Chapter

Modeling Resilience in Electrical Distribution Networks

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Abstract

Electrical distribution networks deliver a fundamental service to citizens. However, they are still highly vulnerable to natural hazards as well as to cyberattacks; therefore, additional commitment and investments are needed to foster their resilience. Toward that, this paper presents and proposes the use of a complex simulation model, called reconfiguration simulator (RecSIM), enabling to evaluate the effectiveness of resilience enhancement strategies for electric distribution networks and the required resources to implement them. The focus is, in particular, on one specific attribute of resilience, namely, the readiness, i.e., the promptness and efficiency to recover the service functionality after a crisis event by managing and deploying the available resources rapidly and effectively. RecSIM allows estimating how and to what extent technological, topological, and management issues might improve electrical distribution networks' functionality after the occurrence of accidental faults, accounting for interdependency issues and reconfiguration possibilities. The viability of implementing RecSIM on a real and large urban network is showcased in the paper with reference to the study case of the electrical distribution network (EDN) of Rome city.

Keywords: electrical distribution network, resilience metrics, interdependence, outage recovery, vulnerability

1. Introduction

Electrical distribution network (EDN) delivers a fundamental service to citizens. Unfortunately they are still very vulnerable to natural hazards as well as to cyberattacks; both can affect electricity infrastructures, leading to power outages that might distress and delay the recovery of the impacted communities. In Europe, for example, adverse space weather, riverine floods, and earthquakes are recognized to be the prevalent hazards with high potential for disrupting the functions of the power grid. While high-voltage overhead transmission systems proved to be robust to earthquake hazard, earthquake-induced ground motion was recognized to cause inertial damage to electric distribution system, in particular, to heavy equipment, such as generators and transformers, and brittle items, such as ceramics, as well as to the building housing the substations; earthquake-induced ground failure and soil liquefaction were identified as one the main causes of damage to buried electric infrastructure components [1–3]. The time required for restoring power supply following earthquakes was seen to range from few hours to months (being more frequently in the range from 1 to 4 days) depending on the repair capabilities (e.g., availability of man power, machinery, and spare material) and on the level of access to damaged facilities, possibly delayed by damages to the road network and/or by traffic congestion [1].

As far as adverse meteorological conditions are concerned, both the transmission and distribution systems have been adversely affected by water bomb causing flooding, extreme snowfall or windstorm, and overheating [1]. As an example, high-voltage overhead lines might be subjected to failure due to ice sleeves on conductors during snowfalls; medium-voltage overhead lines might be subjected to failure due to fall of trees during windstorms, while overheating can cause catastrophic failure of underground cables [4, 5]. As an example, a clamorous case occurred in Auckland, New Zealand, in 1998 that involved the failure of four major underground cables due to overheating in the summer period. The failure of the underground cables kicked off a 5-week-long power outage across the central city and caused an estimated long-term economic impact equivalent to 0.1–0.3% New Zealand's gross domestic product.

From the few facts mentioned above, it is clear that additional commitment and investments would be worthwhile, if not needed, to foster the resilience of the EDNs.

EDN resilience can be pursued steadily before, during, and after crisis situations by putting in place, in an integrated and balanced way, various actions aimed at increasing the *robustness* of the network components; the *redundancy* of the system; the *resourcefulness*, i.e., availability of resources (such as backup systems, human and material resources); and the *readiness*, i.e., the promptness and efficiency to recover the service functionality after a crisis event by managing and deploying the available resources rapidly and effectively [6].

The works presented in this paper focuses on the resilience enhancement *after crisis events*, with particular emphasis on the factors that might increase the *readiness*.

A further aspect examined by this work is the interdependency of EDNs with other critical infrastructures (CIs) and the implication that this has on the resilience of EDNs. EDNs are, in fact, essential for the functionality of other services such as water, telecommunications (tlc), roads, and other public services; on the other hand, EDNs depend on other critical infrastructures to deliver their service. In particular, EDNs are highly dependent on telecommunication that provides telecontrol functionality to EDN, to such an extent that it is fair to assume that electrical and telecommunication networks do represent a unique, connected *system of systems* whose control, protection, and management should be performed as if it was a unique system.

The paper is organized as follows. Section 2 presents relevant works related to existing methods for the resilience assessment of EDNs. Section 3 contains a description of the abstract model representing the topology and the constitutive elements of a large EDN. Section 4 identifies metrics for assessing the resilience of EDNs in terms of induced service impacts after different kinds of perturbations. Finally, Section 6 presents the implementation on the case study of Rome, Italy.

2. Related work

All definitions of resilience point to quantify a *dynamic, adaptive property of a system* (or of a *system of systems*) expressing its ability to withstand perturbations and to recover, rapidly and effectively, to equilibrium condition as similar as possible to that prior to perturbation [6–9]. When dealing with a technological system, the property of being "adaptive" inevitably leads to think of a number of factors influencing the way the system might adapt other than its mere technological qualities (such as robustness, technological update of the components, etc.): these factors might include risk awareness and preparedness, to ordinary and emergency management capabilities, in general to management skills which must support the technological and the design quality of the network. Moreover, in the case of a *system of systems*, the resilience of a system also depends on the degree of resilience of the other systems whose services should be available for the recovery process and on the level of dependency that is between them. The nowadays emphasis on the resilience property of technological systems is a direct symptom of the increased awareness that networks' functional dependency is one of the major issues that must be considered for improving CI protection and, as such, should be always appropriately considered when dealing with modeling and simulation activities of these systems. In particular, in Europe different resilience assessment and management methods as well as new approaches and guidelines are proposed within interesting EU projects. The project SMR [10] proposes the guidelines and system dynamic modeling and simulation techniques to increase the resilience of cities, whereas the IMPROVER project [11] is more focused on CI. The project DARWIN [12] is focused on improving responses to expected and unexpected crises affecting critical societal structures during natural disasters (e.g., flooding, earthquakes) and man-made disasters (e.g., cyberattacks). To achieve this, DARWIN developed resilience management guidelines aimed at critical infrastructure managers, crisis and emergency response managers, service providers, first responders, and policy makers. Other interesting EU project results can be found in [13–15]. The main objective of these projects is the proposal of European Resilience Management Guideline (ERMG) frameworks to drive decision and policy makers, local governments, and CI operators toward more resilient cities, societies, and infrastructures. ENEA has proposed CIPCast a framework for the resilience evaluation of a specific area that is compliant with the general guidelines proposed, for example, in [10]. CIPCast allows geographical information system, GIS-based risk assessment, and situational awareness through the continuous acquisition of different kinds of data from the field (e.g., weather forecast, infrastructure network status). Furthermore, CIPCast allows the assessment of the impacts and consequences of possible damage scenarios due to the prediction of natural hazards (such as heavy rain, flash floods, earthquakes) on the infrastructure networks and services and on the affected communities [17, 18]. The present work describes RecSIM [19], a specific module of CIPCast allowing the operational resilience assessment of electrical distribution grids. Indeed, there is an increasing demand for resilience framework assessment of power grids due to the fact that electrical power grids are recognized as critical lifelines that have to cope with different threads including extreme natural disasters and man-made attacks [20–25]. An extensive review of the existing metric system and evaluation methodologies, as well as a quantitative framework for power resilience evaluation, is presented in [9] where a classification and review of the different approaches proposed in literature are provided. Firstly, the proposed resilience evaluation approaches can be classified as qualitative methods and quantitative methods. Qualitative methods, thorough general picture of the system, provide guidelines for long-term energy policy making. In contrast, quantitative methods are often based on the quantification of system performances. The different methods can be further classified as simulation-based [20], analytical-based [21], and methods based on statistical analysis and historic outage data [22]. According to this classification, RecSIM can be classified as a quantitative-simulation-based approach. In particular, RecSIM takes in input a damage scenario (i.e., the set of electrical grid components in failure), the resource available to face the crisis in terms of crews available, and the functioning status of the supervisory control and data acquisition (SCADA) system and computes, in output, the power grid performance degradation in terms of the number of electrical users disconnected times the minutes of disconnection. As metrics for characterizing, in a posteriori analysis, the resilience of the power grid is proposed in [24] in terms of outage duration, dependency and interdependency relations, and the existence of energy storages, and a mathematical model for their calculation is proposed and implemented with respect to test cases focusing on recent natural disasters hitting major countries. In [25] the authors adopted the definition of resilience provided by the NIAC [26] that considers robustness, redundancy, and rapid recovery as main resilience features and developed a sequential Monte Carlo-based model for assessing the impact of weather on EDN resilience and applied to transmission networks. Their model considers the impact of human response during weather emergencies through the characterization of the delay required for the restoration of damaged components (due to delay in the development of individual situation awareness in the affected control centers) and the delay in the information sharing between the system agents, namely, the transmission system operators (TSOs) and the repair crews. As a test case, the model was applied to the transmission network considering extreme wind events, and simulation results show the resilience of the network in terms of robustness, redundancy, and response measures. Other past works also included the effects of humans [27], and others consider the dependencies [28] on resilience.

Similar to the approach proposed in [24] but considering the performance of EDN grids in complex urban contexts, RecSIM considers, simultaneously, the influence of different key features that might affect the time required for restoring the functionality of EDNs after extreme events, namely, (1) the degree of dependency with other networks providing essential services; (2) the network topology; (3) the number of repair crews available; (4) the number and functionality of SCADA telecontrol devices; and (5) the conditions of the road network and of the traffic that might delay repair activities.

3. Model description

The proposed model aims at providing a model scheme, for the resilience assessment of EDNs, where all the abovementioned influencing factors could be appropriately considered.

Having recognized that resilience mostly starts with a number of activities that are performed during the normal operational mode of the network such as ordinary management of assets, accurate prediction of the events, and subsequent efficacy in performing preparedness actions rather than only with a "last minute" emergency management; the idea was to realize advanced technological tools enabling CI operators to improve the operational procedures during the normal operation mode while ensuring a continuous monitoring of external scenarios to forecast possible perturbing events, accompanied to some ex ante prediction of the expected impact (in terms of both economic losses and reduction of citizen's well-being) of possible emergency scenarios. With this objective in mind, ENEA has designed and realized a decision support system (DSS), called CIPCast, enabling to provide an operational (24/7) forecast and risk analysis for the CI in a specific area [16]. CIPCast includes a map of CI elements which could be hit and disrupted by predicted natural events (flash floods, snow, landslides, flooding) or occurred events (such as earthquakes). CIPCast allows to estimate:

- The physical impacts induced on EDNs following earthquakes [17] and flooding events

- The impact on service functionality associated with the predicted damage of CI elements (in terms of outage duration and geographical extension), also considering possible perturbation cascades toward other networks and services [29, 30]

- The consequences of the predicted outages, according to several metrics accounting for economic losses, reduction of citizen well-being, and impacts on the quality of service

Within CIPCast, the RecSIM simulator represents the basic module for the resilience assessment of the EDN, as better described in Section 4.

This section describes the theoretical model used to represent the topology of a large EDN within RecSIM. **Figure 1** shows the main elements of the proposed model.

EDNs are composed of a number of primary substations (PS). Each PS originates one (or more) medium-voltage (MV) line(s) ending into a further PS. The MV line is cut at a certain stage by a switch which decouples the line into two halves, each one supplied by one of the two overlooking PS. Each line connects a number of secondary substations (SS) that, from the technological point of view, can be of one of the following types: "normal," "remotely telecontrolled," "automated," and "frontier" substations (represented, respectively, as white, gray, orange, and purple nodes in **Figure 1**). The "automated" substations are key elements of the network as they are able to perform automatically the isolation and restoration procedures needed to react to failures happening to their downstream substations. "Frontier" substations can be used to restore a portion of a MV line from another MV line. The configuration of the network switches defines the running configuration of the network. The electrical operator attempts to operate the network in order to maintain as much as possible the grid in a so-called normal configuration which is chosen by the operator as being able to allow the optimal operability of the grid (i.e., a good trade-off between robustness and efficiency, with the lowest possible electrical losses).

During a crisis, the electrical operator can change the configuration of the network by operating the switches along the perturbed lines; the operator brings the network into a "contingency" configuration, in order to restore as fast as possible the electrical service to the final users.

The model considers, furthermore, the dependencies between the electrical distribution grid supervisory control and data acquisition (SCADA) systems and the telecommunication components providing the telecontrol service. As shown in **Figure 2**, the telecontrolled substations use the communication service provided by the telecommunication (tlc) network components (i.e., the base transceiver

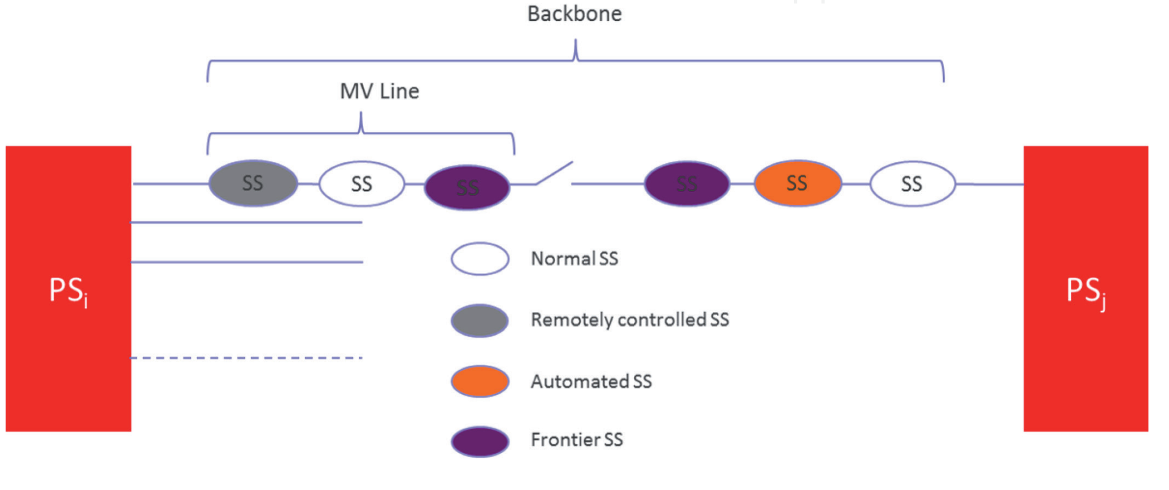

Figure 1.
The elements considered in the electrical distribution grid model.

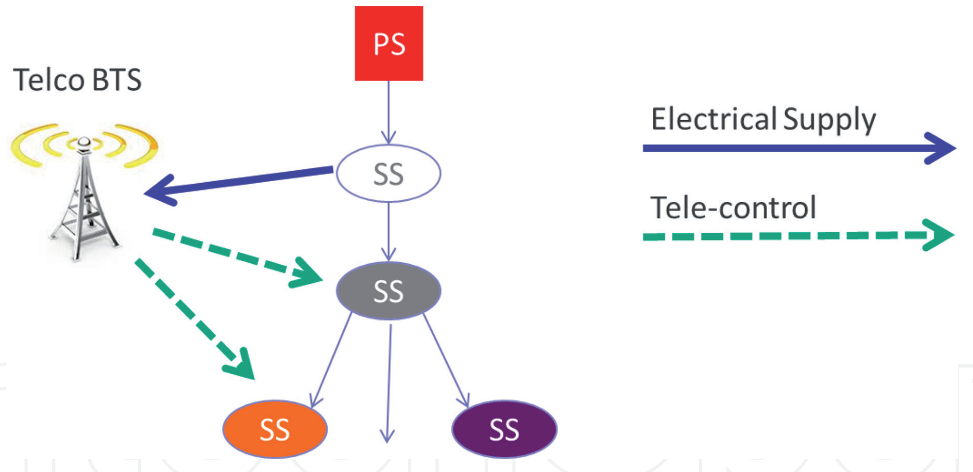

Figure 2.
Electrical distribution grid SCADA system and tlc dependencies.

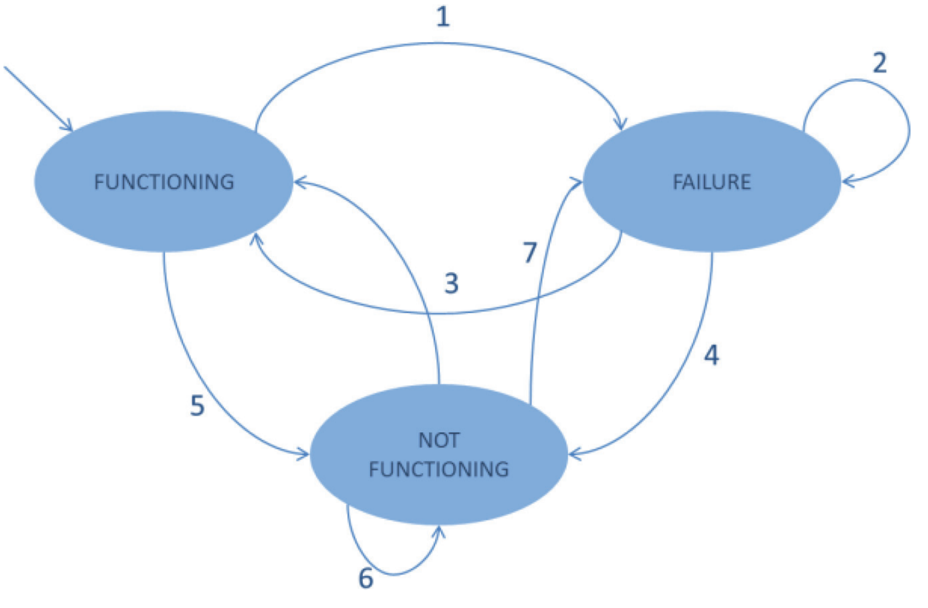

Figure 3.
Secondary substation (SS) finite state model.

station—BTS hereafter—of the telecommunication network). In turn, BTS are supplied by the energy provided by the SS of the EDN, thus configuring a dependency loop (no energy on a specific BTS, no telecontrol functionality of this BTS in favor of other SS of the network). In this work, we suppose that BTS do not have power backup, i.e., we will simulate the worst possible case. This implies that if a certain BTS depends on a certain substation SS that is in a damaged (or disconnected) state, that specific BTS will immediately stop functioning.

Each SS can be modeled as a finite state machine as shown in **Figure 3**. In normal conditions, the SS is in the initial "functioning" state. Starting from this state, the secondary substation (SS) can move into two different states:

- Failure state: when a failure in the SS occurs, transition 1 is activated. The SS remains in this state for the expected failure duration;

- Not functioning state: in case of a contingency, the protection devices of the grid will disconnect a number of secondary substations that will change their state from "functioning" to "not functioning." For example, when a SS moves into the failure state, all SS on the same line move into their not functioning state. A SS remains in this state waiting for restoration. The duration of the restoration can be in the range of few minutes (about 3–5 minutes) if the SS can be telecontrolled or much longer (50–55 minutes to few hours) depending on several factors (e.g., time required by emergency crews to reach the faulted substation and to restore it).

4. Resilience metrics

Let us assume to have an EDN characterized by its topology, with nodes $\boldsymbol{N}$ and links $\boldsymbol{L}$ corresponding to electrical stations and electrical lines, respectively. The function representing the *functioning state* for all the elements of the EDN is referred to as $\boldsymbol{F}$:

$$\boldsymbol{F}(\boldsymbol{N},\boldsymbol{L},\boldsymbol{t}) = \mathbf{0}\forall \boldsymbol{t} \tag{1}$$

if all elements $\boldsymbol{N}$ and $\boldsymbol{L}$ are in a *functioning state* and all telecontrol functionalities are active. Let us now introduce a perturbation function $\boldsymbol{P}$ that can change the state of one EDN element from the *functioning state* to one of the other possible states. In such a case

$$\boldsymbol{P}:\boldsymbol{F}(\boldsymbol{N},\boldsymbol{L},\boldsymbol{t}) \rightarrow \boldsymbol{F}'(\boldsymbol{N},\boldsymbol{L},\boldsymbol{t}) \tag{2}$$

where $\boldsymbol{F}'(\boldsymbol{N},\boldsymbol{L},\boldsymbol{t}) > \mathbf{0}$ for $\boldsymbol{t} \in [\boldsymbol{0},\boldsymbol{T}]$ and zero elsewhere. For the sake of simplicity, we will apply the perturbation P only to the electrical secondary station (referred to as SS). Time T represents the time when all elements have been repaired and the network comes back to its fully functional state $\boldsymbol{F(N, L, t)} = 0$. A perturbation $\boldsymbol{P}$, in principle, could affect one (or more) electrical station and bring it (or them) from the functioning state to the not functioning or the failure states.

The damage of a SS consequent to the introduction of $\boldsymbol{P}$ produces a sequence of perturbations on the network. These consist in the disconnection of other nodes along the line due to instantaneous opening of protection switches. The damaged nodes are replaced by power generators (PGs) to ensure electrical continuity to the node's customers. The damaged nodes will not be repaired in the time space of the simulation, but their function will be restored through the settlement of PGs. The disconnected nodes, in turn, are reconnected either through a telecontrol operation (if available) or by dispatching technical crews to provide manual reconnection. All such interventions require specific times, which are considered when defining a restoration sequence of interventions. The impact of the perturbation $\boldsymbol{P}$ on the EDN is measured using a key performance indicator (KPI) that is currently used by the Italian Energy Authority to estimate the level of service continuity of an EDN. Such KPI is expressed as the number of disconnected customers $\boldsymbol{ni}$ of the *i-th* EDN node times the duration τ_i of its disconnection. Such a value is expressed in terms of *kilominutes* (i.e., 10^3 minutes). Thus, if the damage of the *i-th* SS of the network will result in the disconnection of $\boldsymbol{m}$ SS, each one for a time τ_j $(\boldsymbol{j} = \mathbf{1},\boldsymbol{m})$, the overall KPI outage metrics will be measured in terms of $\boldsymbol{\Gamma}_i$ that is defined as follows:

$$\boldsymbol{\Gamma}_i = \sum_{j=1}^{m} \boldsymbol{n}_j \boldsymbol{\tau}_j \tag{3}$$

For a given perturbation $\boldsymbol{P}$, the integral over the simulated time span of Eq. (3) represents the perturbed functional state of the grid defined in Eq. (2):

$$\int_0^T \boldsymbol{F}'(\boldsymbol{N},\boldsymbol{L},\boldsymbol{t})\boldsymbol{dt} = \boldsymbol{\Gamma}_i \tag{4}$$

Γ_i, thus, represents the ***impact*** that the damage of an EDN element (the *i-th* node) can produce, by using an official KPI as a metric. The larger the value of Γ_i, the weaker the capability of the network to withstand the perturbation in terms of impacts produced on the EDN customers. In general the value of Γ_i depends on different factors (described in detail in Section 4) ranging from the topology of the network and the employed technologies to the efficiency of operator restoration procedures; therefore, it would not be inappropriate to correlate the value of Γ_i with the inverse of the resilience concept $\boldsymbol{R}$. In other terms

$$\boldsymbol{R}^{-1} \propto \boldsymbol{\Gamma}_i \tag{5}$$

We can generalize the concept by checking the EDN behavior versus all possible perturbations. The overall operational network resilience will be thus associated with the inverse of the value of the integral of the distribution function of all the Γ_i values ($D(\Gamma)$) resulting from the failure of each one of the N nodes of the EDN (normalized with respect to the total number of nodes N):

$$\boldsymbol{R} \propto \frac{1}{<\Gamma>} = \frac{\int D(\Gamma)d\Gamma}{\int \Gamma D(\Gamma)d\Gamma} \tag{6}$$

The higher the impact, the lower is the resulting operational resilience of the EDN network.

5. The simulation scheme and the reconfiguration simulator (RecSIM)

The RecSIM represents the basic module of the proposed framework for the resilience assessment of the EDN. RecSIM enables to carry on a "crisis game" consisting in the estimation of all Γ values resulting from the application of different perturbations. The simulator allows configuring different parameters allowing, in turn, the simulation of different electrical operational conditions (e.g., SCADA system not available, traffic jams, etc.) and the analysis of how the resilience indicator varies in these different operation conditions.

Figure 4 shows the input of the RecSIM and its output (i.e., the consequence of a perturbation in terms of Γ_i). RecSIM inputs are:

- *Network topology*—expressed as the EDN graph and the perturbation P represented by the SS brought in the damaged state.

- *SCADA system*—expressed in terms of the set $\boldsymbol{\Omega}$ of SS that can be remotely telecontrolled.

- *Efficiency of SCADA system*—expressed in terms of the functioning status of the BTS b_i providing communication service to the EDN and in terms of tlc_t the time needed to perform a remote operator action (using the EDN SCADA functionalities).

- *Efficiency of restoration procedures*—expressed in terms of the time needed by an emergency crew to reach a damaged SS ($\boldsymbol{tr_t}$), to perform a manual reconnection action ($\boldsymbol{m_t}$), and to set in place a PG to feed the users of the damaged SS (or of other SS which will result to be isolated, thus needing a PG as they were damaged) (PG_t). The input time values represent "mean" values as they have been provided by the electrical operator as resulting from its standard

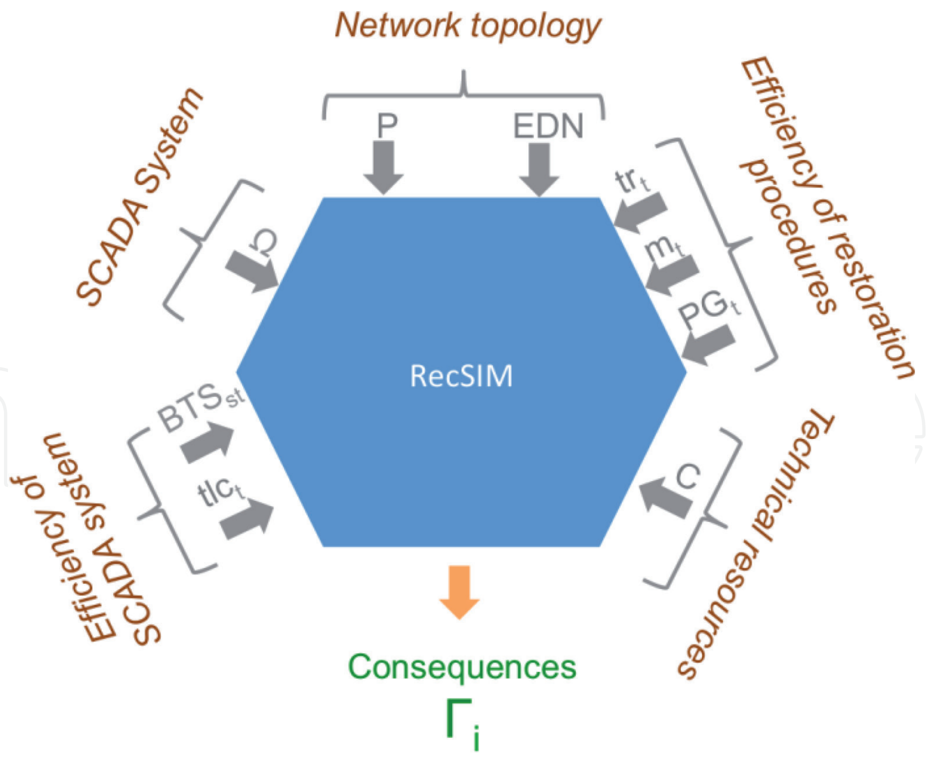

Figure 4.
The RecSIM input and output components.

operation times. RecSIM performs simulations by using these values as mean values of a flat distribution from which time values to be used in the simulation are randomly extracted from the flat distribution.

- *Technical resources*—expressed in terms of the number C of technical crews available in the field. The number of available PGs is assumed to constitute an unlimited resource. Further development of the algorithm will consider the finiteness of available PGs.

The output of RecSIM is represented by the value of the impact of the damage scenario (caused by the perturbation $\boldsymbol{P}$ and by its cascading effects) on the EDN, considering all the restoration actions performed (in series or in parallel, if several technical crews were simultaneously available): the substitution with a PG of a damaged node and, whenever the case, of an isolated node; the manual reconnection of disconnected nodes by the available technical crews; and the automatic reconnections made through remote telecontrol operations. These actions are needed to restore the EDN and to bring it back to its normal operating condition. Upon these actions, all users are supposed to be reconnected to the grid. As previously said, damaged SS are just substituted by a PG, and, at the end of the simulation, they are still in the damaged state although their function is guaranteed by the PG. The impact of the perturbation $\boldsymbol{P}$ on the EDN is thus computed using Eq. (3).

6. Simulation, analysis, and discussion of the results

In a previous work [19], the EDN of the metropolitan Rome, area (Italy), was deeply investigated by extensive calculations enabling to estimate its resilience score, according to the definition reported in Section 3. RecSIM has been used to study the behavior of the whole EDN of the metropoli-Rome EDN that is a large EDN grid composed of 139 PS and 14938 SS distributed along 1607 MV lines.

The power grid has 6348 telecontrolled SS (i.e., 42% of the total SS) and 1012 automated SS (i.e., 6% of the total SS). Considering the MV lines, the power grid has 1447 MV lines that contain at least 1 telecontrolled SS (90%) and 510 MV lines containing at least 1 automatized SS (31%). The considered power grid is set in the so-called normal configuration that is:

1. A specific topology of the network (consisting of a given number of SS, with a given fraction of telecontrolled, automatic, and frontier SS)

2. With the switches along the medium-voltage lines located in specific points,

3. The telecontrolling BTS providing services to a certain extent (in our simulation we consider a default fraction of unavailable BTS leading telecontrolling functionality unavailable—apparently a "physiological" conditions of dependent networks)

4. A given number of technical crews available in the field for the manual recovery operations

5. Standard times for the solution of the different actions to be performed for SS restoration

When referred to "normal configuration," we will refer to equal (1)–(5) conditions. The reported simulation has the character of a "stress test." Two different stress schemes have been adopted: the *unbiased* perturbation scheme and the *heuristic* scheme.

In the *unbiased* perturbation scheme, each electrical substation (SS_i i = 1, N), one at a time, has been set in the damage state and the resulting impact of electrical crisis estimated in terms of the Γ_i defined in Eq. (3). **Figure 5** reports the distribution function $D^1(\Gamma)$ for all resulting Γ_i. This simulation will be referred to as the "(N− 1) analysis," as it involved the set in the damage state of a single SS (at a time).

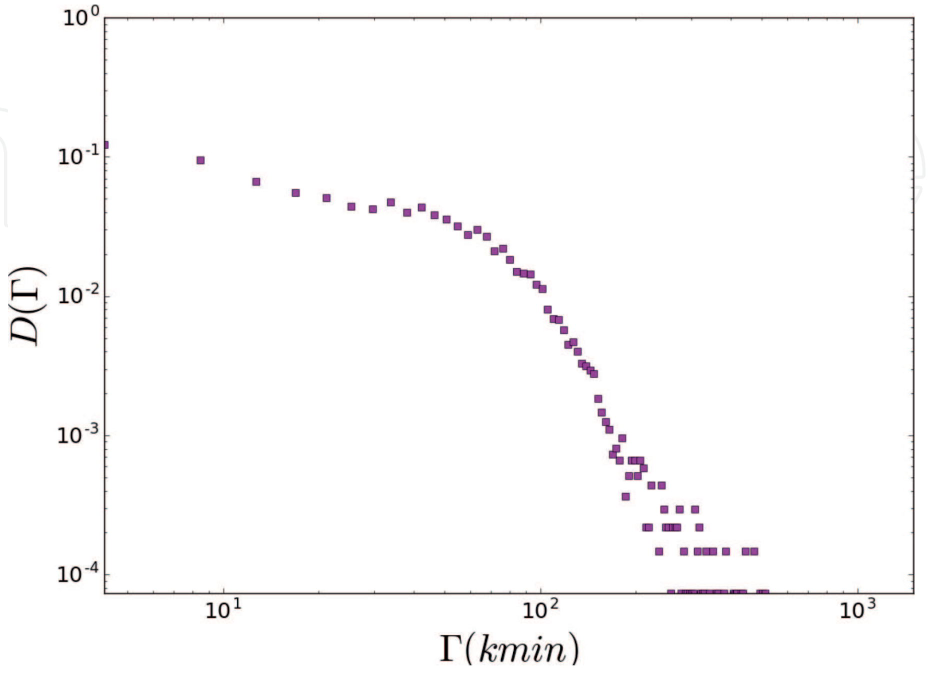

Figure 5.
$D^{(1)}(\Gamma)$ distribution of the resulting impacts as functions of the impacts, for a N − 1 analysis, i.e., in the event of one node damaged.

The same stress test could be repeated by setting in the damage state two, three, or more SS simultaneously, in a way intended to generate crisis situation of higher impact (although with a lower probability of occurrence. Each case will produce a distribution function of the Γ values such as $D^{(2)}(\Gamma)$, $D^{(3)}(\Gamma)$, etc.

The impact distribution $D^{(i)}(\Gamma)$ functions do provide the generating function for the resilience score, which has been associated to its normalized integral Eq. (6): the larger the integral of the distribution, the lower the resilience. In fact, for an infinitely resilient network, each damage should correspond to the lowest possible (or vanishing) impact in the terms expressed by Eq. (3). The overall system resilience could be estimated as a series of terms each one representing the contribution toward resilience for different (and progressively large) perturbations:

$$\boldsymbol{R} = \boldsymbol{a}^{(1)}\boldsymbol{R}^{(1)} + \boldsymbol{a}^{(2)}\boldsymbol{R}^{(2)} + \boldsymbol{a}^{(3)}\boldsymbol{R}^{(3)} + \dots \tag{7}$$

While the terms $\boldsymbol{R}^{(i)}$ will be achieved by applying Eq. (6) to the different $D^{(i)}(\boldsymbol{\Gamma})$, the terms $\boldsymbol{a}^{(i)}$ can be related to the probability of the event; this would produce a series of progressively smaller terms which will reduce the impact of the high order contributions to the total value. The first terms related to $(\boldsymbol{N}-1)$ and $(\boldsymbol{N}-2)$ events would thus dominate the series in Eq. (7) which will provide an *unbiased* estimate of the global resilience of the network when perturbations are imposed following an exhaustive scheme rather than a heuristic method.

A different perturbation scheme (the *heuristic* one) has been also applied to provide a further possible perturbation scheme aiming to realize a resilience assessment which, in such case, will be measured by estimating Eq. (6): this will be done through the use of a distribution function $D^{(h)}(\boldsymbol{\Gamma})$ resulting from the application of the *heuristic* perturbation scheme. The *heuristic* scheme has been thus designed and applied to compare the resulting resilience score $\boldsymbol{R}^{(h)}$ with that obtained through the use of the *unbiased* perturbation scheme.

Instead of producing systematic damages (as in the *unbiased* scheme), we have produced "educated" damage scenarios where SS have been set in the damaged state as a function of their effective rate of faults (as declared by the electrical operator). The heuristic perturbation scheme is thus carried out in the following way. Let us assume to know the *rate of faults per day* $\boldsymbol{\rho}\mathbf{I}$ of each SS of the network, expressed in terms of the average number of times that the SS have been recorded to be out of order. Statistics have been collected along several years and the number of observed faults normalized over the number of days of observation. The ρ_I value could be thus assimilated to the daily probability that the specific substation goes in a damaged state. The cause of SS fault could be different: the SS could be hit by some external event (i.e., natural hazard and/or its consequences) or by some internal event (i.e., the disruption of some component). The statistical fault rate per component does not distinguish between the origins of fault; we will thus consider this fault rate as an "intrinsic" property of the EDN element.

The *heuristic* perturbation scheme has been thus applied to the network "normal configuration" by simulating $\boldsymbol{M}$ working days: in each day of operations, the damaged state of each SS has been sampled (as in a Monte Carlo scheme) by extracting a random number r_i $(r_i = [0, 1])$ and by comparing it with the $\boldsymbol{\rho}_i$ value: if $r_i < \rho_i$, the i-th SS is put in the damaged state where it remains unperturbed elsewhere. The SS set in the damage state have been put simultaneously in the damaged state, in order to simulate the worst-case scenario. This procedure is repeated $\boldsymbol{n}$ times to scan each SS and then repeated $\boldsymbol{M}$ times to simulate different working days.

This procedure generates very few damages, as the rate of faults of the substations is usually particularly small. However, it generates cases where one (or even more than one) substation will result in a damaged state. This procedure thus allows to sample

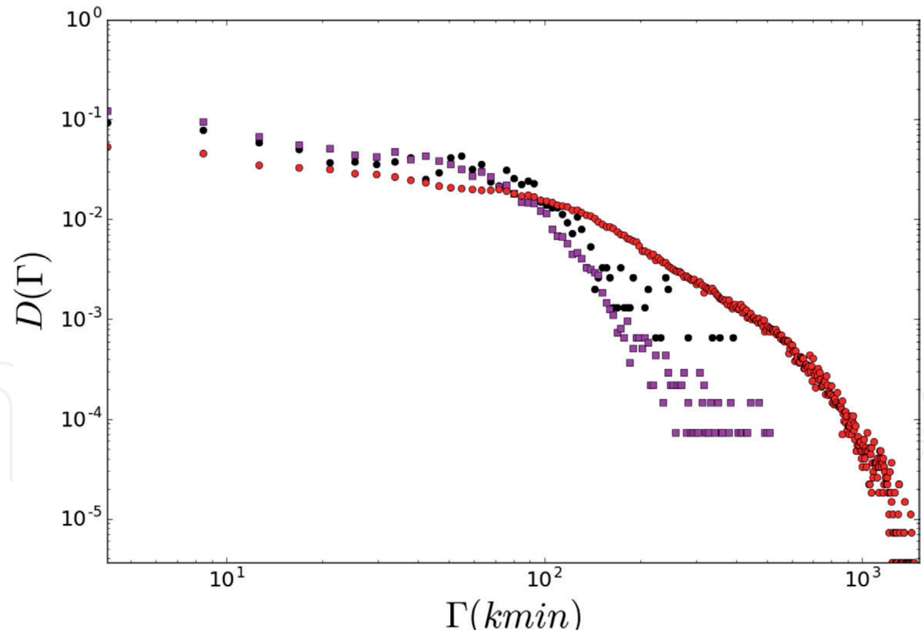

Figure 6.
Comparison of the $D(\Gamma)$ distribution values for the $N - 1$ and $N - 2$ unbiased scheme simulation resulting from the simulation via the heuristic scheme (red = unbiased ($N - 2$), purple = unbiased ($N - 1$), and black = heuristic scheme).

(among the manifold of possible damaged network states) those states where one or more SS are simultaneously damaged, in agreement with the rate of faults of the different stations. Over $\boldsymbol{n}^h$ = 1515 damaged configurations were obtained with the Monte Carlo sampling, of which 1163 were constituted by a single damaged SS; 296 with 2 damaged SS; 49 with 3 damaged SS; 5 with 4 damaged SS; and 2 with 5 damaged SS.

Figure 6 summarizes all the results obtained thanks to the simulations by using the ($N - 1$) and the ($N - 2$) *unbiased* scheme and the *heuristic* perturbation scheme. In all simulations (both for the *unbiased* and for the *heuristic* schemes), the same number of technical crews $\boldsymbol{C}$ available for the service restoration has been assumed ($\boldsymbol{C}$ = 2). The three curves, however, derive from simulations scheme which have produced different amounts of crisis scenarios whose impacts have been measured through Eq. (3). In fact, for the *unbiased* ($N - 1$) simulation, a number of crisis scenarios $\boldsymbol{n}$ equal to the number of nodes $\boldsymbol{N}$ have been produced ($\boldsymbol{n}^{(N-1)} = \boldsymbol{N}$ = 13,618). In the case of the unbiased ($N - 2$) simulation, a number of crisis scenarios $\boldsymbol{n}^{(N-2)}$ = 271,581 have been produced (this number corresponds to the total number of double faults occurring along the same medium tension line).

For the heuristic perturbation scenario, the number of cases was, in turn, $\boldsymbol{n}_h$ = 1515 as previously stated. The most relevant feature of the three distributions must be observed in the impact dimension. The perturbations produced by using an unbiased ($N - 2$) scheme produce very large effects, as they tend to involve a large number of SS, which impose a sequence of interventions (with the provided number of technical crews $\boldsymbol{k}$ available, not all SS could be simultaneously repaired).

The estimate of the corresponding $R^{(1)}$, $R^{(2)}$, and $R^{(h)}$ [through the use of Eq. (6)] appropriately renormalized all the distributions. Application of Eq. (6) to the three different distribution functions provides the following values: $R^{(1)} = 2.17 \times 10^{-2}$, $R^{(2)} = 7.60 \times 10^{-3}$, and $R^{(h)} = 1.78 \times 10^{-2}$.

It is interesting, in turn, to notice that crises produced by the *heuristic* scheme (i.e., involving SS which have shown a large propensity to fault), although in some cases involving more than a SS produces impacts which, even in the largest cases, are of the same dimension of those produced by worst cases in the ($N - 1$) unbiased simulation. This is probably due to the fact that more vulnerable SS are located along lines, which do not produce relevant outages in case of fault (either for the presence of a few not remotely controlled SS and/or for the presence of a not too large number of connected customers).

Different scores are the results of the different adopted simulation schemes. Rather than the absolute resilience score, what should be estimated which might have a technological meaning are "resilience score variations": when the same network (and/or its management properties) is modified, the same simulation scheme can be adopted and the resilience score measured again. The difference of the resilience score (before and after the modifications) will provide an indication on if modifications have (or have not) produced benefits to the overall network resilience.

7. Conclusions

The work presented in this chapter that built a great amount of work done on the same topic [18, 19] presents the RecSIM system and its relevant capabilities to represent and simulate real urban system and in particular problems related to the reconfiguration of electric distribution systems following faults. In particular two major achievements are highlighted, one related to the possibility to account for a number of issues, which have not been appropriately considered in the resilience assessment process in the existing literature, and the second concerning the viability of implementing RecSIM (and its scalability) to large, real EDN. In particular reference has been made in the paper to the case study of Rome city that has a quite large distribution network containing more than 13,500 electrical substations.

As for the general achievements in the area of the models for estimating resilience of EDN, a novel, computable scheme has been identified, on which the RecSIM engine, described in the paper, is based on. The RecSIM model considers different factors encompassing all the phases of risk management, including the technological properties of the network, the fault management procedures, and the network interdependency with the telecontrol network. In many cases of previous works on the same topic (recalled in Section 2), the resilience estimates have been done by using models which considered just the electrical response of the network, thus disregarding the topological and technological features of the network, as well as the management skills and procedures, and the external and environmental constraints. The EDN management model behind the RecSIM tool, in turn, is able to reconstruct the impact of a crisis by considering all the abovementioned factors (recalled in Section 4) which play a critical role in determining the overall systemic resilience of the EDN. Moreover, the possibility of relating the resilience to the distribution of impacts generated by a range of possible perturbations, described in this chapter, provides a further improvement to the prosed approach. Many different perturbation schemes could be therefore investigated, and a resilience score, more suitable for to the user's requirements, can be therefore assessed. Last but not the least, this scheme could also be prone to be modified by varying the outage impact metrics. Whereas in this work the outage impact Γ was assessed in terms of the KPI adopted by the Italian regulatory agency [Eq. (3)], it can be expressed by considering further metrics, able to account, for instance, the economic losses or the level of wealth reduction caused to the citizens [19].

As from the analysis of the data resulting from the case study analyzed, i.e., the Rome city EDN, the profile of the impact distribution functions resulting from the different simulations made on the basis of the *unbiased* and the *heuristic* schemes has revealed two main results.

Firstly, the *unbiased* ($N-2$) scheme provides the worst-case scenario. The simultaneous damage of two SS residing along the same medium-voltage line, produces (as expected) impacts of a significant severity since several other SS are involved. In this case, the model would be able to help the detection of the most impacting causes and to validate the possible improvements which could be introduced by acting on specific issues (i.e., by increasing the quantity of telecontrolled SS along the lines and/or by increasing the number of technical crews available and/or by improving the telecontrol strategy). This information would be particularly useful for electrical operators for the planning of new activities for enhancing resilience.

Secondly, the *heuristic* scheme, where SS are damaged according to their effective rate of fault (as measured and reported by the electrical operator), provides a resilience score which is slightly lower than the one resulting from the $(N-1)$ unbiased scheme. As previously discussed, this could be the result of the correct management of the operators which has "segregated" more vulnerable assets along the lines whose disruptions cause less relevant impacts on services. The RecSIM tool, in this respect, could be useful for assessing which should be the correct way for further improving this score by selecting the substations (among those which have produced the crisis scenarios accounted for in the simulations) whose robustness improvement could further reduce the impact and thus increase the resilience score. Moreover, the tool can be used within more general framework as, for example, the emergency management support tool CIPCast-ES [16] which allows to explore a realistic earthquake event occurring in an urban area by predicting disruptions on buildings and critical infrastructure and by designing a reliable scenario, accounting for road obstruction due to building collapse, to be used to design an efficient contingency plan.

In conclusion, the RecSIM model, being able to gather into a unique scheme several EDN features, can provide a reliable tool for the analysis of large and complex infrastructures. This is going to be exploited in Italy through the establishment of a competence center for risk analysis and forecast of critical infrastructure called EISAC.it (*European Infrastructure Simulation and Analysis Centre Italian node* [31]) which will deliver competences and services to support operators and public authorities committed to the protection and the emergency management of critical infrastructure.

Acknowledgements

This work has been triggered by the project CIPRNet (funded by EU under the FP7 program through GA no. 312450) and the Italian (MIUR) funded project RoMA (SCN_00064): all project partners are acknowledged for their support in the RecSIM elaboration. Areti SpA, the electrical distribution company of the city of Rome, is also acknowledged for the available network's data, in particular ING. Silvio Alessandroni is acknowledged for his constant support and for being the source of illuminating suggestions and comments.

List of acronyms

EDN	electrical distribution network
CI	critical infrastructures
TSO	transmission system operator
DSS	decision support system
PS	primary substations
MV	medium-voltage line(s)
SS	secondary substations
SCADA	supervisory control and data acquisition
tlc	telecommunication network components
BTS	base transceiver station

N	nodes
L	links
F	functioning state function
P	perturbation function
t	time
T	time when the functioning of the system is re-established
PG	power generator
KPI	key performance indicator
ni	number of disconnected customers
$\boldsymbol{\tau}_i$	disconnection duration
$\boldsymbol{\Gamma}_i$	impact
R	resilience
$\mathbf{D}(\boldsymbol{\Gamma})$	distribution function of all the values
$\boldsymbol{\Omega}$	set of secondary substations
$\boldsymbol{tr_t}$	time required to reach a damaged link or node
$\boldsymbol{m_t}$	time required to perform a manual reconnection action
$\mathrm{PG_t}$	time required to install power generator backups
C	number C of technical crews available in the field
$\mathbf{D}^1(\boldsymbol{\Gamma})$	distribution function for the resulting impacts
(N-1)	analysis performed in the hypothesis of one nonfunctioning node
a(i)	factor related to the probability of a crisis event
(N-2)	analysis performed in the hypothesis of two nonfunctioning nodes
$D(h)(\Gamma)$	distribution function for the resulting impacts for an heuristic perturbation scheme
ri	random number
M	M working days
n	number of crisis scenarios

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