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A Novel Method for Evaluating the Resilience of Distribution Networks during Heat Waves

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***Abstract*—This paper describes a methodology for the evaluation of the distribution networks resilience in large metropolitan areas during heat waves. These weather conditions (very hot and dry periods) in recent years have become more and more frequent due to climate changes. Thus, procedures to evaluate their impact on electricity networks assumed a particular interest. In the paper, a novel approach for the modeling of heat waves is presented and an example is provided based on a simple network in order to better highlight how the procedure works, the results obtained and the methodology potentials. A combination of three in-cascade models is used to evaluate the fault risk of each network component: a thermal, an aging and a reliability model. On the basis of the work described in this paper, a software tool has been implemented, used by the Italian DSO Areti SpA for evaluating the resilience of the distribution system of the Italian capital of Rome.**

***Index Terms*—Distribution grids; resilience; heat wave; thermal model; Arrhenius law**

I. INTRODUCTION

Over the course of recent years, in Italy, a significant increase in prolonged interruptions of the electricity supply, due to extreme, particularly violent and wide-ranging meteorological events, has been observed. In this context, events particularly significant were those occurred in Emilia Romagna and Lombardy in February 2015, when over 360,000 customers were without power for more than 8 hours, and more recently in the Abruzzo and Marche regions in January 2017, with disruptions that lasted over 72 hours for 39,000 customers [1]. Large snowfalls still remain in Italy the weather factor more impacting on the continuity of service of electricity networks [2], especially for the accretion of ice sleeves along bare conductors of overhead lines. However, many other critical factors are potentially cause of wide-ranging outages, as for example floods from heavy rainfalls or “cloudbursts” (particularly critical for underground power substations), or windstorms causing the falling of trees on power lines. A further weather phenomenon that is assuming an increasing interest in recent years, especially for the distribution systems of large metropolitan areas, is represented by heat waves.

According to the definition of the World Meteorological Organization, a heat wave is a weather condition characterized by five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5 ℃ or more [3]. The detrimental effects of these events on the networks’ operation and users everyday life is well-known, since a few events occurred in the last years around the world testify their potential risk, such as the power outages occurred during the 2006 North American heat wave or the 2009 South Eastern Australia heat wave. In the past, these phenomena were typical of warm and dry climate areas of the planet. However, today, due to climate changes, there are becoming quite recurrent also in temperate zones.

A heat wave is a weather condition that involves particular stress for the distribution networks [4], especially for those ones covering large urban areas, where the load density is high and the grid is mainly (even, almost completely) constituted by underground cables: during very hot and drought periods, the network is often subject to a large number of faults, as a consequence of the over temperatures the power lines are exposed to. The thermal stress is caused by the combination of a few phenomena taking place during heat waves:

- The high ambient air temperature, which often excesses the 40 ℃;
- The rise of thermal resistance of the ground, making it difficult to dissipate the heat originated from the cables by Joule losses;
- The increase of conductors’ operating current, caused by the new trends in users’ consumptions (i.e. the growing use of air conditioning systems), which can result critical especially during the reverse-feeding of MV lines (i.e. after the occurrence of a first fault on the grid).

It is worth considering that, with the evolution of users’ habits and the increasing dependence of household appliances on the electric energy carrier (heat pumps, induction cooktops, etc.), today also household customers

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are asking for a highly reliable power supply. Therefore, DSOs must ensure an adequate resilience of the network, with the goal to minimize the impact of heat waves and other extreme events in terms of faults occurrence and support the rapid recovery of power supply in the case of outages. A reliable power supply is also a key to avoid safety concerns for the people involved (as better explained in the next section, power outages during major weather accidents can last hours or even days).

In order to push DSOs to move in the direction of ensuring a better resilience of their networks, the Italian Regulatory Authority for Energy, Networks and Environment (hereinafter, ARERA) carried out in the last years a wide set of actions [5]. In the regulatory framework for the period 2019-2024, in particular, a reward/penalty scheme has been defined by ARERA in order to support DSOs in the development of initiatives aimed to improve the reliability of the grid to cope with critical meteorological events. To have their resilience-oriented investments admitted to this novel reward/penalty mechanism, DSOs have to prove that they are worth to be realized with high priority. This must be done through a combination of risk analysis and cost-benefit analyses, based on suitable models of the distribution network, but also of the conditions at the boundaries affecting the grid's components (e.g. weather phenomena).

In the literature, many works can be found on how improving the reliability of a network through the support of local flexibility resources (such as dispersed generation and energy storage systems) [6], [7]. In some cases, also the possibility of an islanded operation of the network is considered, in order to avoid power supply interruptions [8]. Other approaches aim at improving in an integrated way all the energy systems (e.g., the power grid and the natural gas network) in a given region or district [9].

In the outlined framework, this paper describes a method for the evaluation of the resilience of distribution networks against the interruptions that are likely to occur during heat waves, focusing in particular on the modeling of the accelerated thermal aging of cable power lines and on the evaluation of its effects on the reliability of the power supply service. The procedure, in perspective, can be a useful tool for the DSOs to prioritize the network's investments according to a quantitative estimation of their benefits on the continuity of supply. The approach described has been actually adopted by the Italian DSO Areti in order to elaborate a resilience plan for the years 2019-2021 for the medium voltage distribution system covering the capital of Rome [10].

The next sections of the paper are organized as follows. After this Introduction, in Section II the approach put in place by the Italian Regulatory Authority to promote the improvement of distribution grids' resilience is presented. Then, in Section III, the methodology developed in order to assess the resilience of distribution MV networks in urban areas against heat waves is discussed. The method is exemplified through a numerical example in Section IV. Finally, some conclusions are drawn.

II. ITALIAN REGULATION FOR THE POWER SYSTEM'S RESILIENCE

Although, starting from 2000, incentive regulatory mechanisms have been enforced by ARERA with the purpose to foster a better continuity of service [11], in the last years, a noticeable increase in the number and duration of supply interruptions occurred, especially due to extremely severe weather events, that are excluded by the indicators (SAIDI and SAIFI+MAIFI, both net of interruptions due to exogenous stress beyond the design limits of the networks) used for incentivizing improvement in continuity of supply.

Extreme weather events can provoke a large number of interruptions, in some cases also with very long duration. For example, in 2015, on a national average, 41 minutes of customers' power supply have been lost for faults of responsibility of the DSOs (interruptions subject to the standard reward/penalty scheme in place in Italy for the continuity of service) and 69 minutes for faults out of the control of the DSOs (due to so called *force majeure* events, mostly caused by extreme weather events). The problem is also related with the duration of these interruptions, usually much longer than the standard ones. In this regard, in the extreme weather events occurred in Italy in the last 6 years (2012-2017), about 300 thousand users experienced power outages with a duration of 1-2 days, and more than 30.000 for more than 4-5 days [12].

Due to the exclusion of *force majeure* events from the SAIDI and SAIFI+MAIFI incentive regulations, in the past DSOs were not stimulated to improve the quality of service to those customers connected to the weakest portions of distribution networks, which therefore bear the highest risk to be disconnected in case of extremely severe weather. Therefore, ARERA deemed necessary to investigate how to increase the resilience of electricity grids according to two aspects: on the one hand, increasing network robustness by raising, where economically sustainable according to a risk assessment, the design limits that identify the infrastructural capability to withstand extreme stresses (e.g., by raising, to an economically sustainable level, design limits of electrical lines); on the other hand, improving the effectiveness and promptness of service recovery, i.e. the system's capability to return to acceptable working condition, even by means of temporary measures (e.g. the temporary repowering of unsupplied electrical substations using mobile gensets).

With Decision 31/2018/R/eel [13], ARERA introduced, after a wide consultation process [1], the obligation for major DSOs (20 DSOs connected to the Transmission grid and serving 99.3% of the Italian customers), to prepare and publish every year - as part of their Network Development Plans - their own "Resilience Plan", a rolling three-year plan of investments selected by each DSO, according to priority criteria, to increase the robustness of its own distribution grid against severe weather phenomena. Investments correspond to a plurality of projects, each one referring to a distribution line, with the possibility of being extended to its own back-feeding line(s) too. Each project must be identified, among other parameters, by risk index before and after the intervention, forecasted costs, estimated benefits, and by expected starting and completion dates.

Benefits must be estimated by DSOs mainly as lower customer outage costs thanks to the highest network resilience that can be obtained through the project under consideration; this benefit is valuated using regulatory values for avoided interruptions (12 €/kWh not supplied for household consumers and 54 €/kWh not supplied for the commercial and industrial consumers), and a given duration of interruptions, assessed looking at interruptions occurred in emergency conditions: 16 hours for damages to overhead lines and 8 hours for underground cables. Other minor benefits have been considered as well.

For each project included in the Resilience Plan, a risk index (IRI) has to be computed by the DSO. It is defined as the ratio between the impact of a power outage in terms of expected number of customers involved in the interruption (NUD) and the return time (TR) of the fault event:

$$\mathrm{IRI} = \frac{\mathrm{NUD}}{\mathrm{TR}} \tag{1}$$

The index of (1) is functional to define a merit order (from higher risk to lower risk) among the projects selected by the DSO to increase the grid resilience. It requires, in order to be assessed, a proper modeling of the electrical network and of the weather and physical phenomena under analysis.

III. THE METHOD PROPOSED FOR THE EVALUATION OF THE POWER SYSTEM RESILIENCE

In the framework outlined in the previous sections, Politecnico di Milano developed a numerical methodology for the assessment of the risk index of medium voltage distribution networks during heat wave events. The algorithms have been implemented in a software tool used by the Italian DSO Areti SpA for evaluating the resilience of the distribution system of the capital of Rome. The output of the analysis is the yearly risk of customers' interruption during heat waves, which constitutes the basis of the quantitative assessment required for the submission of the Resilience Plan to ARERA.

The flow diagram of the numerical procedure is reported in Fig. 1. It has been designed as a combination of three in-cascade modules:

- A thermal model aimed at evaluating the operating temperature achieved by the cable and its insulation during the heat wave;
- An aging model having the goal of computing the deterioration of insulation characteristics resulting as effect of the calendar life and over temperatures;
- A reliability model that, starting from the outputs of the previous stages, computes the expected fault rates during heat waves.

It is important to point out that, in spite of the fact the proposed model could be used to estimate the probability of any supply interruption caused by the aging of grid's components, in the context outlined about the power systems resilience, only the risk of double faults (i.e. the occurrence in sequence, e.g. within a few hours, of two faults on the same portion of network, e.g. a MV feeder and its back feeding MV circuit) is of interest. In fact, in medium voltage distribution grids, in the case of a first fault, the users' continuity of service can usually be restored after some seconds/minutes through the network automation (e.g. by back feeding the faulted line). This because in Italy distribution networks are typically designed as meshed systems, when possible (and economically feasible), with two ways of supply of each electrical substation, although each feeder is operated radially. If a second fault occurs before the fixing of the first one, however, there is the risk for the part of the grid involved to remain isolated, thus preventing the possibility of restoring the supply service of the downstream users until the accomplishment of the repair works, even if a reconfiguration of the network is carried out.

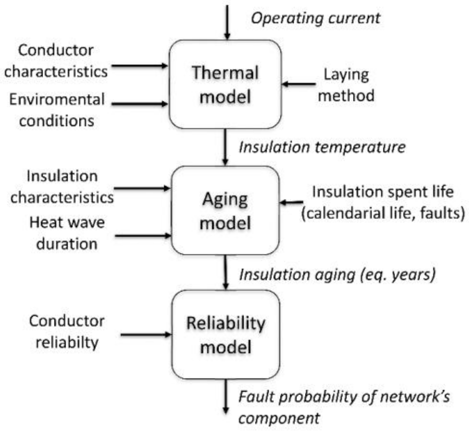

Fig. 1. Flow diagram of the numerical procedure adopted.

The procedure has been developed in the Matlab programming language and then, in order to be able to apply it systematically to the overall Areti power distribution system, implemented in the DigSilent PowerFactory software environment. To perform all the calculations required, the software collects and processes:

- The topological structure of the MV electricity network;
- The data characteristic of branches, as type of cable, length, laying method, year of construction, number of joints;
- Data relevant to electrical busses, as number and power of and downstream users and category of the load supplied (residential/non-residential);
- Power withdrawals of each secondary substation on a year (peak and off-peak conditions).

Moreover, in the procedure, currents in the various operating conditions (standard configuration and back feeding configuration following a fault) are calculated by means of power flow calculations.

Each fault scenario, modeled by a specific network configuration, is reconstructed by acting on the switching devices modeled in PowerFactory (the faulted branch is opened, and the back-feeding branch is closed).

A. Thermal Model

The thermal model is aimed at estimating the temperature achieved by the insulation during the heat wave event. Its parameters depend on the technical characteristics of the MV cable, on the method adopted for its laying and on the specific environmental conditions in place.

Regarding the MV cable, in particular, the following data should be considered in the modeling:

- Cable section;
- Conductor material (copper, aluminum);
- Structure of the cable (number of cores, layers number and thickness, etc.).

The main impact of cable structure on the thermal behavior of the insulation is related to power losses for Joule effect: under the same working conditions of the cable (same operating current and same environmental conditions), if the conductor's electrical resistance increases, the Joule heating also increases. Therefore, the probability of over temperature will be greater and so also the probability of an accelerated aging of the insulation. Similarly, also the cable structure affects the temperature assumed by the insulation during the heat wave, because it influences the ability of the cable to dissipate heat to the ground.

In the proposed model, the temperature of the cable insulation material (θ_c) is determined through the electro-thermal analogy. The layers considered (Fig. 2) are:

- Between conductor and sheath (T1);
- Between sheath and reinforcement (T2);
- Of the outer covering of the cable (T3);
- Of the external means in which the cable is immersed, such as air, concrete or ground (T4).

In Fig. 2, θ_a represents the ambient temperature. The calculation of thermal resistances of the cable and ground has been performed according to IEC 60287-2-1: 2015 standard: "Electric cables - Calculation of the current rating - Part 2-1: Thermal resistance - Calculation of the thermal resistance".

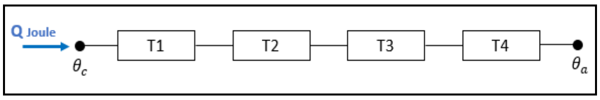

Fig. 2. Thermal model adopted in the study obtained through electro-thermal analogy.

B. Aging Model

In order to evaluate the impact of the cable operating temperature obtained by the thermal model in terms of useful life reduction in case of operation beyond the design limits, a proper aging model has been adopted in the study. It allows evaluating the deterioration of the mechanical and electrical characteristics of the electrical joint or cable insulation, depending on the temperature assumed during the heat wave.

The model has been derived from the Arrhenius law, which is commonly used for the evaluation of the thermal aging of polymeric materials and allows to correlate, according to an exponential equation, the rate at which the material degradation reaction takes place (degradation rate) and the temperature at which the insulation is exposed. In the study, the Arrhenius laws is used to describe the relationship between the material degradation rate, the operating temperature and the duration of exposure to the condition under analysis. A common formulation of the law is:

$$t_c = t_0 \cdot e^{-\frac{E_a}{k_b}\left(\frac{1}{\theta_c}-\frac{1}{\theta_0}\right)} \qquad (2)$$

Equation (2) computes the expected lifespan of the insulation (t_c) as a function of the following parameters [14]:

- Activation energy E_a, defined as the energy required to activate the reaction with the material, varying for different polymers between 0.9 and 1.8 eV;
- Boltzmann constant k_b [eV/K];
- Max. service temperature of the insulation θ_0 [K];
- Actual operating temperature of the insulation θ_c [K];
- Expected life of the insulation at the max. service temperature t_0 [years];
- Expected life of the insulation at the actual service temperature t_c [years].

Therefore, according to (2), the exposure of an insulation at temperature θ_c for a period of time t_c produces a degradation equivalent to its exposure at a temperature θ_0 for a time t_0. Then, exposing a material to a higher temperature for a shorter duration will result in a degradation equivalent to an exposure for a longer time at a lower temperature (see Fig. 3). For the EPR (the most common insulation material for MV cables), the values of θ_0 and t_0 are, respectively, equal to 90 ℃ and 30 years.

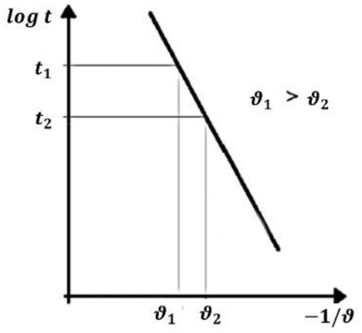

Fig. 3. Effect of the service temperature on the expected life of the insulation according to Arrhenius law.

Fig. 4 shows the operating temperature of a cable as a function of its operating current, in standard conditions (blue characteristic) and during a heat wave (red one). In the former case (standard conditions), the ambient temperature is assumed equal to 30 ℃ and the ground thermal resistance to 1.5 K*m/W, while in the latter one (during heat waves) the ambient temperature and the ground thermal resistance are supposed to increase up to, respectively, 40 ℃ and 2.5 K*m/W. The *ampacity* of a cable is defined as the current that in standard conditions causes the increasing of the cable temperature to the max service temperature. Therefore, during the normal operation, any amount of current lower than the rated one will originate a temperature lower than the max service one. Consequently, the lifetime of the insulation is expected to be equal to the rated one (30 years for EPR). During heat waves, the lower heat dissipation through the ground causes the insulation temperature to be higher. In particular, a range of current will exist, lower than the rated ampacity of the cable that will cause over temperature of the insulation and consequently its accelerated aging (red area in Fig. 4).

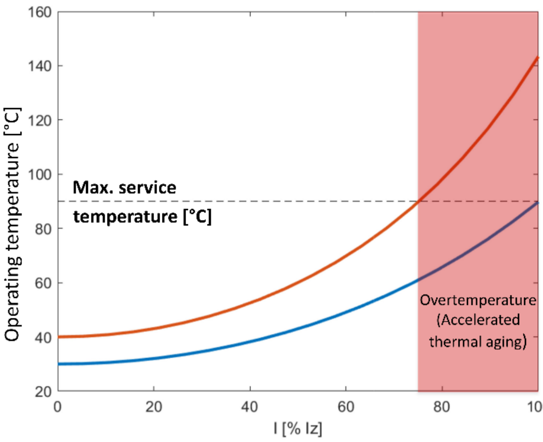

Fig. 4. Cable temperature as a function of operating current (in % of ampacity in standard conditions). Blue = temp. in standard conditions; red = temp. during heat waves.

C. Reliability Model

In order to evaluate the risk of fault of each electrical line of the distribution network, a reliability model based on the 2-parameters Weibull failure rate distribution has been adopted in the study:

$$h(t) = \frac{k}{\lambda^k} t^{k-1} \tag{3}$$

where λ is the scale parameter or characteristic life of the component and k is the shape parameter. The value of these terms has been defined according to the historical continuity of service indexes measured on the Areti distribution system and to literature data [15].

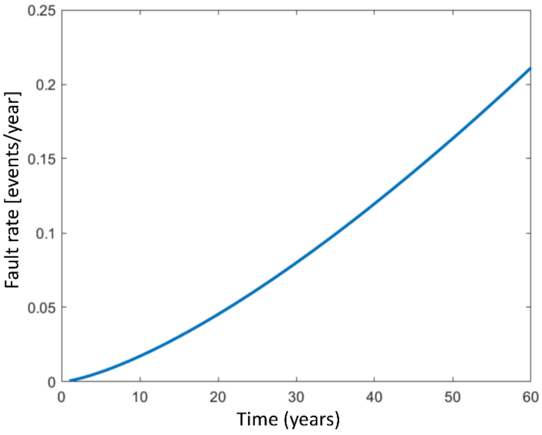

Fig. 5. Fault rate of a unitary length of cable as a function of the relevant life.

Fig. 5 reports an example of failure rate distribution for a unitary length of MV cable. On the x-axis, the spent life of the conductor is represented. Each grid's element has its own Weibull characteristic, depending on the type of component under analysis (underground cable or electrical joint), its past history (number of overcurrent events involving the line) and calendar age at the time of the simulation.

IV. THE METHOD PROPOSED: A NUMERICAL EXAMPLE

For a better understating of the effectiveness of the procedure proposed in evaluating the resilience of distribution networks, in the present section the approach is applied to a simple model of 15 kV grid (Fig. 6). The network is composed by two MV feeders, departing from two different Primary Substations (PS), supplying four Secondary Substations (SS), each one with 250 low voltage users downstream. At the end of the two feeders a tie-switch is assumed to be present, which allows the mutual back feeding of the lines in case of fault.

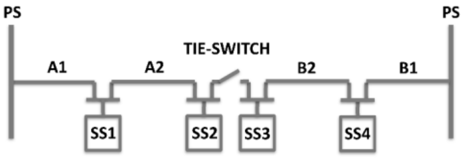

Fig. 6. Single-phase diagram of the example distribution grid under analysis.

Each trunk is assumed 5 km long and made of a 150 mm^2 underground aluminum cable, with laying depth of 1 m. The fault rate characteristic of Fig. 5 is considered for each line, which are assumed 20 years old.

The current flowing on the network is reported in Table I, before the 1st fault (standard configuration) and after the 1st fault (reverse feeding configuration). In the reverse feeding configuration, currents are usually higher, because the same amount of power (all users are supposed to be still connected to the network) must be carried by a lower number of branches (the healthy ones). The risk of 1st fault is evaluated on 20 heat waves of 12 hours each. After the fault, the network is reconfigured, the risk of the 2nd one is computed in the 6 hours that follow the reconfiguration maneuver. Finally, in Table I the combined risk of 1st+2nd fault on each couple of lines, so called double fault, is reported.

According to the risk analysis in Table I, the resilience indexes in Table II has been computed for the network. Because of the very simple topology considered, for the four SS a similar risk of interruption and return time have been obtained. As on can observe in Table I, the double faults involving sections A1 and B1 have, according to the method proposed, a risk of occurrence much greater than the other combinations. This because, if a 1st fault occurs on the branch of line departing from the PS (e.g. A1), the grid is reconfigured supplying all the substations by the opposite feeder. The branch atop of the line used for back feeding (e.g. B1) is the most stressed, because, in this new condition, it must carry the overall power required to supply all the substations. In spite of the factthat the current flowing on the back feeding line is lower than the cable rated ampacity (200 A vs 289 A), the different boundary conditions during heat waves are cause of over temperatures (equal to 153 ℃, value in output to the thermal model adopted), resulting in an accelerated aging of cable insulation.

TABLE I: RISK OF FAULTS EVALUATED ON THE EXAMPLE DISTRIBUTION GRID

1st fault branch	Current on the branch of the 1st fault [A]	Risk of 1st fault [events/year]	2nd fault branch	Current on the branch of the 2nd fault [A]	Risk of 2nd fault [events/year]	Double fault risk [events/year]
A1	100	1,51E-02	A2	50	3,77E-04	5,68E-06
A1	100	1,51E-02	B1	200	7,79E-01	1,18E-02
A1	100	1,51E-02	B2	150	6,97E-03	1,05E-04
A2	50	1,51E-02	A1	50	3,77E-04	5,68E-06
A2	50	1,51E-02	B1	150	6,97E-03	1,05E-04
A2	50	1,51E-02	B2	100	3,77E-04	5,68E-06
B1	100	1,51E-02	A1	200	7,79E-01	1,18E-02
B1	100	1,51E-02	A2	150	6,97E-03	1,05E-04
B1	100	1,51E-02	B2	50	3,77E-04	5,68E-06
B2	50	1,51E-02	A1	150	6,97E-03	1,05E-04
B2	50	1,51E-02	A2	100	3,77E-04	5,68E-06
B2	50	1,51E-02	B1	50	3,77E-04	5,68E-06

TABLE II: RESILIENCE INDEXES OF SECONDARY SUBSTATIONS

Substation	Risk of interruption [events/year]	Return Time [years]	IRI [n.users/years]
SS1	2,37E-02	42,14	5,93
SS2	2,39E-02	41,77	5,99
SS3	2,39E-02	41,77	5,99
SS4	2,37E-02	42,14	5,93

V. CONCLUSION

In this paper, an overview of the incentive regulation introduced by the Italian regulator ARERA to improve the power system's resilience at distribution level has been summarized. Then, a novel approach for the evaluation of the resilience of MV distribution grids covering large metropolitan areas has been described.

The method, developed by Politecnico di Milano – Dept. of Energy in the framework of a collaboration with the Italian DSO Areti, allows evaluating the frequency and the impact on users' continuity of service of heat waves. In recent years, the occurrence of these extreme weather conditions is increasing also in temperate climate areas of the world, such as Italy, thus motivating the development of proper actions to increase the power systems' resilience against this risk factor and to improve the restoration readiness of the power supply service.

The procedure proposed is compliant with the guidelines provided by ARERA and will allow for the prioritization and selection of the investments proposed by the DSO to improve the resilience of the distribution systems in urban and metropolitan contexts.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Davide Falabretti designed and developed the algorithm proposed in the paper and applied it to the network of example presented in Section IV. Stefano Liotta and Alessandro Palazzoli supported the research, providing information about the DSO's needs, role and experience in the resilience evaluation. Luca Lo Schiavo provided guidance on the regulatory framework relevant to the topic outlined in Section I. All authors discussed the approach and results, contributed to the final manuscript and had approved it.

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