Resilience Assessment in TDE's Distribution Grid: Risk Model for Tree Falls

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***Abstract*—Climate change due to global warming implies an increased frequency of critical events, such as snowstorms, windstorms, floods, water bomb and heat waves, even in areas not usually affected by these events. These extreme weather events can have a significant impact on the operation of electricity distribution and transmission grids, with potentially disastrous effects that can affect a significant number of customers. In this context, Terni Distribuzione Elettrica (TDE, which is the Distribution System Operator, DSO, of Terni, a city placed in the center of Italy), according to the prompt of the Italian Regulatory Authority, is working to plan improvements in resilience of its grid against extreme weather events. In this paper, authors discuss the resilience management of the TDE's grid with respect to tree falls, according to previously developed methodologies, which have been already applied to evaluate the resilience of the electrical grid versus several critical threats, such as forming of ice sleeves, heat waves and floods.**

Keywords—resilience, distribution grids, risk management, tree falls.

I. Introduction

Frequency increase of extreme meteorological events due to climate changes, such as snowstorms, windstorms, floods and heat waves, also in unusual areas, may have a high impact on the operation of electrical distribution and transmission grids [1]. Since the possible unavailability of grids could affect a huge number of users, the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) has solicited distribution (DSOs) and transmission system operators (TSOs) to plan resiliency improvements of their grids [2], [3]. To this purpose, Terni Distribuzione Elettrica (TDE) [4] (as the productivity unit of ASM Terni S.p.A., it is the DSO of Terni's city), has developed differentiated methodologies, described in previous papers and in this one, in order to assess the resilience of its electricity grids against different threats.

According to ARERA Directive 31/2018/R/eel, the assessment of the resilience of energy systems must take into account several risk factors linked to extreme weather events [5]. The TDE, in previous work, has already assessed the main impacts on its network, as well as the related mitigation measures, caused by some extreme meteorological events, such as:

- ice or snow sleeves formation (due to icing phenomena and heavy snowfalls also on lowland areas) on bare conductors of the overhead lines with their consequent breakage [6];
- local flooding (due to very intense rains in a short time, commonly referred as "water bombs") or river flooding (due to prolonged rains) that may cause outages of secondary substations [7];
- extreme heat waves (due to high temperatures for several consecutive days associated with prolonged drought phenomena inhibiting heat dissipation) that can lead to failures both in secondary cabins and underground lines (on cables and joints) [8];

In this document, the evaluation method applied by TDE is described to drive the grid reinforcement design and planning against wind storms, which can directly stress overhead lines, cause tree falls on them or lead to the detachment of tree branches, which can hit the overhead lines even if they are distant from the woods.

In particular, this paper presents a procedure able to assess the resilience of a distribution grid considering the tree fall threat. The aim is to validate a workflow, through which a DSO can evaluate the resilience of its own infrastructure as is and it can easily identify the remedial actions that can be adopted to enhance grid resilience.

The paper is organized as follows: Section II describes the methodology to evaluate resilience of a distribution network and describes how tree fall events have been modelled; Section III presents results obtained applying the model on a real distribution network (i.e., the distribution grid operated by TDE), as well as criteria to design network enforcement driven by resilience; in Section IV, a discussion of the results is presented. Finally, Section V concludes the paper.

II. Resiliency Management Model for Tree Falls

The main elements and indices needed to calculate resilience of each single asset (e.g., in this study, of all overhead lines, OHLs) of the distribution network are described.

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A. Risk Factors

The analysis of resilience is based on a risk index of the power supply disconnection, due to tree falls on overhead lines.

This risk index (*IRI*) is the product between the probability (defined as the inverse of the return period, *TR*, of the event, i.e. $PD = TR^{-1}$) that the tree fall will produce a lack of service and the extent of the damage produced by the disruption; the damage is evaluated as number of low voltage users disconnected (*NUD*) during the event [3], that is:

$$IRI = PD \cdot NUD = NUD \cdot TR^{-1} \tag{1}$$

The resilience index (*IRE*) is the inverse of the risk index and is therefore equal to the return period of the event divided by the number of low voltage users disconnected:

$$IRE = TR \cdot NUD^{-1} \tag{2}$$

The evaluation of the return period associated with tree fall has not yet been coded by ARERA. In the studies carried out by *e-distribuzione* in collaboration with SET Distribuzione, the Trentino Region DSO, equivalent return period (TR_e) is estimated based on the identification of "wooded homogeneous areas", provided by "Institute of Environmental Protection and Research" (ISPRA) by differentiating the territory according to altitude ranges, in which climatic factors and plant species are considered homogeneous [9]. By knowing the number of multiple outages observed in the woods of the homogenous areas due to the tree fall, TR_e is thus calculated.

In the present paper, however, having a detailed characterization of the territory where OHLs are located, but at the same time having a reduced statistical basis for tree fall events, we adopted the following procedure in order to get credible TR_e values. The ratio δ of number of most serious tree fall events N_{faults} (i.e. only events within the Perturbed Condition Periods were taken into account – PCP) recorded in the whole MV network during a time period of years N_{years} to the time period of years N_{years} is at first calculated:

$$\delta = \frac{N_{faults}}{N_{years}}. \tag{3}$$

Subsequently, after calculating the aggregate "tree-covered" length, *ATCL* (km), of the MV distribution network, the fault rate per kilometer $\tau_{f,km}$ (faults·years^{-1}·km^{-1}) may be evaluated:

$$\tau_{f,km} = \frac{\delta}{ATCL}. \tag{4}$$

Defining the return period per kilometer, TR_{km}, as the inverse of $\tau_{f,km}$, the *TR* of each branch of the whole MV distribution network, TR_{branch} (years·faults^{-1}), is obtained from the ratio of TR_{km} to the "tree-covered" length (*TCL*) of each MV branch:

$$TR_{branch} = \frac{TR_{km}}{TCL} \tag{5}$$

Lastly, the equivalent return period, TR_e, assigned to each MV/LV secondary substation, SS, supplied by the MV distribution network is the minimum TR_{branch} amongst the MV branches whose faults may disconnect the SS. Details about *TCL* and *ATCL* calculations are provided in Section III.

The above described approach is, in the authors' opinion, particularly suitable to assess TR_e values locally, with a sufficient accuracy level even in the presence of a small number of events recorded over time. Of course, its accuracy can be significantly improved extending its application to larger geographical areas (e.g., of provincial or regional extension), for which there may also be available a significant statistical basis for this type of events.

B. Resilience Indices

In addition to the *IRE* previously defined, the authors have introduced further performance indices aimed at assessing the grid resilience [6-8]; they are:

- the *IGCR* index, which evaluates the network ability to perform back-feeding, defined as

$$IGCR = \frac{\sum_i k \cdot NUC_i}{NUT} \tag{6}$$

  where, considering a generic threat, *k* is 1 if there is always a path to perform back-feeding ($TR_{e,i} = \infty$), otherwise *k* is 0 if $TR_{e,i} \neq \infty$ ($TR_{e,i}$ is the TR_e of the i-th node), while NUC_i and *NUT* are the number of LV users connected to the node *i* and to all the network respectively; the sum is calculated for all the nodes of the network; this index does not depend on the type of threat, since it is a property of the network, representing its capability to perform back-feeding;

- with respect to the considered threat, the degree of network resilience (*IGRR*) is the following:

$$IGRR = \frac{\left[\sum_i \left(1 - \frac{1}{TR_{e,i}}\right) \cdot NUC_i\right]}{NUT} \tag{7}$$

- regardless of the threat, the index of users' vulnerability (*IGVU*) from the network is calculated as follows:

$$IGVU = \frac{\sum_j NUD_j}{NUT} \tag{8}$$

  when the *j*-th asset of the network is disconnected, NUD_j is the number of LV users unsupplied; the sum is applied to a number of scenarios equal to the number of branches of the network.

C. Simulation Model

The whole MV distribution network is represented as a graph, in order to define the complete network topology in terms of nodes and connection between nodes, i.e. branches. To each element of the graph, typology is then assigned (i.e., HV/MV transformer, MV/LV transformer, switching, disconnector, tee-off, OHL and cable line). Moreover, number of users supplied by each MV/LV transformer is obtained. All these input data are provided by the SCADA (Supervisory Control and Data Acquisition) system installed in the TDE distribution network. Other relevant inputs for the assessment of resilience in case of tree fall threat are δ, *ATCL* and *TCL*, by means of which TR_{branch} for each branch of the MV distribution network and TR_e of each MV/LV transformer may be computed with (3)-(5).

Calculation of indices *IRI* and *IRE* with (1) and (2), respectively, requires the evaluation of *NUD* for each fault in the network: this is performed by applying all possible faults to the completely meshed network (i.e., considering that all switches and connections are close, so as to take into account the back-feeding possibility) and identifying for each fault the isolated nodes: in such a way, it is possible to assess *NUD* for each network asset. In case of tree fall threat, only faults related to MV branches with *TCL* greater than zero, i.e. TR_{branch} is a finite number (Section III describes how *TCL* is calculated for each MV branch), are considered. Together with *IRI* and *IRE*, other outputs of the model are the remaining resilience indices *IGCR*, *IGRR* and *IGVU*, calculated with (6), (7) and (8), respectively. The entire described model has been implemented in a procedure, developed by the authors in the Octave environment. More detailed descriptions of the procedure are provided in [6]-[8].

The indices introduced and the simulation model implemented are independent with respect to the type of threat, and are able to consider the effects on the grids of single or multiple extreme natural events and human attacks. This approach allows to better evaluate the improvement actions that may be introduced in the distribution grid [6]-[8]. In particular, in this document, the corrective actions to improve the grid resilience with respect to the threat represented by falling trees will be analysed.

III. Results

A. Area of Interest

The procedure has been applied to the MV distribution network owned by A.S.M. Terni S.p.A. and operated by TDE. The network is located in Terni, in the center of Italy, and is connected to the Italian HV Transmission network through three HV/MV substations. Moreover, since the MV network is operated at two different voltage levels, 10 kV and 20 kV, respectively, six MV/MV substations are installed. About 65600 LV users are connected, for an aggregate 250 MW installed capacity and 890 MWh average daily energy supplied. MV distribution network is about 645 km long, of which 62.23% are overhead lines and the remaining 33.77% are underground cables.

The area covered by the distribution network is about 212.5 km^2 and is characterized by a 1008 m elevation gain (the minimum height is 97 m, the maximum one is 1105 m). For the 22.74% of the area under study, altitude is higher than 600 m, for the 37.72% altitude is between 300 m and 600 m, for the remaining 39.54% of the area altitude is lower than 300 m [10]

With respect to tree fall threat, in the area covered by the distribution network five different subareas, derived from the city's land-use plan, have been identified:

- woods;
- agricultural areas;
- rows of trees;
- river parks;
- redevelopment areas;

A map defining the above described areas has been developed in the Geographical Information System (GIS) environment; the graph of the MV distribution network has been then overlapped to the map. In this study, the considered graph elements are: nodes (all the possible supply points, i.e. HV/MV transformers, MV/LV transformers, stiff connections, disconnectors) and branches (i.e. network elements connecting two nodes). For each branch, the incidence of each previously defined subarea (in terms of percent of length) has been obtained by comparison with GIS representation.

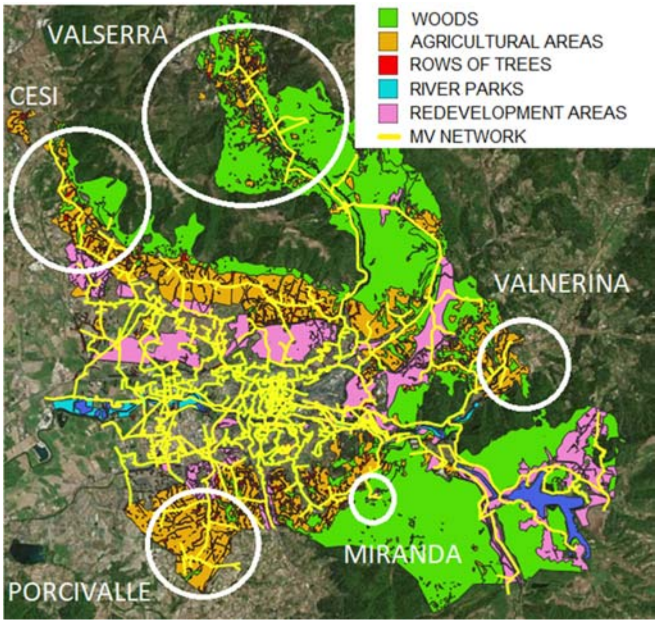

Fig. 1. Subareas in Terni municipality according to tree fall.

In order to evaluate the *TCL* of each MV branch (a segment of an MV feeder between two different network assets, which are MV/LV substations, disconnectors and tee-offs) of the distribution network, different weights are assigned to each subarea:

- *TCL* for a branch in woods is equal to the real branch length;
- *TCL* for a branch in agricultural areas is obtained by multiplying the length by 0.3;
- *TCL* for a branch crossed by rows of trees is obtained by assigning to each tree crossing an equivalent length equal to 50 m;
- *TCL* for a branch in river parks is obtained by multiplying the length by 2;
- *TCL* for a branch in redevelopment areas is obtained by multiplying the length by 0.7;
- *TCL* for a branch outside the five areas is zero (i.e. urban areas).

By means of the above described weights, for each branch all incidences in the subareas may be evaluated in terms of meters of “equivalent wooded area”, obtaining the equivalent *TCL*. Summing *TCLs* of all MV branches, the “equivalent wooded area” is thus calculated, obtaining *ATCL* = 101.5 km, against an overall MV network length of 645 km.

Figure 1 reports the map of Terni municipality subdivided in the previously described five subareas; also most critical zones are pointed out.

The evaluation of δ in (3) has been carried out considering only the most relevant fault events (Perturbed Condition Periods) caused by falling of trees on the distribution network in a 12 years time period (i.e. N_{years}=12), obtaining N_{faults}=20. Applying (3) and (4), the MV network fault rate (also equal to

TR_{km}^{-1}) of about 1 event each 60.9 km per year has been calculated. Weighting the *TCL* of each MV branch with TR_{km}, TR_{branch} due to tree fall may be thus evaluated with (5). Each node of the graph representing a SS has been further weighted with the number of LV users connected to SS: in such a way, applying the algorithm described in [6] TR_e of all SSs are evaluated and, consequently, also *IRI* and *IRE* may be assessed. Clearly, SSs with highest *IRI* values are the most critical ones with respect to tree fall threat.

B. Numerical Results

In the area of interest, 942 network assets have been considered: moreover, for each one of them a critical MV branch (i.e., the MV branch with the minimum TR_e due to tree falls) has been identified. For each network asset, *IRI* has been calculated according to (1). As an example, Fig. 2 shows the most critical (i.e. with the highest *IRI*) asset in the network, which is an MV/LV substation located in the critical zone named "CESI" of Fig. 1.

IRI of 209 out of 942 network assets are greater than zero. In order to reduce the impact of tree fall threat, reinforcements are required with the aim to increase the network meshing (i.e. new MV branches must be added as to increase the ability to perform back-feeding). Amongst all possible reinforcements, only the ones whose installation cost is economically sustainable, compared to the obtainable TR_e, have been taken into consideration. Under this constraint, only five reinforcements have been selected, which, however, are able to improve back-feeding only for 32 assets out of 209 with *IRI* greater than zero.

Table I summarizes the effect of reinforcements proposed by the procedure in terms of *IRI* (assets are sorted in decreasing order with respect to *IRI* ex ante; only the first nine and the last assets are shown), whereas Table II reports the TR_e increase for the same assets shown in Table I. A summary of the effect of proposed five cost-effective reinforcements with respect to *IRI* index of the above-mentioned 32 network assets is shown in Fig. 3. It is worth noting that very small but not nil *IRI* ex post values refers to SSs not connected with in-out insertion scheme, but connected in antenna by means of very short stretches of OHL.

Figure 4 shows a comparison between *IRI* ex ante and *IRI* ex post values for all the 209 assets with *IRI* ex ante values greater than 0 users·faults·years^{-1}. For the sake of clarity, *IRI* values have been grouped in intervals with 0.2 users·faults·years^{-1} width, whereas the number of assets is in percent of the overall number of assets, i.e. 209. It can be seen that, after reinforcements, no asset has *IRI* greater than 1 (largest *IRI* ex post value is 0.941 users·faults·years^{-1}); moreover, the effect of reinforcements is to increase the number of assets with *IRI* value lesser than 0.2 users·faults·years^{-1} (89% against 82% without reinforcements). Lastly, Table III reports the ex ante and ex post values for other indexes regarding the whole network, namely *IGCR*, *IGRR* and *IGVU*, which however are less relevant than *IRI* of each asset in this case study.

IV. Discussion

The analysis of the numerical results shows that:

- the network is already adequately resilient, its degree of pre-intervention resilience is in fact very close to the unit (see Tab. III),

$$IGRR_{\text{ex-ante}} = 0.99957$$

  so, all reinforcements could only produce negligible increases in this index;
- the proposed countermeasures have been identified according to the *IRI* index (see $IRI_{\text{ex-ante}}$ values in Tab. I);
- remedial actions are in agreement with those in progress and envisaged in the Network Development Plan, confirming the reliability of the proposed simulation model;
- the benefit of all selected mitigation actions are confirmed by noteworthy reductions of $IRI_{\text{ex-post}}$ values (see Tab. I) and by a simultaneous increase of equivalent return periods, $TR_{\text{e,ex-post}}$, of the corresponding assets (see Tab. II) ;
- although the mitigation actions detected cannot produce appreciable improvements in the *IGRR* index (as previously observed), they are nevertheless capable of producing a significant reduction of the grid degree of vulnerability, the *IGVU* index is reduced by 63.44%, passing from 0.40048 to 0.25408 (see Table III); this confirms the benefits of these reinforcements in terms of reducing the number of users disconnected during this and other possible threats;
- it must be highlighted that *IGVU*=0 is theoretically reachable if all SSs are connected with in- out insertion scheme, i.e. no SS is supplied in antenna;
- *IGCR* increases from 0.82317 to 0.83146, with only a 1% improvement and this is basically due to two main reasons: *IGCR* does not depend on the typology of the threat (in this case, tree fall); reinforcements proposed by the procedure aim at improving the network meshing only with respect to the specific threat (in fact, if reinforcements were proposed to increase generically the network meshing, without focusing on tree fall threat, they would increase *IGCR* but, at the same time, would be less effective with respect of tree fall threat, leading to higher values of $IRI_{ex\ post}$ index);

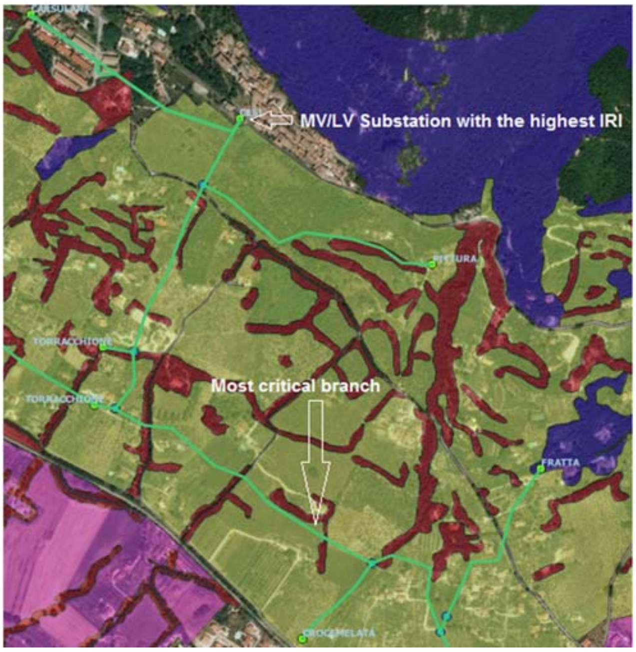

Fig. 2. The most critical asset identified in the MV distribution network, together with its critical MV branch.

TABLE I. *IRI* REDUCTION DUE TO REINFORCEMENTS

N°	*IRI* ex ante	*IRI* ex post	Reinforcement #
1	1.3832	0.0000	4
2	1.2800	0.7934	3
3	1.0909	0.0360	5
4	0.9820	0.0000	4
5	0.8485	0.2902	5
6	0.7273	0.2400	5
7	0.6364	0.1173	5
8	0.5571	0.1080	1
9	0.5303	0.2108	5
…			
32	0.0077	0.0074	5

TABLE II. TR_e INCREASE DUE TO REINFORCEMENTS FOR THE SAME ASSETS IN TABLE I

N°	Users	TR_e ex ante	TR_e ex post
1	231	167	∞
2	192	150	242
3	72	66	2000
4	164	167	∞
5	56	66	193
6	48	66	200
7	42	66	358
8	39	70	361
9	35	66	166
…			
32	1	130	136

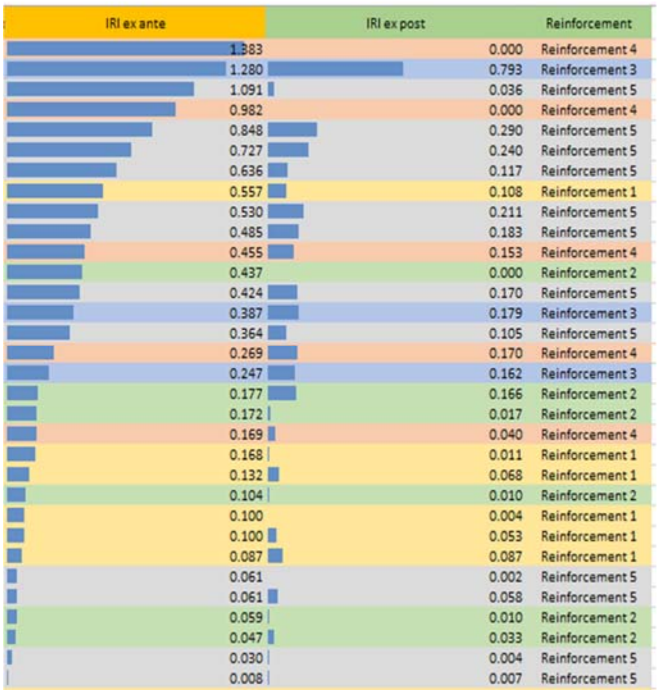

Fig. 3. Reduction of *IRI* index due to the five detected cost-effective reinforcements for the 32 network assets.

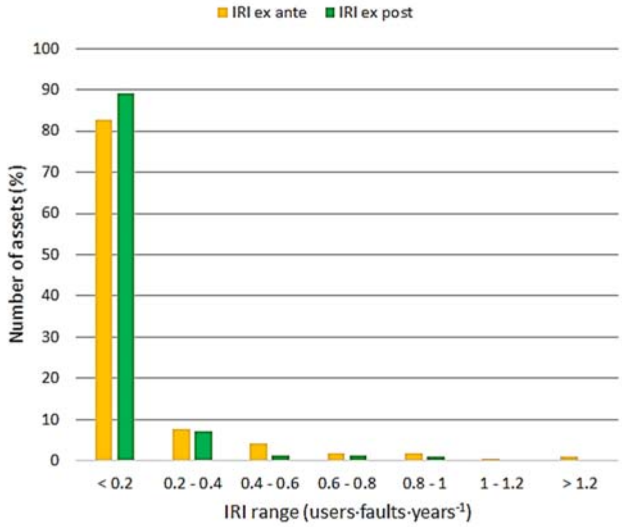

Fig. 4. Comparison between *IRI* values before and after reinforcements for all the 209 network assets with *IRI* ex ante greater than zero.

TABLE III. GLOBAL RESILIENCE INDICES COMPARING EX-ANTE AND EX-POST STATUS OF THE NETWORK

Global resilience indices	ex-ante	ex-post
Degree of back-feeding – *IGCR*	0.82317	0.83146
Degree of resilience – *IGRR* (tree falls)	0.99957	0.99971
Degree of vulnerability – *IGVU*	0.40048	0.25408

As a general remark, it should be pointed out that all results obtained regarding network resilience depend on *NUD*, simply evaluated as the sum of LV users supplied by the SSs involved in the fault, as coded by the Italian Authority ARERA in [3]. This approach does not allow taking into account the impact of possible overloading of lines during degraded service conditions, which depends on the actual load and not only on the number of users. By using *NUD* resilience indices are thus indifferent to the energy demand variation over time. Another crucial point heavily affecting resilience assessment is the representation of the MV distribution network. Since the methodology proposed by [3] does not require to take into account network constraints (i.e. maximum power flows through branches and maximum and minimum voltages at nodes), the procedure only represents the network topology, as described in Section II.C. In such a way, it is not possible to check if back feeding can cause some violation of network constraints. A Monte Carlo procedure, able to account for different load profiles over time and coupled with a power flow program in order to represent the whole MV network, would be able to overcome the above described limitations.

V. CONCLUSIONS

In this paper, the authors have applied a procedure, developed and validated in previous studies, able to assess the resilience of a distribution network threatened by several possible extreme weather events (such as snowstorms, floods, water bombs and heat waves). In particular, this study assessed the resilience of distribution grids against the threat caused by tree falls due to wind and/or rain storms.

The absence of a well-established and coded methodology for the evaluation of return periods associated with all assets exposed to this threat has required the preliminary definition of criteria to determine these values that may be applied both locally (e.g., on a municipal scale) and on large geographical areas (e.g., on a regional and/or national scale). The proposed methodology, based on statistical data (also coming from a reduced number of events) and land classification provided by the local authority made it possible to define the return periods of all assets threatened by tree falls in the geographical area corresponding to the Municipality of Terni (Italy), assuming the TDE distribution grid as case study.

The proposed tool is able to evaluate the resilience of a distribution grid with respect to tree falls threat. Starting from the network graph, evaluated by assuming closed all the switches and all the equipment that allows back-feeding, all the possible failures associated with tree falls were analysed, taking into account the return periods of every asset, which have been calculated on the basis of the criteria introduced. All possible scenarios have been evaluated providing the list of unsupplied nodes and, consequently, computing all relevant indices able to assess resilience. Remedial actions have been identified and rated by their impact on resilience. Several simulations have been carried out in order to evaluate the effects of the remedial actions about either increasing the meshing degree of the network or reducing the vulnerability of the secondary substations. The effectiveness of the remedial actions proposed by the procedure has been validated by the increasing of the resilience indices. Finally, results show that the algorithm is reliable and robust regardless the type of the threat and the network configuration, helping DSO to assess the resilience of its grid and to identify the most suited remedial actions.

The generality of the approach and indices proposed, as well as the robustness of the implemented methodology for the evaluation of remedial actions, have made this tool applicable for the assessment of the distribution grid resilience with respect, not only to tree falls, but also to several other threats. Those so far considered by the authors were the ice sleeves, floods, heat waves and tree falls, each of which was supposed to act individually. In future works, the authors will analyze the resilience of a distribution network and its increase, as a result of the simultaneous action of extreme weather events, that expose all assets to multiple threats simultaneously. Moreover, different MV load profiles will be taken into account and the proposed remedial actions will be checked against the violation of network constraints.

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