	*NuSil r-1009, mildly hydrophobic*
3	*15m span ø11.5mm*	*Producer1*
4	*15m span ø9.5mm*	*ALK[1] over sandblasted surface, mildly hydrophobic*
5	*15m span ø9.5mm*	*SIVO[2] over sandblasted surface, super-hydrophobic*
6	*15m span ø9.5mm*	*PTFE over fiberglass tape, spiral mounted, mildly hydrophobic [15]*
7	*1x3m ø31.5mm*	*Reference*
8	*2x0.75m ø31.5mm*	*ALK over smooth surface*
9	*2x0.75m ø31.5mm*	*ALK over sandblasted surface*
10	*1x0.75m ø31.5mm*	*SIVO over sandblasted surface*
11	*1x0.75m ø31.5mm*	*SIVO over shot-blast surface*
12	*1x1.5m ø31.5mm*	*PTFE over spiral fiberglass*
13	*1x1.5m ø31.5mm*	*Producer2*

The performances of each coating are assessed qualitatively with respect to the reference uncoated one by analysing the 15' images coming from different cameras, and correlating the results with the characteristics of the snowfall. Acquired data and images allowed to establish some criteria by which to evaluate the response of the coatings, and to retrieve several feedback elements useful for their development:

- the time delay in the first snow film formation over the conductor. Delaying this stage allows to significantly reduce the maximum sleeve load accretion at the end of the event.
- the early shedding of the sleeve from the conductors. Anticipating this stage means to mitigate the sleeve load over the lines during the event.

By the application of these criteria to the observation carried out in three years of testing it was possible to divide the most effective coatings into two groups:

- coatings able to delay or inhibit the snow accumulation at air temperatures below 0 °C and dry snow conditions with very low LWC (super-hydrophobic coatings like SIVO, Producer2).
- Coatings able to facilitate the sleeve detachment at temperatures greater than 0 °C in wet snow conditions (moderately hydrophobic coatings like NuSil, PTFE, ALK, Producer1).

The division into two groups is closely linked to the type of snowfall (dry or wet), even if it does not emerge a well-defined behavior around 0°C for both groups. A deepening of results of the comparison conducted during the last winter seasons is shown in the paper “A comparison of anti-ice and anti-snow coatings performances: laboratory and field testing” [14].

D. *Snow rings and wet snow sleeves*

Snow sleeves can rotate over conductor surface if the snowfall is characterized by high LWC and density even if the conductor is heavily tightened as shown in Fig. 6 (left).

Fig. 6 - sleeve rotation over conductor (left), snow rings on ACSR 31.5 conductor (right)

At the WILD station, a sleeve rotation over conductor was noticed during two distinct wet snowfall events of the winter season 2017-2018. During these episodes the temperature remained above 0°C and the density of fresh snow was more than $300kg/m^3$. In order to avoid these effects, for the winter season 2018-2019 a series of snow rings have been installed every 70 cm over the conductor, as shown in **Fig. 6** (right), to assess their ability to reduce the sleeve formations. No evidences were obtained during last winter due to the lack of wet snowfall events.

E. *LWC measurements*

The sleeve accretion over conductors is strongly influenced by the LWC of the snowflakes. The CIGRE TB 438 [10] indicates a mass percentage range of LWC between 10 and 40% for the sleeve accretion. Below this range a sleeve cannot grow significantly, while above it the snowflakes lose their adhesive and cohesive capabilities. Also the shedding phase is affected by the LWC.

[1] ice-phobic coating with functionalized alkylated siloxane (Evonik ®Dynasilan)

[2] ice-phobic coating with functionalized fluorinated siloxane (Evonik Dynasilan ®SIVO CLEAR)

The LWC measurements of fresh snow and inside the sleeves would allow to establish a correlation with the mass accretion, and the critical values for the detachment phase. So far, calorimetric methods have been used to estimate the LWC of sleeves [11], but the authors themselves hope in non-destructive approach to measure the LWC. During 2018 RSE acquired a "Snow Fork" (i.e., a non-invasive instrument already used in avalanche studies [12] to measure the water contained in the snowpack). The Snow Fork, produced by TOIKKA (Finland), is able to deduce the volume percentage of LWC and the density through the accurate measurement of the dielectric constant of the snow. To obtain the LWC mass percentage the following relation is used (4):

$$LWCmass[\%] = \frac{LWCvolume[\%]}{density[\frac{g}{cm^3}]} \quad (4)$$

The mass of water contained inside the snow pack is obtained by the relation (5):

$$LWC[\frac{g}{cm^3}] = density[\frac{g}{cm^3}] * \frac{LWCmass[\%]}{100} \quad (5)$$

Unfortunately the lack of snowfalls during last winter didn't allow to carry out a campaign to measure the LWC inside the sleeves at the WILD station. An example of LWC comparison between a calorimetric method and the Snow Fork, performed in a climate chamber able to produce a snowfall, is shown in Fig. 7:

Stage	LWC vol [%] Snow Fork	Density [kg/m3] Snow Fork	LWC mass [%] Snow Fork	LWC mass [%] calorimeter
1	2.70%	300	9.00%	7.40%
2	4.80%	380	12.60%	15.80%
3	0.40%	204	1.80%	4.40%
4	3.80%	260	14.60%	12.50%
5	5.50%	180	30%	32%

Fig. 7 – LWC comparison between snow fork and calorimeter

The Snow Fork is shown in Fig. 8 during the first snowpack tests.

Fig. 8 – Snow Fork employed in snowpack tests

III. TEST UNDER IN-SERVICE OF ICE-PHOBIC COATINGS

A collaboration is underway involving TERNA and some of the major technology providers for overhead lines, with the aim of testing the coatings that are gradually available at the WILD station, and assigning the most promising treatments to an experimentation on operational lines. An example is the experience started at Malga Ciapela site (1450 m aslm, province of Belluno), with the installation of three ice-phobic Ground Wires (GWs). An experimental campaign has been started after the installation with the aim of evaluating qualitatively, having not yet installed load cells, the performances of the coated GWs with respect to an uncoated one. An overview of the Malga Ciapela test site is shown in Fig. 9. A couple of cameras, scheduled to take pictures every 15', allow to assess the delay in the first deposit formation or the early detachment of the sleeve with respect to the uncoated one.

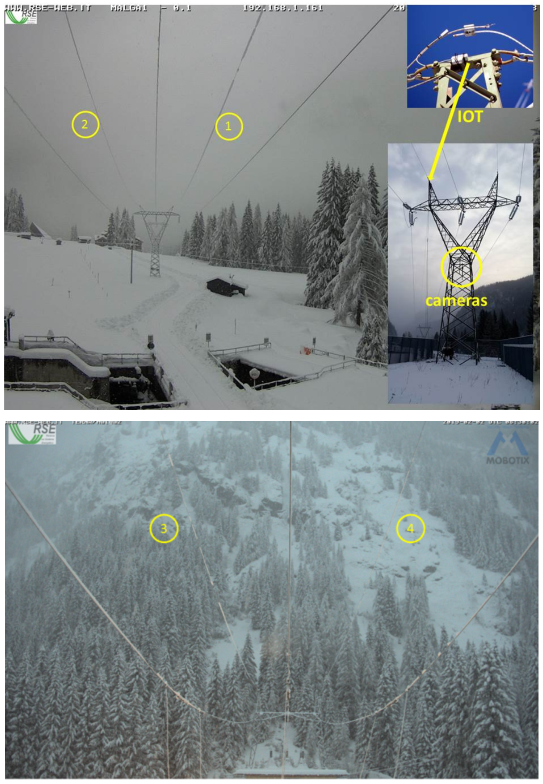

Fig. 9 - experimental setup of GW at Malga Ciapela site

Referring to Fig. 9, the experimental setup of the winter campaign is shown in the following table.

TABLE II. EXEPERIMENTAL SETUP OF GROUND WIRES AT MALGA CIAPELA SITE

Span	*Coating*	*Diameter*	*Length*
1	*Uncoated, reference*	*9.5mm*	*140 m*
2	*Producer1*	*11.5 mm*	*140 m*
3	*ALK*	*9.5 mm*	*80 m*
4	*SIVO*	*9.5 mm*	*80 m*

A. Performances evaluation of ice-phobic coatings for conductors

During the last winter, in the Eastern Alps there was a lack of snowfalls and only two massive events allowed to analyse the response of the coatings (1-3 February 2019 and 4-5 April 2019). The behaviour of the GW during the snowfall occurred on 4-5 April 2019, in terms of sleeve coverage, is shown in Fig. 10. The coverage of GWs due to sleeve formation is expressed in ten levels from 0 (no coverage) to 1 (total coverage), deduced by analyzing the 15' camera images. It is noticed that during the snowfall the 2-m temperature was between 0 and 0.2°C, the GWs temperature remained at -0.2°C, the snow rate considerable and the total water equivalent was 75mm. The coated GWs performed better than the uncoated one, especially after 6 hours from the beginning, where SIVO delayed in a considerable way the accretion event though the eq. snow rate was over 6mm/h. Also ALK and Producer1 performed well, showing an early detachment if compared to the uncoated reference.

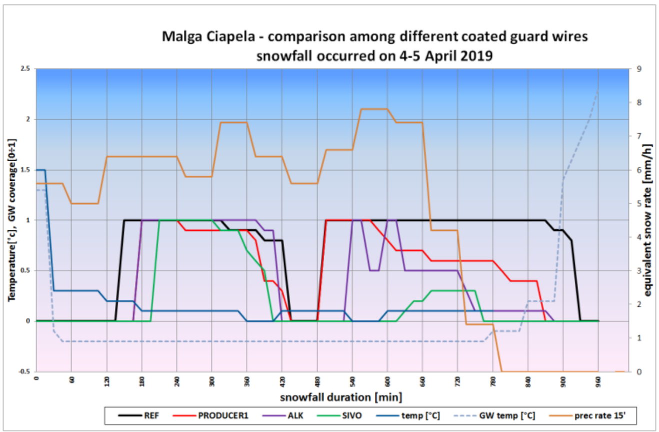

Fig. 10 - sleeve coverage trend over coated GWs during the snowfall event as function of eq. precipitation, air temperature and GWs temperature at Malga Ciapela site.

To translate what was observed, the single steps coverage observations for each GW have been integrated, and a coverage coefficient was obtained. Normalizing it with respect to the value obtained for the reference GW, a first indication of the mitigation introduced by the coatings could be estimated for this event. For the described snowfall event, the following table provides the coverage coefficient and the mitigation obtained for each coated GW. The mitigation coefficient is obtained as a difference between the unitary normalized coverage for the reference GW and the same value estimated for the coated GW.

TABLE III. RESULTS OF SLEEVE COVERAGE AND MITIGATION COEFFICIENT FOR EACH GW AT MALGA CIAPELA SITE

Results	Ref	Producer1	ALK	SIVO
coverage coeff	*46.6*	*31.5*	*25.5*	*13.8*
normalized coverage coeff	*1.00*	*0.68*	*0.55*	*0.30*
mitigation coefficient	**0**	**0.32**	**0.45**	**0.7**

A deepening of results of the comparison conducted in the last winter seasons is shown in the paper "A comparison of anti-ice and anti-snow coatings performances: laboratory and field testing" [14].

B. *IOT sensors*

A pair of IoT LORA sensors have been installed during the stringing phase of the GWs, as shown in Fig. 9. Temperature of the GWs and humidity are gathered every 15', and are very useful to evaluate the response of the coatings during the snowfall events. Fig. 10 shows the reference GW temperature during the snowfall event occurred on 4-5 April 2019. A series of low cost IoT inclinometers could be soon installed over the GWs in order to measure the slope due to the sleeve formation during snowfall events and to estimate the mitigation effects introduced by the coatings.

IV. MONITORING SLEEVE ACCRETION ON MV SPANS

In order to fine-tune the accretion model employed in the WOLF system, an experimental activity is being started in collaboration with the Italian DSO with the aim of measuring the snow load on MV spans. Three sites, characterized by a different climatology in North, Centre and South of Italy have been chosen for this experience by using a frequency map of wet snowfall days updated to 2018. In each site a 80-100m length test span equipped with three MV conductors of different diameter is being installed together with a meteorological stations, totally ice-free, and cameras. The wet snow load, measured by load cells, is an important element of feedback that RSE wants to integrate into the alert system WOLF as forecast trigger. Data coming from load cells together with a new high resolution MEteorological Reanalysis Italian DAtaset (MERIDA [13]) will be useful to validate the accretion model employed for the revision of the Italian wet-snow map of the NNA (CEI-EN-50341-2-13) for the mechanical design of power lines. The comparison of the accretion on different conductor's diameters is also an interesting information. A list of experimental sites, real time acquired measurements and employed conductors is shown in the following table.

TABLE IV. EXPERIMENTAL SITES AND MONITORING EXEPERIENCES

SITE	***MEASUREMENTS***	***CONDUCTORS***
Frabosa Sottana - Maritime Alps - 950 m aslm	*Snow load, wind, temperature, humidity, precipitation, pressure, pictures*	*CU35 ø7.5 mm* *CU70 ø10.8 mm* *AA150 ø15.9 mm*
Isola del Gran Sasso- Central Apennines – 500 m aslm		*CU25 ø6.4 mm* *CU35 ø7.5 mm* *CU70 ø10.8 mm*
Cecita – Southern Apennines – 1200 m aslm		*CU16 ø4.5 mm* *CU25 ø6.4 mm* *CU35 ø7.5 mm*

V. CONCLUSIONS AND FUTURE DEVELOPMENT

A detailed monitoring of wet snowfalls and their effects over conductors is a way to obtain helpful information to address the problem of sleeve accretion. This knowledge allowed to develop the alert system WOLF and to study active and passive mitigation strategies, and working closely with electric operators is very important at this aim.

TERNA is active in promoting the develop of solutions to mitigate the problems caused by wet snow on the OHTL and to make its assets and personnel available for testing new techniques and new materials. The collaborations with RSE and Italian conductor's manufacturers on the coatings topic is an example of this.

e-distribuzione is also interested in monitoring the sleeve formations on different MV conductors in three Italian climatic situations, and the experiences achieved at the WILD station can be very useful.

Interesting results come from the field test of coatings for conductors and GWs. A first evaluation of their behavior in different snowfall conditions was possible through the winter campaigns carried out at the WILD station and at the Malga Ciapela site. At the WILD station super-hydrophobic coatings, like SIVO, perform better in dry snow conditions delaying the snow accretion, while the mildly hydrophobic ones seem to promote the early shedding in wet snow. Instead, on operative GWs lines at the Malga Ciapela site, SIVO perform well also in the detachment phase during the two significant events occurred. However a larger series of events is required, especially of wet snow, to define with greater certainty the mitigation induced by the coatings tested in both places.

LWC measurements in fresh snow and inside the sleeves at the WILD station will be very useful in order to introduce this parameter in a semi-empirical shedding model based on forecasted weather variables correlated to LWC.

IoT technology is beginning to be used on OHL spans and could constitute the future basis for monitoring snow sleeves formation on the lines.

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