Quantifying benefits of grid reinforcement measures to power system resilience against wet snow events

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Abstract— **A major concern for Transmission System Operators (TSOs) is to effectively manage power systems during extreme weather events. This need calls for new methods and tools to support operational planning by forecasting critical conditions in the grid, and to quantify the benefits of the measures deployed to improve system performance under these events. For this reasons, the concept of resilience is particularly useful to build a proper assessment framework. This paper presents an in-depth resilience assessment methodology supporting the evaluation of the system response under different assumptions on threat intensity and component vulnerability, including the modeling of countermeasures aimed to improve system resilience. In particular the paper investigates the models for anti-torsional devices and ice-phobic coatings, i.e. two grid hardening measures against wet snow events. The case studies applied to a model of a realistic EHV/HV transmission system demonstrate the potentialities of the tool, which can be useful for a future quantitative techno-economic assessment of the portfolio of resilience boosting measures.**

Index Terms— **anti-torsional devices, ice-phobic coatings, power system, resilience, risk, wet snow.**

I. Introduction

Extreme meteorological events affect power systems more and more frequently, therefore Transmission system Operators (TSOs) are urged to achieve two goals: (a) to assess the impact of multiple, dependent outages of components, and (b) to elaborate preventive or corrective countermeasures to absorb the effects of disruptive events and to recover fast, i.e. to increase system resilience [1][2] also taking into account the stringent requirements posed by regulatory entities [3].

Different classes of measures can be adopted to boost system resilience [4], considering different time frames: long term planning, operational planning, and real time operation. Some measures aim to make components more robust (hardening measures), others aim to improve situational awareness of operators or to suggest changes in operating conditions over a shorter time horizon (active measures) [4]-[6]. The choice of the best combination of hardening and operational measures is a complex task, calling for methods and tools able to assess the benefits brought by different measures to system resilience for different intensities of the threats.

A first step towards a techno-economic assessment of the best portfolio of hardening and operational measures consists in a methodology able to quantify the technical benefits of these measures in terms of reduction of loss of load risk.

In this perspective, the paper presents a flexible platform for resilience assessment which allows to model the resilience boosting measures and to perform sensitivity analyses on the parameters which characterize both the measures and the threats. In this way, the tool is able to assess the effectiveness of these measures for different threat severities and for different design choices of the countermeasures themselves.

The paper is organized as follows: Section II presents the framework for resilience assessment and enhancement. Section III describes the models adopted for two mitigation measures, namely ice-phobic coatings and anti-torsional devices, aimed to counteract the wet snow sleeve accretion phenomenon. Section IV describes the simulation results. Section V draws some conclusions.

II. Resilience assessment and enhancement

The tool for resilience assessment, named RELIEF "REsiLIEnce measures For the grid", is a specific application function of the Integrated Security Assessment Platform (ISAP) developed at RSE [7]. RELIEF combines short term forecast models of different natural threats with component vulnerability curves, in order to assess component failure probability from few hours to few minutes ahead of operation, and to rank and select critical (possibly multiple) contingencies. After a preliminary selection phase, each retained contingency is applied to the power system model to simulate its effect taking into account protection, defense and control systems. The tool models countermeasures at two levels, namely component vulnerabilities and power system response. The computation of risk and resilience indicators for base-case scenario and for the scenario with a specific deployed countermeasure allows to quantify the benefits to the system resilience. The classification of the resilience boosting countermeasures in [4] distinguishes between passive and active measures, aimed to improve respectively the ability of the infrastructure not to be damaged in case of threats and the system absorption capability and recovery speed. The indicator used to assess countermeasure

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effectiveness is the Loss Of Load (LOL) risk, defined as the expectation value of the unsupplied load (in MW) due to j-th contingency (LOL_j), and computed as in (1).

$$R_j = LOL_j \times prob_j \tag{1}$$

where $prob_j$ in (1) is the probability of occurrence of contingency j. Due to the wide range of values it may assume, R_j can be expressed in dB over a base level. The total LOL risk is the sum of the risk indicators related to all the contingencies of the set. A resilience indicator RE_j can be derived from (1) for each contingency, see (2), and the system-level resilience indicator can be defined as the minimum value of individual indicators of the contingencies, as in (3).

$$RE_j = 1/R_j \tag{2}$$

$$RE_{sys} = \min(RE_j) \tag{3}$$

Other indicators quantify the ENS (Energy Not Supplied) by a conventional evaluation of the restoration time.

III. Modeling of Countermeasures to Wet Snow

Wet snow events are significant threats that have frequently affected the Italian EHV transmission system in the last decades [8], causing severe damages to overhead lines due to combined mechanical load of snow sleeves and wind. Different passive measures to increase system resilience are studied to reduce the wet snow sleeve [9]. In particular, mechanical anti-torsional devices aim to avoid or at least to limit the conductor rotation which causes sleeve accretion. Likewise, ice-phobic coatings can delay the sleeve formation by reducing the sticking capability of the wet snow on the conductor or favor the sleeve shedding process. Further studies are required to model these countermeasures under a probabilistic point of view. The present paper describes the models proposed to perform sensitivity analyses on the passive measures mentioned above. The modeling starts from the investigation of the literature related to the laboratory tests that were performed to better characterize the phenomenon of the accretion of wet snow sleeves.

A. *Modeling approach*

Some of the phenomena dealt with in the paper are still subject to investigation, e.g. effects of anti-torsional devices on rotation. This section presents the preliminary model used to simulate such complex processes. It is worth noting that further experiments are required for a better insight into, and to model, these countermeasures in a probabilistic setting. In any case, the simulation of these countermeasures is of paramount importance to correctly quantify their effectiveness in terms of reduction of the risk of load disruption.

In general, (a) a reasonable model and (b) adequate values for the parameters must be taken into account to simulate a physical phenomenon. The tool for resilience evaluation tackles these aspects as follows:

- It implements the most reasonable model based on the state of the art in the field.
- When model parameters are difficult to measure/retrieve, the tool performs a sensitivity analysis, by sweeping a reasonable range of values for these parameters.

Thus, the modeling approach consists in a state-of-the-art model where the effect of some more critical parameters is assessed by a sensitivity-based approach where parameters range over reasonable values. This approach will be applied to the models of anti-torsional devices and ice-phobic coatings.

B. *Wet snow sleeve accretion: the Makkonen model*

Wet snow events typically occur in the temperature range of -1°C/+2 °C when snowflakes have a Liquid Water Content (LWC) in the range of 20%-30% of the total mass. Under these conditions, the snowflakes settle on the conductor and join together not only by the collision mechanism, but also for the strong coalescence due to capillary adhesion forces that favour the growth of a typically cylindrical sleeve around the conductor (Figure 1).

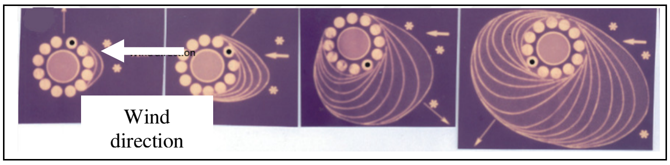


Figure 1. Cylindrical ice sleeve accretion on conductors in a wet snow event

The typical duration of heavy wet snow events is 18-24 hours, producing snow sleeves up to 30 cm in diameter and causing an extra load on conductors up to 20 kg/m. This overload can produce serious damages to overhead lines. In some cases, the conductor undergoes an extra load due to the intense wind blowing during the accretion event.

The model implemented in the platform to forecast the mechanical loads due to snow and wind accounts for four main variables, namely the precipitation rate of the wet snow, the wind speed intensity and direction, and the ambient temperature. The wet snow accretion is based on (4).

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 * w * A * V \tag{4}$$

Equation (4) models the accretion of snow mass M described in the ISO standard for icing of structures [10]: α_1 is the collision efficiency; α_2 is the sticking efficiency, α_3 is the accretion efficiency; w is water content (kg/m^3); A is the cross-sectional area (m^2) perpendicular to object; V is the particle impact speed perpendicular to object (m/s). Details can be found in [8][10].

C. *Modeling of anti-torsional devices*

Anti-torsional devices (Figure 2a) increase the torsional stiffness of the conductor and they are used in order to avoid the trigger of the process which leads to the wet snow sleeve formation [11]. The study of the effect of anti-torsional devices on the wet snow accretion process has been studied in literature for a long time [11][12], even though a definite conclusion on the effectiveness of these devices still needs experimentation and it is subject to discussions. The presence of the device causes an increase of torsional rigidity, which reduces or eliminates the conductor rotation, thus the formation of wet snow sleeve on the conductor. A first modeling step consists in a realistic quantification of the reduction of rotation due to these devices. To this aim, reference [12] provides some quantitative considerations about the observed reduction of ice loading due to the application of one or four anti torsional devices. Starting from these experiments, the second step is to elaborate an analytical expression assuring the same reduction factor of ice loading on the conductor.

The analytical model is based on function $F(x, N)$ in (5) which models the rotation at distance x from one line end and with N anti-torsional devices. Function $F(x, N)$ is obtained by superimposing the absolute value of *sin* function over the span of the line with a maximum rotation value of 19° (reasonable value for design) on the absolute value of a shorter period *sin* function.

$$F(x,N)=\max\left(0,\left(a-bN^{c}\right)\times\left|\sin\left(\frac{\pi\cdot x\cdot(1+N)}{L}\right)\right|+d\times\left|\sin\left(\frac{\pi\cdot x}{L}\right)\right|\right) \quad (5)$$

In (5), x=[0:1:L] is the distance from one end of the line, where L is the span length. The parameter values are derived by trial and error approach from [12] and set to: a=71, b=12, c = 0.7, d = 19. A reduction factor (RF) is defined as in (6).

$$RF=\frac{mean\left(\min\left(F(x,N),F(x,0)\right)\right)}{mean\left(F(x,0)\right)} \quad (6)$$

An example of the estimated value of rotation angle of a conductor along a 500 m span is shown in Figure 2b in case of no anti-torsional devices (red curve) and in case of 4 equally spaced anti-torsional devices (blue curve).

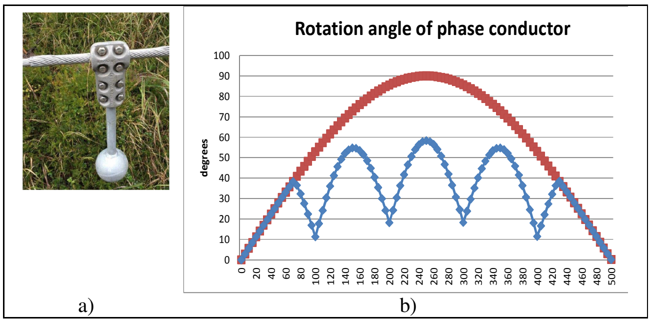


Figure 2. Anti-torsional devices: (a) a photo of the device; (b) comparison of the rotation angle of a conductor in two cases: no anti-torsional devices (red curve) and 4 equally spaced anti-torsional devices (blue curve)

The reduction factor is multiplied by the intensity of wet snow accretion I_0 in the Makkonen model [8] to derive the derated intensity $I_{derate} = RF \times I_0$. This relationship assumes that the accretion intensity reduction is proportional to the reduction of the rotation angle.

D. *Modeling of ice-phobic coatings*

Anti-ice coatings are based on hydrophobic or super-hydrophobic materials. Although the mechanisms of their anti-ice or anti-snow functions are still under investigation, a possible modelling of the coating behavior can be formulated assuming a delay in the formation (sticking) of the first layer of snow on the conductor surface. Moreover the ambient temperature has a key role in the ice and snow adhesion forces to a metallic substrate [13][14]. This is due to the temperature dependent phenomena of the heat exchange at the conductor/snow interface, of the solidification velocity of the water present in the snow flakes and also of the water repellent behaviour of the hydrophobic coatings. The overall effect is a balance among the above mentioned phenomena, and in presence of a super-hydrophobic coating a negative slope of the ice adhesion force as a function of the temperature is observed, particularly in the range around 0 °C, possibly thanks to a reduced heat exchange flux due to the coating roughness [15]. All these assumptions can be expressed by a time variant collision $\alpha_1(t)$ which is a function of ambient temperature $T_{amb}(t)$, as in (7) .

$$\alpha_1(t)=\begin{cases}0 & if\ T_{amb}(t)<-0.5°C \quad AND \quad t-t_0\leq TLIM \\ 1 & otherwise\end{cases} \quad (7)$$

In (7), *TLIM* is the delay introduced by the coatings (in hours) and t_0 is the starting time of the wet snow accretion phenomenon. *TLIM* clearly depends on the action mechanism of the coating and on environmental conditions where it acts.

IV. Case Study

The sensitivity analysis is performed considering two resilience boosting measures M1 and M2, and two wet snow storm intensities S1 (severe) and S2 (moderate). Table I and Table II respectively report the parameter ranges used for threat characterization and the list of analyzed cases.

TABLE I – Expected values for parameters of wet snow events

Hazard parameter	Measurement unit	S1	S2
Peak wind speeds	m/s	10-15	5-10
Precipitation Rate	mm/h	2	1
Initial precipitation Level	mm	20	20
Air temperature	°C	-0.6 (for S1m) +1.0 (for S1p)	-0.6

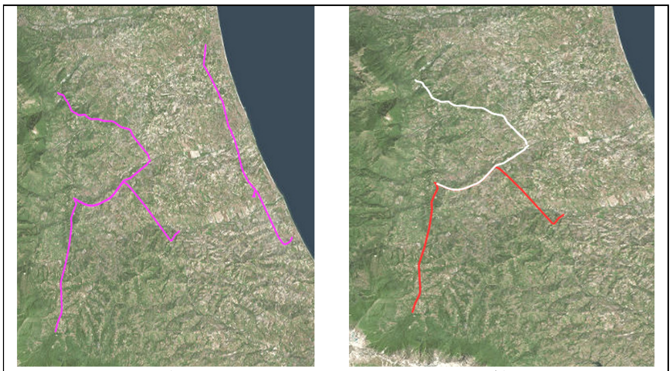
TABLE II – Cases for the sensitivity analysis

Measures \ Threat	S1m	S1p	S2	Case description
BC: base-case	S1m	S1p	S2	No countermeasures deployed
M1: anti-torsional devices	S1m+M1	S1p+M1	S2+M1	Application of anti-torsional devices to critical lines with distances among devices of {50, 100} m
M2: coatings	S1m+M2	S1p+M2	S2+M2	Application of coatings for critical lines assuming different delay times {3, 6, 9, 12} hours

In order to select the critical component the tool adopts the cumulative screening method [4] with a fraction of explained total failure probability set to 90% for all the cases. The time interval for the analysis is equal to 10 minutes. Unless differently specified, expression "S1" used in the sequel refers to threat scenarios S1m.

A. *Storm scenarios S1 and S2: the base-cases*

Figure 3 shows the geolocalization of critical overhead lines due to severe storm S1 and to moderate storm S2. The color transition from magenta through red to white represents a decreasing order for failure probabilities.



a) b)

Figure 3. Geolocalised maps of critical components for (a) severe wet snow storm and (b) for moderate wet snow storm

Table III reports the list of critical components for the two wet snow scenarios. Table IV reports the number of contingencies and the contribution to the total LOL risk per contingency category for scenarios S1 and S2.

TABLE III – LIST OF CRITICAL COMPONENTS FOR SEVERE (LEFT) AND MODERATE (RIGHT) WET SNOW STORM

Severe wet snow S1		Moderate wet snow S2	
Line ID	Failure prob. (/ 10 min)	Line ID	Failure prob. (/ 10 min)
ALDR – GIUR	>0.90	CLTR - TRMR	0.768
GIUR – ROSR	>0.90	TRMR - IGSR	0.396
TRMR – IGSR	>0.90	TRMR - TRWR	0.199
CVDR – TRWR	>0.90	CVDR - TRWR	0.167
TRMR - TRWR	>0.90		
PINR - ROSR	>0.90		
CLTR - TRMR	>0.90		

TABLE IV – CONTRIBUTION OF CONTINGENCY CATEGORIES TO TOTAL LOL RISK FOR SEVERE STORM (S1) AND FOR MODERATE STORM (S2)

	Severe wet snow S1		
	Nr of ctgs	LOL risk, MW	% of total risk
N-1	7	2.00×10^{-2}	0.11
Common mode branch N-k	120	1.85×10^{2}	99.89
Dependent N-k	7	2.70×10^{-3}	1.45×10^{-3}
TOTAL	134	185.38	100

	Moderate wet snow S2		
	Nr of ctgs	LOL risk, MW	% of total risk
N-1	4	1.29	23.56
Common mode branch N-k	11	4.18	76.38
Dependent N-k	4	2.95×10^{-3}	5.39×10^{-2}
TOTAL	19	5.47	100

In severe events the largest contribution to the risk of load disruption come from multiple contingencies which are typically neglected in conventional security analyses. Moreover, it is worth noting that in moderate events lower order contingencies provide a larger percentage of the total risk of load disruption with respect to very severe events: e.g. N-1 and N-2 line outages represent 54% of the total risk in S2 against 1.1% of the total LOL risk in S1.

B. Application of anti-torsional devices

Scenarios S1 and S2 are simulated after applying anti-torsional devices to the critical lines identified in the base-cases. Anti-torsional devices are characterized in terms of: (1) mass of each device set to 10 kg; (2) relevant bracing of about 50 cm; (3) distances among devices in the set {50, 100} m and subject to a sensitivity analysis. Table V reports the list of critical components for the scenarios with anti-torsional devices applied to the lines detected as critical in the base-cases.

TABLE V - LIST OF CRITICAL COMPONENTS FOR WET SNOW SCENARIOS WITH ANTI-TORSIONAL DEVICES APPLIED TO CRITICAL LINES

Severe storm, inter-device distance = 50 m		Severe storm, inter-device distance = 100 m	
Line ID	Failure prob. (/ 10 min)	Line ID	Failure prob. (/ 10 min)
VLLR - VLVR	1.88×10^{-2}	TRMR - IGSR	6.90×10^{-1}
		GIUR - ROSR	4.53×10^{-1}
		CLTR - TRMR	9.20×10^{-2}
		CVDR - TRWR	9.05×10^{-2}
Moderate storm, inter-device distance = 50m		**Moderate storm, inter-device distance = 100m**	
Line ID	Failure prob. (/ 10 min)	Line ID	Failure prob. (/ 10 min)
GIUR - ROSR	1.60×10^{-1}	GIUR - ROSR	1.60×10^{-1}
		CLTR - TRMR	1.28×10^{-2}

In scenario S1 with 50 m inter-device there is only one line with a very low probability of failure, which demonstrates the effectiveness of this measure. Figure 4 compares the total LOL risk and its composition for moderate and severe storm S2 and S1 in terms of contingency category for the base-cases and inter-device distances of 50 m and 100 m. The scenario with a 50 m distance leads to negligible LOL risk in both wet snow scenarios.

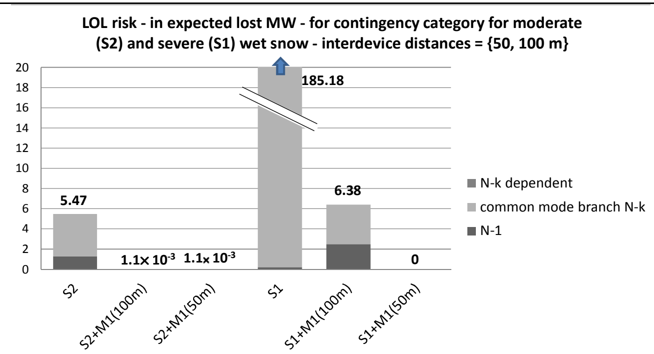


Figure 4. Risk of loss of load (LOL) for severe (S1) and moderate (S2) storm scenarios, and two different inter-device distances

In particular, in case of the severe storm S1, a 50 m inter-device distance is sufficient to assure a negligible risk of load loss: a lower number of devices allows to strongly reduce the total risk of loss of load and especially the contribution due to N-k common mode branch contingencies.

The TSO's actual experimentation of anti-torsional devices on some HV lines considers a 50-60 m inter-device distance (depending on span length and on conductor type), which the tool confirms to be an adequate value to get an effective measure also for severe events.

C. Application of coatings

This subsection reports the results of the simulation of the severe (S1) and moderate (S2) storms where the ice-phobic coatings are applied to the critical lines identified by the base-case simulation. The sensitivity analysis is performed on:

- the time delay *TLIM*, in hours, achieved by the coatings. The value range is {3, 6, 9, 12} hours.
- the air temperature (in °C) which determines the effectiveness of the measure. The range is {-0.6, +1°C}.

For S1 storm Figure 5 shows the total LOL risk and the system level resilience indicator (with base level 10^{-2}) for the base-case and the cases with coatings with different time delays (3 thru 12 hours). A 3 hour delay already reduces the total LOL risk by 60%; a 9 hour delay almost brings the risk to a negligible value if temperature remain below -0.5°C.

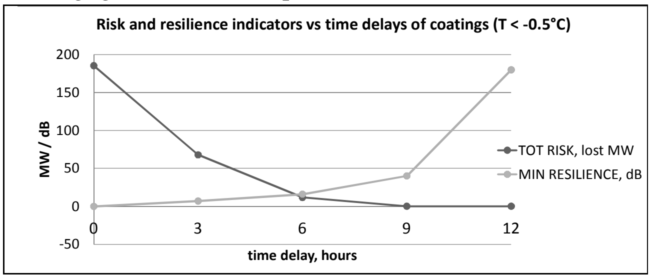


Figure 5. Risk and resilience metrics for different time delays – scenario S1

Comparing the results of cases with 9 hours delay and two air temperatures (-0.6° and +1°C) confirms the little effectiveness of the coatings at the air temperatures where wet snow phenomenon mainly takes place, i.e. [-0.5 ÷ 1.5°C], which is in line with latest assumptions based on more recent experimentations (see subsection III.D). Figure 6 reports the same metrics for S2 storm and for time delays of 3, 6 and 9 hours (the 12 hour scenario leads to negligible LOL risk).

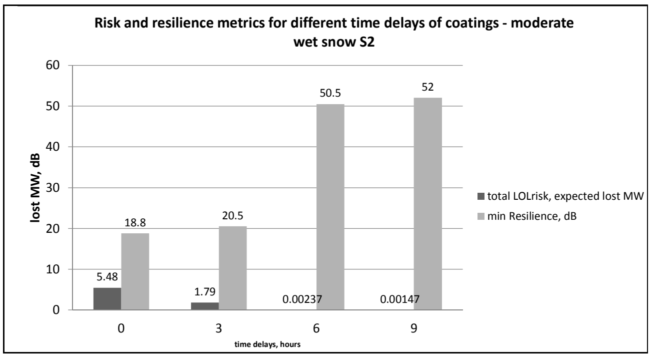


Figure 6. Risk and resilience metrics for different time delays – scenario S2

It is worth noting that a drastic improvement of system resilience to moderate storms can be achieved with a 6 hour time delay: adopting a 9 hour time delay brings only a slight increase of resilience.

V. Conclusions

The paper has presented an innovative tool to assess power system resilience in case of different natural threats and to quantify the benefits to resilience due to passive countermeasures installed on the grid infrastructure, specifically anti-torsional devices and coatings. The tool flexibility in modeling threats and the physical vulnerability of the components makes it ideal to perform "what if" analyses, comparing different technologies for grid enhancement. Simulations performed on a realistic model of EHV/HV Italian transmission system confirm the ability of the tool to easily integrate and run models for various grid enhancement solutions, leading to a quantification of their benefits in terms of reduction of load disruption risk for different severities and extents of the weather events. Further work consists in integrating the available models for resilience enhancement measures into an optimization framework to evaluate the optimal portfolio of active and passive measures in a time period ranging from long term planning to real time operation.

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