Power Systems' Resilience Against Ice Sleeves: an Assessment Methodology Tested in the Smart City Vizze Project

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Abstract— **In recent years, climate changes caused an increase of violent and wide-ranging meteorological events, often with significant effects on the power systems continuity of service. Moreover, evolutions of users' habits and the increasing dependence on the electric energy carrier are motivating the request for a more and more reliable power supply. In this framework, the work presents a methodology aimed at evaluating the resilience of electric distribution grids against interruptions due to the ice and snow sleeves accretion on overhead lines. The approach proposed is applied to the MV network supplying the Vizze Valley, managed by the Italian DSO Edyna, and represents an essential step to perform a selection of the corrective actions to be implemented on the network according to their expected benefits and costs.**

Keywords— resilience; distribution networks; ice sleeves; continuity of service;

I. Introduction

With the evolution of users' habits and the increasing dependence of household appliances on the electric energy carrier (heat pumps, induction cooktops, etc.), the need of a highly reliable power supply is becoming more and more pressing, also for household consumers. Consequently, in Italy, the Energy Authority (ARERA, Autorità di Regolazione per Energia Reti e Ambiente) activated in the last years a wide set of actions aimed to improve the quality and continuity of users' power supply service. The regulatory schemes envisaged by ARERA to foster a better power quality perceived by MV/LV users on distribution grids date back to year 2000. The regulation built over time provides two parallel mechanisms, both focused on the continuity of service: *a)* a rewards/penalties scheme applied to Distribution System Operators (DSOs) based on the duration (SAIDI) and number (SAIFI) of long (lasting more than 3 min), accidental, interruptions and on the number of short interruptions (lasting more than 1 s and less than 3 min); *b)* the automatic compensation of MV users subject to a number of long interruptions greater than a given threshold (worst served customers).

In the same period, ARERA promoted the collection of data on disturbance phenomena by the installation of power quality monitors on 400 MV busbars of HV/MV transformers (10% of Italian MV grids), able to acquire the voltage quality parameters defined in standard EN 50160.

In the subsequent regulatory period (2012-2015), ARERA further improved the regulatory scheme based on SAIDI and SAIFI (Res. ARG/elt 198/11), by extending the automatic compensation mechanism involving worst served MV customers also to short interruptions. Moreover, Res. ARG/elt 198/11 [1] paved the way for the future regulation of voltage quality on MV networks, requiring all DSOs to monitor voltage dips on their grids (in addition to other disturbance phenomena, such as flicker, harmonics, etc.). The full deployment of the monitoring infrastructure was completed by year 2014.

In the regulatory period 2012-2015, ARERA started to promote DSOs awareness toward a better voltage quality, by publishing and comparing the power quality data collected on the national distribution system. To this purpose, Res. ARG/elt 198/11 prescribed a suitable monitoring architecture, based on the installation of power quality monitors compliant with IEC 61000-4-30 standard at the MV busbars of each primary substation. Moreover, Res. ARG/elt 198/11 required DSOs to put in operation a central system to acquire and process data recorded by power quality monitors, in order to identify the dips origin: faults on the MV network, faults on the HV system, or (in particular cases) saturation phenomena of voltage transformers (the so called "false dips"). After having processed data, DSOs shall make available results to ARERA and publish them in an aggregated form, to allow a comparison of the quality of service with respect to other operators (yardstick competition).

In the present regulatory period (2016-2023), ARERA continued the monitoring of voltage dips with the goal to collect elements toward a future regulation of voltage quality for DSOs based on the actual number and severity of events that are their responsibility. Moreover, ARERA deemed necessary to extend the monitoring and regulation also to the prolonged interruptions caused by violent and wide-ranging meteorological events, usually in the past not regulated because considered as majeure force situations [1]. Such

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events are significantly increasing in recent years, and often cause prolonged interruptions of the electricity supply to customers distributed in wide areas. Particularly significant events in this context include those that occurred in Emilia Romagna and Lombardy in February 2015, when over 360,000 customers were unsupplied for more than 8 hours, and in Abruzzo and Marche in January 2017, with disruptions that lasted over 72 hours for 39,000 customers (and approximately 2,800 customers were inconvenienced for more than 7 days).

During these events, ARERA observed that the service interruptions were usually caused by failures of transmission and distribution lines, since their structural design limits were exceeded. Moreover, the difficulty of implementing the prearranged emergency plans for some exceptional reasons, such as impassable roads, greatly affected the time required for the service recovery. ARERA also noticed that the cause of the faults occurred on the network frequently were related to the "ice sleeve" phenomenon, which originates on bare conductors of overhead power lines in the presence of wet snow and wind. In addition, other phenomena concern the falling onto power lines of trees (even outside the buffer zone) due to the weight of wet snow.

Two ways to increase the resilience of a system need to be investigated (as observed by DCO 645/2017/R/eel [2]): on the one hand, the increase of network robustness is possible by raising the design limits that identify the infrastructural capacity of the grid to withstand extreme stresses; on the other hand, improvements can be achieved thanks to effectiveness and promptness of the recovery measures, i.e. the system's capability to return to acceptable working conditions, even by means of temporary arrangements. For example, for an electric system exposed to snowfall with "ice sleeves" forming on overhead lines, the network robustness can be improved by raising, up to an economically viable level, the maximum mechanical stress caused by ice load and wind force considered in the design of bare conductors. While the temporary supply through emergency generators could be a means for a fast recovery of the service in areas where the network has been damaged. However, the improvement of networks resilience cannot be limited to increasing their robustness, because a system with high resilience entails higher costs, i.e. the higher costs are not always justified in relation to the benefits that can be obtained; the system's resilience has to be improved only by means of an adequate balancing between actions aimed at increasing network robustness and aimed at improving the recovery capability.

In order to push toward a better resilience of national distribution networks, ARERA, through art. 77 of TIQE (Attachment A to Res. 646/2015/R/eel [3]), requested that DSOs serving more than 50,000 users have to transmit to the Authority a workplan describing the actions deemed necessary to improve the resilience of their electrical system. These workplans must take into account the development plans already set up for the network reinforcement, e.g. to improve the grid's hosting capacity and continuity of service. Moreover, they must be coordinated with the interventions carried out by the Transmission System Operator (TSO) on the national transmission system. The workplans must contain, in addition to a technical examination of the interventions, a cost-benefit analysis developed assuming as reference for the estimation of the risk of the phenomena (in terms of occurrence and number of users involved) the severe and persistent weather events occurred in the last 15 years. According to ARERA prescriptions, after the first release, the DSO will have to update these plans periodically. The workplans can consider, among the critical factors, the previously mentioned phenomena of ice sleeves accretion and the falling of trees onto overhead lines, but also other phenomena affecting grid's resilience, such as the flooding in urban areas. In addition to a clear evaluation of the actual extent of the issue in the involved area (based also on a quantitative assessment), the workplans have to identify proper solutions, highlighting the sustainability of the investment.

In the outlined framework, this work aims to present a method for the assessment of the resilience of MV network against ice and snow sleeves accretion (Section II). The tool developed is applied to a real distribution system (Section III), proving its effectiveness in providing useful information to the DSO about the actions best suited to increase the reliability of the grid. Finally, some conclusions are drawn (Section IV).

II. Resilience Evaluation: the Approach Proposed

This work describes a methodology developed by Politecnico di Milano – Dept. of Energy to evaluate the distribution grids resilience, with particular reference to the ice and snow sleeves phenomenon. The procedure, for each Secondary Substation (SS) of a given MV distribution grid, determines which overhead lines are more subjected to conductors breaking due to the mechanical stress caused by ice sleeves accretion and, consequently, which is the risk of supply interruption for the LV users downstream.

The procedure proposed is structured as follows.

a. For each segment of overhead lines of a given MV network, the value of the maximum mechanical load due to ice and snow sleeve and wind force expected with a return period of 50 years is evaluated. The estimation is carried out according to the prescriptions of EN 50341-1 and EN 50341-2-13 standards, based on the type of conductor, the expected growth of ice and snow sleeves and the wind intensity in the site of installation of the line. To evaluate the mechanical load, the elevation above the sea level is also considered.
b. For each section of the MV overhead lines, the traction force on the conductor corresponding to the maximum load due to ice and snow sleeves and wind force with a return period of 50 years is evaluated, taking into account the mechanical structure of the line.
c. The traction force with return period of 50 years is compared to the maximum breaking load of the conductor, estimating, according to the prescriptions of standard EN 50341-1, the actual return period of the failure event.

d. For each Secondary Substation (SS), all the possible feeding paths toward the HV grid are identified, assuming all the sectionalizing switches closed.
e. For each feeding path, the relevant critical section of conductor is identified, i.e. the section with the lowest return period of the failure event.
f. Among all the feeding paths, the one having the highest return period is considered, assuming that, in all the meteorological events less severe than those that cause the interruption of this path, at least the power supply line under analysis toward the SS is always active. The value obtained is the return period of the SS.
g. According to the methodology prescribed by Det. DIEU 2/17 [4], the risk of disconnection of the SS (Risk Index: RI) is calculated as the number of LV users supplied divided by the return period of the breaking event:

$$RI = \frac{NU_{SS}}{T_{SS}} \tag{1}$$

Once computed the Risk Index for each SS, the DSO has all the elements to define a strategy of refurbishment of the distribution grid to solve the issues found by the analysis. Some examples of interventions that can be considered to improve the resilience of the network, which in perspective could be included in the workplan of the DSO, are:

- refurbishment of distribution lines ensuring their compliance with standard CEI EN 50341-1;
- strengthening of distribution grid meshing to improve the possibility of back-feed in case of contingencies;
- substitution of bare conductors of overhead lines with insulated conductors (aerial cables);
- replacement and/or upgrading of network components;
- improvement of protection, control and automation systems;
- redesign of the network to allow its intentional islanded operation, by using emergency generators in the availability of the DSO or by advanced operating solutions that involve distributed generation.

The priority order of corrective actions to be introduced on the network is defined according to the benefit/cost ratio of each solution, considering as benefit the reduction of the RI achieved thanks to the overmentioned expedients. Since usually the refurbishment actions impact on many SSs at the same time, the cost/benefit analysis can also be performed on a MV feeder (or even a Primary Substation) basis, considering the cumulative RI obtained as sum of the indexes relevant to each SS in the area supplied by the feeder (or PS).

III. Experimental Application of the Method to a Real Distribution Network

In this paper, the approach proposed for the evaluation of the phenomenon of accretion of ice and snow sleeves on overhead lines is applied and tested on a real distribution grid, managed by Edyna, the DSO of the Italian Autonomous Province of Bolzano. The grid is involved in the Smart City Vizze project [5][6], a pilot experimentation promoted by Alperia (an Italian energy provider) in collaboration with Politecnico di Milano, aimed to research, develop and test a dispatching platform and novel functionalities to support DSOs in managing in an effective manner their networks. The experiment is conducted on the MV network covering the mountain territory of the Vizze valley, supplied by the Prati di Vizze Primary Substation (PS). The PS is equipped with two HV/MV transformers (rated power 40 MVA), each one feeding an MV busbar (rated voltage 20 kV). The grid covers the municipalities of Brennero, Campo di Trens, Racines, Val di Vizze and Vipiteno (Fig. 1). Respectively, 4 and 5 feeders depart from each MV busbar of the Primary Substation. The total load downstream the substation is equal to 38.27 MW.

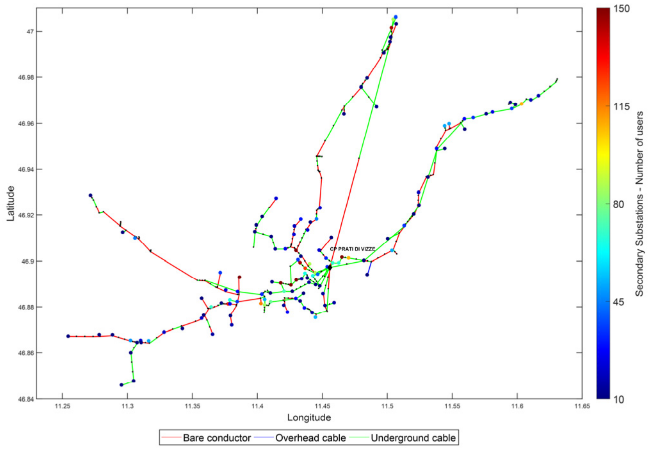

Fig. 1. Power lines types and number of users per SS of Prati di Vizze network.

A. *Resilience of Prati di Vizze Network: the Actual Scenario*

In a first phase, the study aimed to assess the current resilience of the MV network. The output of the analysis constitutes a useful starting point for the DSO in order to arrange the workplan required by the Italian Energy Authority regarding the ice and snow sleeves phenomenon.

Being the network involved in the project deployed on a rural area, the number of LV users per SS (a total of 127 MV/LV SSs is connected to the Prati di Vizze network) is rather small (Fig. 2): for example, 45 SSs feed less than 10 users. Therefore, the risk associated to their supply interruption is also limited. However, in a few cases, the number of LV users supplied is more significant, over 150 units. According to ARERA guidelines, a greater resilience of lines aimed at supplying these SS is required, because an electrical interruption potentially affects a greater number of users.

Fig. 3 and Fig. 4 show the results obtained applying the procedure developed to the MV network Prati di Vizze. Colors represent the severity of the issue evaluated on power lines and SSs. The red color on overhead lines (segments in the figure) means a high probability of a breaking event on conductors due to ice/snow sleeves accretion, while the blue color shows a negligible effect estimated for the phenomenon. Overhead and underground cable lines are immune to the problem, so they are all shown in blue color (return period of the event greater than 50 years). For example, lines shown in orange color, referring to a return period of about 12.5 years, means that the creation of ice and snow sleeves is supposed to cause the breaking of overhead lines bare conductors with a probability of occurrence 1/12.5 (i.e. 8%) per year.

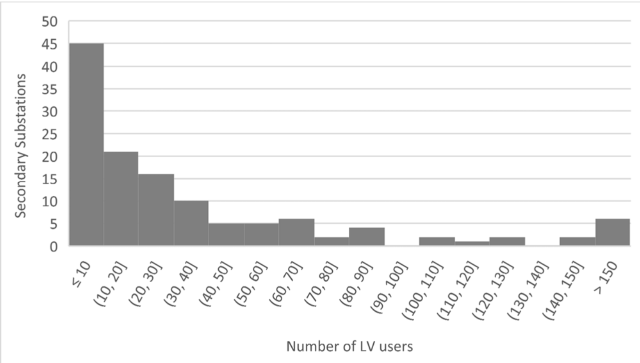

Fig. 2. Distribution number of LV users supplied by the SSs.

In Fig. 3 and Fig. 4, dots represent the return period of supply interruptions for each SS. The effects on users' continuity of service of a line fault change according to the structure and characteristics of the MV network: if it is not possible to reverse feed the faulted MV line, the fault causes a supply interruption for all the SSs downstream; otherwise, it is necessary to find among all the paths allowing for the SS resupply the one having the greatest resilience against ice and snow sleeves. Its return period becomes the return period of the interruptive event of the SS under analysis.

Fig. 4 highlights the altimetric profile of the MV network. Since the elevation of overhead lines also affects the intensity of the snow and ice sleeves accretion phenomenon (usually, the greater the elevation, the greater the stress on conductors), also this parameter has been modeled in the tool and considered in the analysis.

Although the Prati di Vizze grid presents some points of connection with other near distribution systems, for the sake of this study it is considered an "electrical island": i.e. the possibility to use adjacent grids for the recovery of supply in case of fault is not considered. Neighboring MV networks are in fact managed by other DSOs (in this case, minor network operators having in charge the management of only one PS or a portion of MV network in a small area), therefore the characteristics of their grids (e.g. technical specifications of conductors, loading degree of lines, etc.) are mostly unknown to Edyna. With a conservative approach, their contribution is neglected in the resilience assessment.

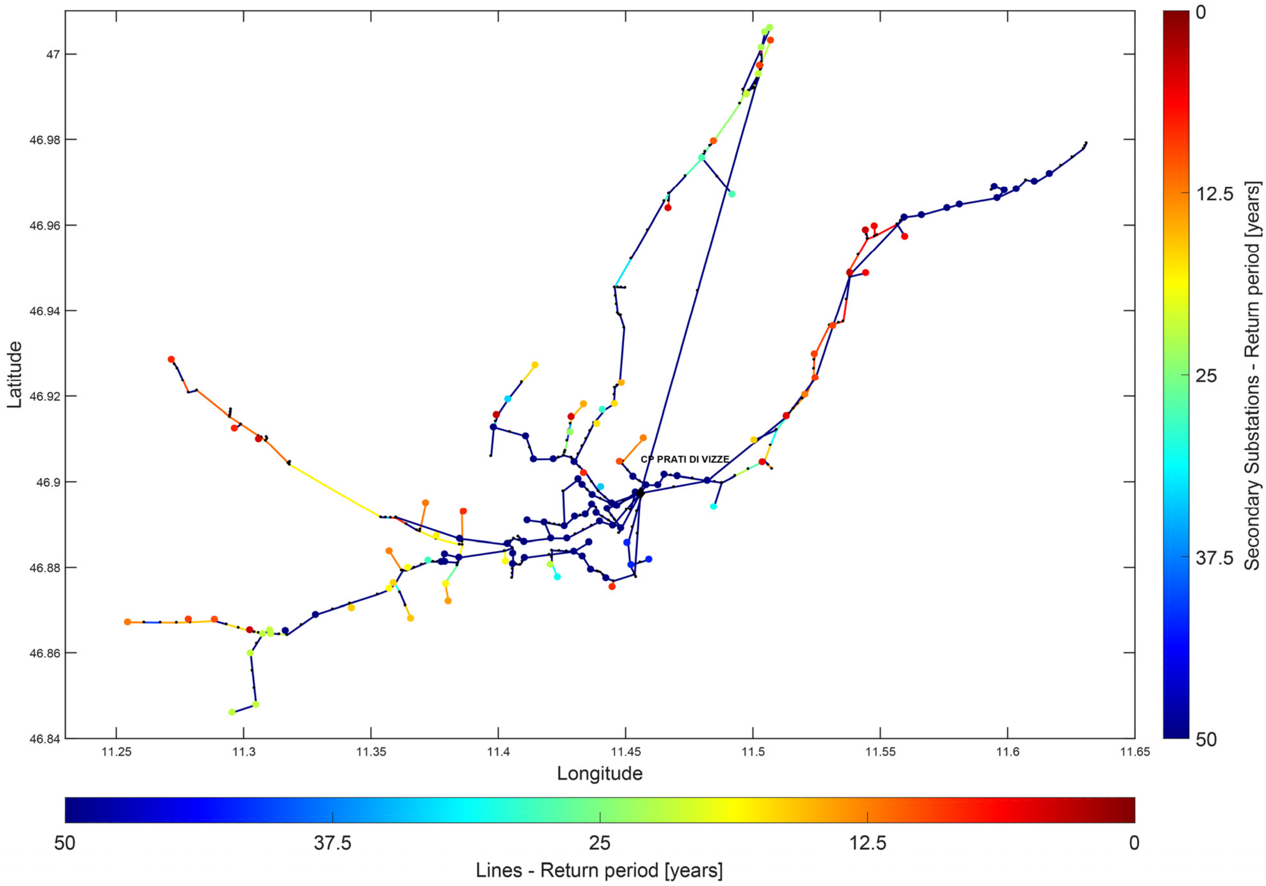

Fig. 3. Return period of power lines and Secondary Substations of MV network.

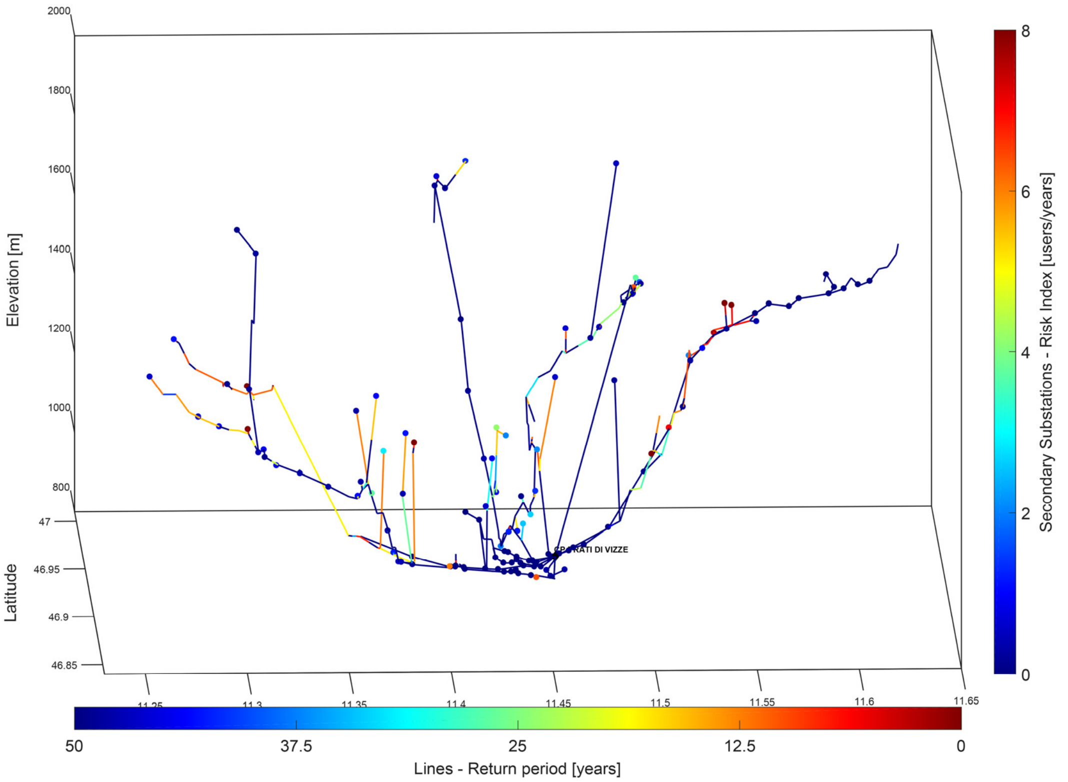

Fig. 4. Return period of power lines and Secondary Substations of MV network – altimetric view.

Fig. 5 reports the distribution of SSs according to their return period (reciprocal of their yearly probability of interruption). As one can observe, almost half of SSs (57 SSs over a total of 127) are affected negligibly by the problem (return period >50 years). However, about 20% of them (24 SSs) present return periods lower than 10 years (for 8 of them < 5 years), resulting in estimated interruption rates due to conductors breaking for the mechanical stress caused by ice and snow sleeves, respectively, greater than 10% and 20% per year.

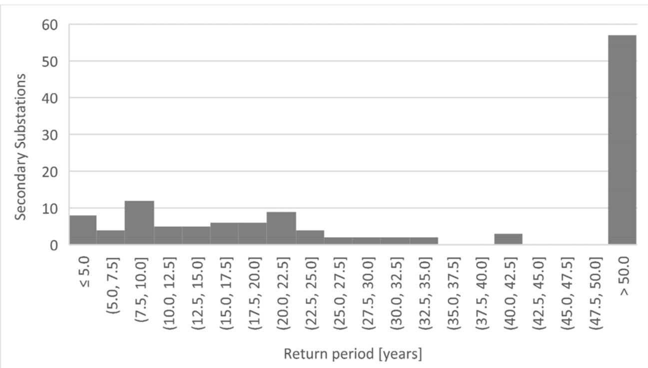

Fig. 5. Distribution of the return periods of SSs.

The Risk Index, evaluated through (1), allows the DSO to identify the actual impact of the phenomenon on the users' continuity of service: it is defined as the ratio between the number of LV users downstream the SS and the return period of the interruptive event assessed with the previously mentioned methodology. Fig. 6 shows the Risk Index evaluated for the SSs of the Prati di Vizze valley (colored dots in figure). Most of SSs show a limited risk associated to the phenomenon, because of the small number of LV supplied and/or the low probability of occurrence of the service interruption. However, in some cases the Risk Index is significantly higher: a RI greater than 5 and 10% has been found, respectively, on 11 and 4 SSs (on a total of 127 MV/LV substations). These substations show the most serious problems, and consequently should have the priority in the resilience workplan of the DSO.

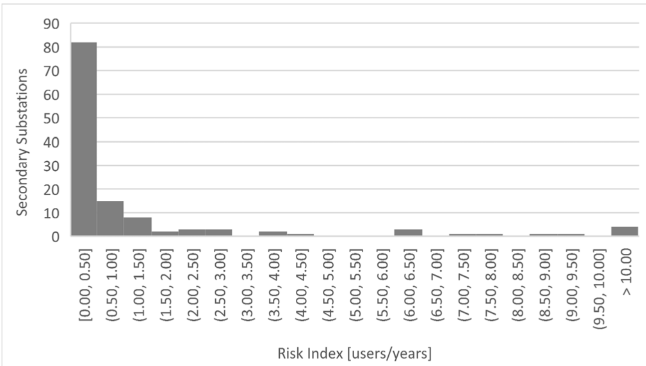

Fig. 6. Distribution the Risk Index of SSs.

B. Improvement of grid resilience by reconductoring: benefits evaluation on a MV feeder

In this paper, the effectiveness of the tool developed is assessed with respect to a hypothesis of refurbishment of the "Val di Vizze" feeder, a MV line departing from the Prati di

Vizze PS, devoted supplying the Vizze valley. The refurbishment is based on the substitution of the segments of line that highlighted significant risks according to ice and snow sleeves phenomenon with conductors with higher section. In particular, the intervention required to upgrade about 8.27 km of MV line. The final section adopted for the (Aluminum) conductors is 70 mm^2. Previous sections were 25 mm^2 (4.92 km), 35 mm^2 (2.71 km) and 50 mm^2 (0.64 km). Fig. 7 shows the Risk Index evaluated after the reconductoring of the feeder (the original situation of the line is shown in the rightmost part of Fig. 3 and Fig. 4).

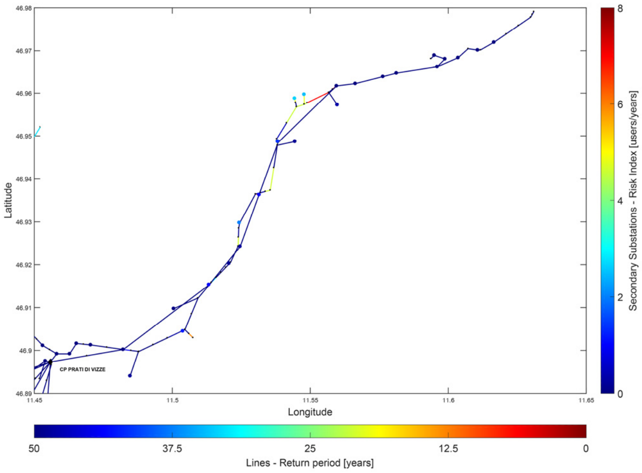

Fig. 7. Risk Index of Val di Vizze feeder SSs after the reconductoring.

Finally, Fig. 8 reports the RI distribution of SSs before and after (respectively, upper and lower graph) the feeder upgrade. It is possible to observe the beneficial effects of the intervention, which significantly reduced the risk of interruption for the 5 most critical SSs.

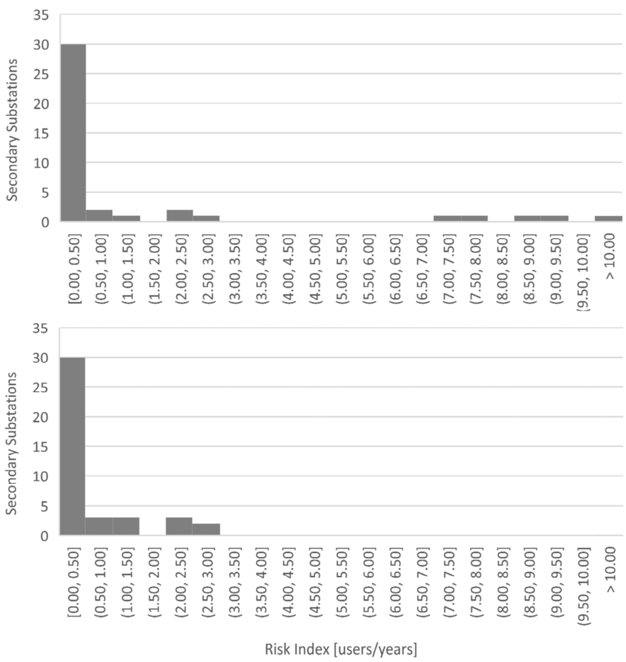

Fig. 8. Distribution the RI of Val di Vizze feeder SSs, before and after the reconductoring (respectively, upper and lower graph in figure).

IV. Conclusion

The study presented a novel methodology for the evaluation of the occurrence and the impact on users' continuity of service of the phenomenon of creation of ice and snow sleeves on conductors of overhead lines. The approach has been developed within the framework of the Smart City Vizze project, a collaboration between Alperia, Edyna and Politecnico di Milano. The procedure is compliant with the guidelines provided by ARERA and will allow for the prioritization and selection of the investments devoted to improving the resilience of the distribution power system.

Acknowledgment

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