THE WOLF SYSTEM: FORECASTING WET-SNOW LOADS ON POWER LINES IN ITALY

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Abstract: The purpose of the system named WOLF (**W**et-snow **O**verload a**L**ert and **F**orecasting) is to provide the ice load on overhead lines during wet-snow events and, sufficiently in advance, to alert the Italian TSO to take appropriate preventive measures and dispatching. The system is based on the outputs of a Numerical Weather Prediction model (NWP) with horizontal resolution of 5 x 5 km, and the forecast is valid for the next 72 hours. The outputs of the NWP feed an ice accretion model, assuming a conservative growth of the sleeve on a cylindrical conductor. The grid of meteorological model is intersected with the path of the Italian transmission lines, so as to obtain for each point of the model, the information regarding to the characteristics of power lines (type of conductor, sections and diameters). The WOLF output is presented to the user on a WEB-GIS allows to display the alert points on several specific thematic layers as paths of power lines, cabins, cartography, DEM, etc.

WOLF provides, for every grid-point, a chart where the time-development of the principal weather forecasted variables is represented, as the air temperature, precipitation amount, wind intensity and its direction. The ice-sleeve growth on conductors, in terms of ice load and thickness, is represented too. For each lines, affected by wet-snow, the anti-icing current is computed by a literature model where the Joule power is dissipated considering the convection and radiation terms. The system also provides the possibility to send an alert message via SMS, whenever the value of ice load exceeds the alert threshold of 5 Kg/m on a specific monitored area. SMS shows the number of points in alarm for each monitored area and the altitudes where the phenomenon is expected. In order to test the WOLF forecasts, mobile field campaigns were organized and some collected data have been used to compare the outputs of ice models. An innovative prototype ice-station has been developed and tests are underway.

1. INTRODUCTION

The overload of ice and snow on overhead power lines is still the principal cause of "major power outages" during the winter season in Italy. The impact of this phenomenon leads to a decrease of the quality of the transmission service and, in some cases, it can also determine serious security problems in the performance of that activity. The algorithm provides an estimate of ice load and thickness of sleeves on wires, calculated using a model of growth [1] [2] [3]. If the alert level is exceed, the system sends an SMS to the referent of the monitored area. Furthermore, the code calculates, through a mathematical model, the minimum anti-icing current on those conductors which is expected the ice accretion. All the outputs of the models have been reported in a user-friendly WEB-GIS tool.

2. RESULTS AND DISCUSSION

The outputs of WOLF have been tested on real electrical disruptions due to wet-snow occurred in Italy. The results in Tab. 1 show that, for all accidents, the system was able to predict the phenomenon and to send alerts two days in advance.

Tab. 1: Major power outages in Italy in the last 2 winter seasons.

Date	**Power outages**		
(gg.mm.aaaa)	Region	Failure	WOLF Alert
01.12.2008	Lombardy Trentino	Tower collapse	Yes
13.12.2008 15.12.2008	Piedmont	Several black outs	Yes
28.04.2009	Valle d'Aosta	Conductor rupture	Yes
10.03.2010	Emilia Romagna	Prolonged power outages	Yes

The preliminary results of experimental campaigns highlight the complexity of sleeve's growth, in which are involved several physical processes. In particular, the critical role of accretion coefficients that greatly vary for little temperature variations across 0°C. Another important factor is the observed ice-shedding that is not considered in the algorithm, and will be subject to further investigations.

3. CONCLUSION

This paper presents a forecast system (WOLF) able to compute ice-accretion on overhead power lines, due to wet-snow. The system provides alarms and displays meteorological and power lines information on an easy GIS interface. WOLF is devoted to the power grid managers that can adopt defence strategies to reduce the effect of possible accidents. In the future, the authors plan to improve the WOLF algorithm introducing more accurate accretion and shedding parameters, by using additional data from the new ice-station.

4. REFERENCE

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key words: wet-snow load, power outages, alert system, anti-icing current.

I. INTRODUCTION

The overload of ice and snow on overhead power lines is still the principal cause of "major power outages" during the winter season in Italy, as reported by TERNA, the Italian TSO [1].

The impact of this phenomenon, leads to a decrease of the quality of the transmission service and, in some cases, it can also determine serious security problems in the performance of that activity [2]. In some cases, as shown in Fig. 1, the ice overloads on wires cause the breakdown of tower lattice.

Fig. 1: lattice tower fell down, due to overload ice on conductors (Puglia; 1995, Italy).

In many Countries, a wide variety of anti-icing techniques have been adopted to prevent the ice formation on conductors [3]; dispatching activities based on weather forecasting have been used too [4] [5] [6]. In Italy, no particular techniques are exploited, except for a 132 kV power line in Valle Stura (Piedmont region), on which counterweights have been mounted. This solution has demonstrated the capability to reduce ice load, blocking the rotation of conductors but, at present, it cannot be proposed for the whole grid. The weather forecast remains the only solution to reduce the total damage in case of ice, diminishing the number of outages by means of dispatching actions.

WOLF wants to solve the need of a forecast system, focused on the grid management and, at the same time, to fill the gap in the Italian icing research. In fact, WOLF can be also used to better investigate the phenomenon of wet-snow and the processes involved into ice accretion, together with the collection of experimental data.

In this paper, the authors present the current version of WOLF, implemented after preliminary experiments with the first release [7].

II. WOLF PROCEDURE

WOLF aims to forecast the wet-snow conditions favorable for ice accretion on overhead power lines in Italy. The algorithm also provides an estimate of the ice mass and the sleeve thickness on conductors, calculated by using an accretion model [8] [9] [10].

Every day, the ice-load hazard level is plotted on a WEB-GIS map, easily accessible to operators of power lines. WOLF integrates an accretion model, an interface for the forecasted data and a GIS display system. A scheme of the algorithm is shown in Fig. 2.

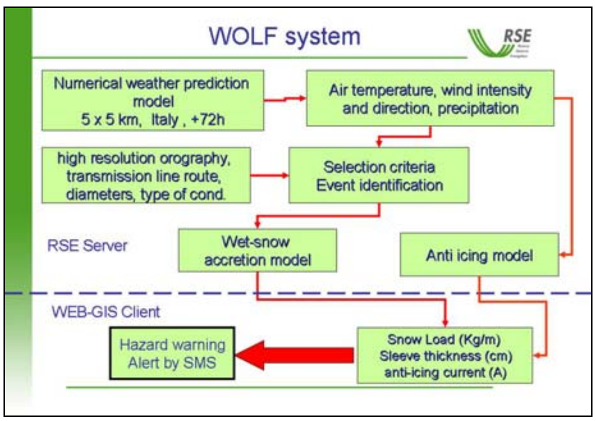

Fig. 2: WOLF algorithm scheme.

The forecast weather data, filtered with appropriate selection criteria for wet-snow identification, converge in an accretion model and in a Joule heating model. The hazard warning is based on a quantitative ice-loads forecast. The alert is sent by SMS to the end-users of service, if the threshold ice-load, set to 5 kg/m, is exceed.

Data processing is done on RSE server, while the product is available online through a WEB-GIS client. The client environment, required for accessing data, is a common Internet browser.

A. *Numerical Weather Prediction*

WOLF processes data coming from a high-resolution non-hydrostatic NWP model (Local Area Model Italy), developed by ARPA-EMR (COSMO Project), the Environmental Protection Agency of Emilia Romagna. The NWP provides, every day, the principal meteorological variables on a regular grid with a mesh of about 5 km, with a forecast horizon of 72 hours.

For each grid point, one or more overhead power lines have been assigned to the cells, by using information of the Atlas of Italian Transmission Lines (ATLARETE). In particular, the following data are available:

- type of conductors;
- diameter of conductors;
- electrical resistance;
- minimum and maximum altitude of overhead; power lines crossing the grid mesh.

The temperature, at the min/max altitude of the power line, has been calculated by using a vertical air temperature gradient in saturated air, equal to 0.6°C/km. If the cell is not crossed by any power line, the algorithm assigns the temperature at the average altitude of the grid mesh.

An event is considered, if the total precipitation amount of the episode, exceeds 10 mm. For each step of forecast (3 hours), a flag is assigned depending on the weather conditions predicted. The selection criteria for the wet-snow identification, are reported in Tab. 2. An accretion event starts only when the temperature is in the range of -0.5°C + 2°C and it is expected to snow. For this forecast, the flag is equal to 1, i.e. wet-snow condition.

If the temperature is below this range, there will be a forecast of "dry-snow" and the flag is equal to 2. There is a neutral condition (flag=2), in which the predicted ice formations of conductor could remain on it, i.e. when the temperature is below 3°C and there is no precipitation.

Finally, two conditions lead to ice sleeve fusion, one for rain and the other one for high-temperature, both with flag equal to -1.

Tab. 2: Selection criteria adopted for wet-snow identification.

Precipitation (mm/3h)	Temperature (°C)	Forecast Conditions	Flag	Event (On/Off)
>= 0.2	>= -0.5; <= 2	Wet-snow	1	On
>= 0.2	> 2°C	Fusion (by rain)	-1	Off
< 0.2	>= 3°C	Fusion (by high temperature)	-1	Off
< 0.2	< 3	Neutral condition	0	On
>= 0.2	< -0.5	Dry-snow	2	On (if already On)

Each event is so identified with a beginning and an end, and the selected variables can be introduced into the model of growth.

B. *Wet-snow accretion model*

Unfortunately, there is no specific model that can well simulate all the physical and mechanical processes involved in ice accretion. This statement is particularly true for the wet snow icing [11] [12].

In this work, the goal of the authors is to use a simplified version of the accretion model, in order to make easier the forecast computation on every grid points.

The method, as proposed by Sundin and Makkonen [13] and adopted by Hungarian Meteorological Service [5], is based on the (1) for a cylindrical conductor :

$$\Delta M = 2PR\Delta t \qquad (1)$$

where:

ΔM = incremental amount of ice load on conductor (kg/m);
P = flux of snow mass or intensity of precipitation (kg/m^2h or mm/h);
R = outer radius of ice-sleeve (m);
Δt = time step of the available meteorological variables.

A scheme of the computational routines included in the wet-snow accretion model, is shown in Fig. 3.

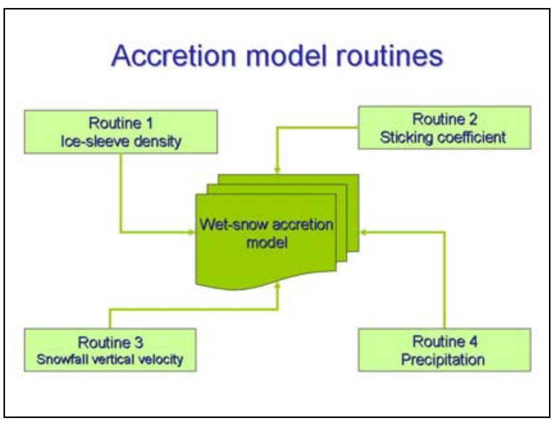

Fig. 3: routines implemented in the wet-snow accretion model

Descriptions of the routines, implemented in the algorithm, are reported below.

Ice-sleeve density ρ (kg/m^3): the input parameters passed to the routine are: the wind intensity (m/s) and the flag assigned to the forecast. The dependence of sleeve density from the wind, is given by the following equation (2), proposed by Admirat [11]:

$$\rho = a + b * V \quad if\,(1 < V < 10m/s) \qquad (2)$$

where:

a, b = dimensionless empirical coefficients;
V = wind intensity expressed in (m/s).

In our procedure, the coefficients are respectively equal to 100 and 20, in case of flag=1. With flag=2, i.e. dry-snow, the sleeve density is forced to 100 kg/m^3. If the wind intensity exceeds 10 m/s, the density is set to 300 kg/m^3.

Sticking coefficient α (dimensionless): this coefficient depends on the liquid content of snowflakes and wind speed. It expresses the adhesive strength of snow on conductor. The equation used is as follows:

$$\begin{aligned} &\alpha = 1 && if\,(V \le 1m/s) \\ &\alpha = 1/V && if\,(1 < V < 10m/s) \qquad (3) \\ &\alpha = 0.1 && if\,(V \ge 10m/s) \end{aligned}$$

where: V is the wind intensity (m/s).

In dry-snow condition, the sticking coefficient α is forced to 0.1.

Vertical velocity of snowflakes V_s (m/s): the data collected during the experimental activity of RSE, indicate a typical vertical velocity of wet snowflakes equal to 2.5 m/s 2.0 m/s for dry snowflakes. These velocities are measured by the laser precipitation monitoring (disdrometer), which also provides the characteristics of the hydrometeors (type and size of particles).

Flux of snow mass P (kg/m^2h): the routine calculates the flux of snow passing through the wire, using the (4), as in Sakamoto [14]:

$$P = P_0 \sqrt{1 + \left(\frac{V \sin \theta}{V_s}\right)^2} \qquad (4)$$

where:

P_0 = the precipitation intensity at the ground (mm/h or kg/m^2h);
V = wind intensity at the conductor height (m/s);
θ = angle between the wind direction and the conductor supposed horizontal;
V_s = vertical velocity of snowflakes (m/s).

In our procedure, θ is set to 90°, because it is considered the worst condition of accretion. Having calculated these parameters, it is possible to apply the (5) for the computation of outer radius of ice sleeve:

$$R(t) = \sqrt{\frac{M(t)}{\rho\pi} + \left(\frac{D_0}{2}\right)^2} \qquad (5)$$

where:

R(t) = outer radius of ice-sleeve (m) at the forecast time *t*;

M(t) = incremental ice-sleeve mass at forecast *t* (kg/m);
D_0= diameter of bare wire.

Finally, the incremental mass is calculated, as following expression (6):

$$dM(t) = 2R(t)P(t)dt \qquad (6)$$

where:

P(t) the flux of snow mass calculated by (4).

C. Anti-icing current

The anti-icing current is defined as the minimum current that maintains the conductor free of ice during the wet snow event.

The mathematical model, implemented in the WOLF algorithm, is proposed by Schurig and Frick [15]. The model considers an ideal conductor with the following features:

- solid and homogeneous isotropic;
- cylindrical shape with horizontal axis;
- no skin effect;
- infinite thermal conductivity.

The anti-icing current calculation is given by (7):

$$I = 5600\sqrt{\frac{(Pc + Pd)D_0}{R_t}} \qquad (7)$$

where:

I = anti-icing current (A);
P_c = power losses by convection (W/cm^2);
P_d = radiative losses (W/cm^2);
D_0 = diameter of conductor (cm);
R_t = resistance of conductor.

The power losses by convection, as proposed by Shurig and Frick, can be calculated by (8):

$$Pc = 0.00316\frac{\sqrt{pv}\Delta t}{T_m^{\ 0.123}\sqrt{D_0}} \qquad (8)$$

where:

p = absolute air pressure (kg/cm^2);
v = wind velocity (km/h);
Δt = over-temperature between air and conductor;
$T_m = (T_0+T)/2$ (K);
$T_0 = 273 + t_0$ (forecasted absolute air temperature) ;
$T = 273 + (t_0 + \Delta t)$ (absolute temperature of conductor).

The radiative losses are given by (9):

$$Pd = 5.7\varepsilon\left[\left(\frac{T}{1000}\right)^4 - \left(\frac{T_0}{1000}\right)^4\right] \qquad (9)$$

where:

ε = emission coefficient on the surface of the conductor (Al-Ac ; ε = 0.5);
T = absolute air temperature forecasted;
T_0 = absolute temperature of conductor (K).

In our procedure, the temperature of conductor is forced to 2°C because, at this temperature, it is very likely that the ice-sleeve melts or it doesn't start to growth. The total contribution of P_c and P_d losses, is well-known as the Joule effect dissipation. This scheme is verified during field campaigns, by means of a controlled heated conductor.

D. WEB-GIS Display

WOLF outputs are reported in an interactive WEB-GIS, allowing to display a large amount of information. The "Alert value" is set to 5 kg/m. When it happens, a "blinking red point" is shown on the Active Desktop.

The ice-load levels are divided into four intervals represented by a chromatic scale, as reported below:

- 0.5 Kg – 1 Kg/m : green
- 1 Kg/m – 2 Kg/m: yellow
- 2 Kg/m – 5 Kg/m: orange
- > 5 Kg/m : red

The WEB-GIS allows to display the time development of the predicted variables for each grid point, by clicking on it. In this graph, are represented the following information:

- an header with minimum and maximum altitude of overhead power line;
- the forecasted temperatures at different altitudes of power line;
- wind intensity and its direction;
- precipitation intensity;
- beginning and end of the event;
- wet-snow load on conductor;
- anti-icing current.

On the Active GIS Desktop, additional layers are displayed:

- the high-voltage power lines network (132, 150, 220 e 380 kV) with some additional information;

- the electric grid information;
- the raster cartography of Italy 1:750:000 ;
- the Digital Elevation Model (DEM) with 250 meters grid spacing ;
- the administrative boundaries of Italy.

III. WOLF EVALUATION

To evaluate WOLF system, forecasts were made for past periods when known transmission failures occurred due to strong wet-snow events. The WOLF outputs were analyzed to determine whether the computed loads would exceed the alert threshold value.

The accidents occurred in Italy, are reported in Tab. 3. The table indicates the dates of events, the areas of power outages and the type of failures. The last column indicates whether the system would have issued the alerts.

A brief description of some case-studies follows.

Tab. 3: Main power outages in Italy (last 2 winter seasons).

Date	**Power outages**		
(gg.mm.aaaa)	Region	Failure	WOLF Alert
01.12.2008	Lombardy Trentino	Tower collapse	Yes
13.12.2008 15.12.2008	Piedmont	Several black outs	Yes
28.04.2009	Valle d'Aosta	Conductor rupture	Yes
10.03.2010	Emilia Romagna	Prolonged power outages	Yes

A. *Case study: Lombardy ; 01.12.2008*

In the beginning of December, a strong cold front affected Northern Italy, causing heavy wet-snowfalls. During this event, the joint action of the wind and snow load determined serious damages to the power lines, causing diffuse and prolonged blackouts. The snow accumulation on ground reached 1.5m above 1500 amsl.

The next graph in Fig. 4, shows the weather forecast nearby the area where the accidents occurred. In the first box, the forecast temperatures are represented at different altitudes of power lines. The second box shows the precipitation, wind intensity and its direction. In the third box, the ice-loads on 2 conductors are represented in the graph. The wet-snow conditions would have occurred above 1300 amsl, and the snow load would have exceeded 5 kg/m on 26.9 mm diameter conductor. The vertical red lines indicate the beginning and the end of the event.

WOLF has correctly forecasted the wet-snow phenomenon in this area two days in advance, predicting ice-load on conductors greater than the alert threshold value of 5 kg/m.

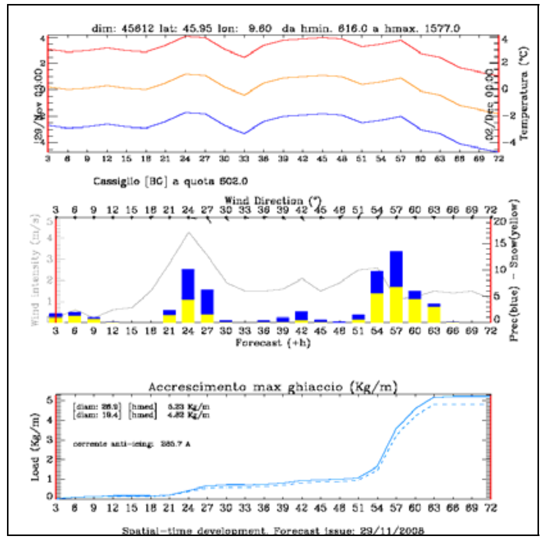

Fig. 4: time development of predicted variables on a grid point nearby the occurred accident.

B. *Case study: Piedmont ; 13.12.2008 – 15.12.2008*

In the Piedmont case, between the 13th and 16th December 2008, a heavy and wide snowfall caused many power line failures. The forecast of total precipitation amount reached 150 mm and WOLF forecasted an ice-load of more than 10 kg/m on conductors.

The snow depth registered in different areas of Piedmont, as in Stura and Ossola valleys, reached 1.5m on the ground. The next map in Fig. 5, extracted from the WEB-GIS Desktop, highlights the wide area where it would expected the significant snow-loads. The red points exceed the alert threshold value. The values in the circle, represent the forecasted precipitation amount. Clicking on the interactive points, the time-develpoment forecast graphs can be obtained.

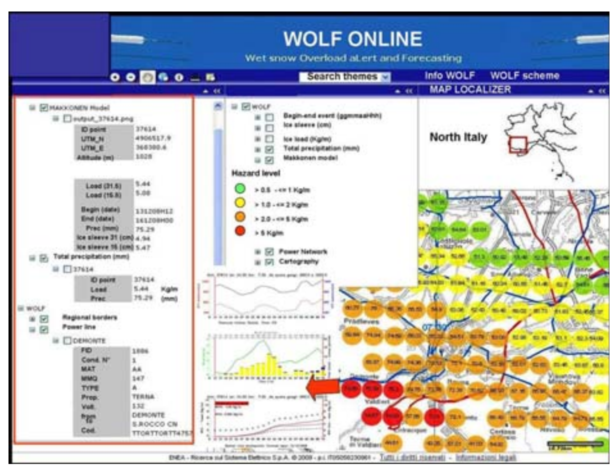

Fig. 5: WOLF outputs on the Active GIS Desktop for the Piedmont wet-snow event.

C. *Case study: Emilia Romagna; 10.03.2010*

The events were characterized by prolonged and wide-area wet-snowfall combined with strong wind-gusts greater than 25 m/s on the coast. The two most affected city by blackouts, were Piacenza and Ferrara.

The accretion model in WOLF provided a value of 1.2 and 4.3 kg/m for city of Ferrara and Piacenza, respectively with an ice sleeve thickness of 3.2 and 9.2 cm. This difference is only due to the different amount of forecasted precipitation, without any wind effect in the accretion model. In particular, the total precipitation forecasted was 47 and 65 mm respectively at Ferrara and Piacenza.

Some local and different observations were available: a total water equivalent of 17 mm at Ferrara and a snow depth of 40 cm at Piacenza. Despite of the precipitation was not heavy in Ferrara, diffuse and protracted black-outs afflicted thousands of users. In this case, it's reasonable to assume that the wind was the main cause of electrical outages due to indirect effects, as trees felling down on the overhead lines. Conversely, the city of Piacenza was afflicted by a wet-snowfall and the accidents were principally due to the ice overload on conductors.

WOLF has not issued alarms for both cities, but many points were on alert in the surrounding area.

IV. Experimental Activity

Field observations and measurements are necessary to improve the knowledge on the physical processes involved into ice formation on conductors, as well to tune the wet-snow accretion models to regional climatic condition [3] [16]. Furthermore, the IEC 61774 rules [17] recommend a strategy for collecting different data sources, in order to obtain the best possible information basis to evaluate the maximum design load.

The preliminary results of previous experimental campaigns, highlight the complexity of sleeve's growth in which are involved several physical processes. In particular, the critical role of accretion coefficients that greatly vary for little temperature variations across 0°C.

Another important factor is the observed ice-shedding that is not considered in the algorithm, and it will be the subject to further investigations.

These suggestions, together with authors experiences gained during past field campaigns, have allowed to design and build an automatic ice-station, whose scheme is represented in Fig. 6.

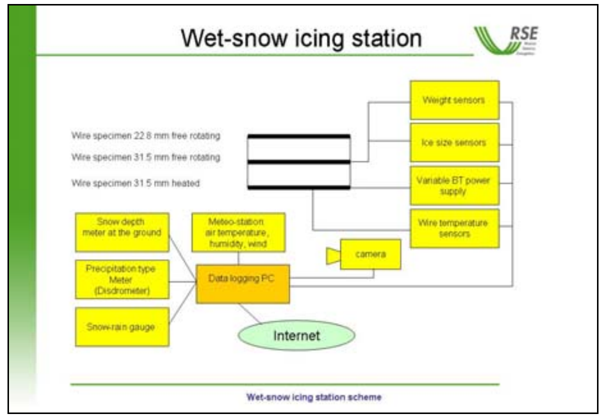

Fig. 6: scheme of the wet-snow icing-station developed by RSE.

The monitoring station consists of the following instruments and devices:

- ice load cells and ultrasonic ice thickness sensors;
- wire temperature sensors;
- variable BT power supply;
- webcam;
- integrated weather station;
- snow depth meter;
- laser precipitation monitoring;
- snow-rain heating gauge;
- data logger PC.

The ice-station monitors two 31.5 mm wire-pieces housed on a frame. The Joule effect is simulated on a wire, through an internal resistance connected to a LV-modulated Power supply. The surface temperature of the wire is regulated by a sensor, which controls the power supply.

The wire load and the ice-sleeve thickness are measured by load cells and ultrasonic sensors respectively. A webcam periodically takes picture of the 2 wire-pieces.

All weather and wire data converge in a data logger, interfaced to the PC. Data are sent to RSE server by FTP protocol, through an Internet connection.

The station will be tested in the 2010-2011 winter season.

V. Conclusion and Future Work

This paper presents the forecast system (WOLF) able to forecast wet-snow conditions in Italy and to compute ice-accretion on the whole HV power grid. The system provides alarms and displays meteorological and power lines information on an easy GIS interface.

The results, obtained from some case-studies, demonstrate the WOLF ability to predict critical events and provide alerts, necessary to adopt dispatching strategies, reducing the effects of power outages.

In the future, the authors plan to improve the WOLF algorithm, introducing more accurate accretion and shedding parameters, thought data collected by the new prototype of wet-snow icing-station.

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