Seismic Resilience of Electric Power Networks in Urban Areas

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ABSTRACT: Recent natural disasters have raised the question of how communities can recover from extreme events. In the last decade the research has been focusing on analyzing interdependencies between different networks. In this paper the focus is on the distribution power network, developing a method to estimate a realistic grid of a virtual city called "Ideal City" freely inspired to the city of Turin in Italy. A software called Matpower developed by the Joint Research Center has been used for the load flow analysis of the power network. Fragility curves, repair costs and downtime are evaluated using FEMA's database. Finally, a strategy to improve the network resilience is proposed considering the complexity of the environment.

1 I NTRODUCTION

Seismic resilience of urban areas is one of the central topics in the actual scientific and political fields. Many recent disasters consolidated the idea that much still needs to be done to reduce human and economic losses due to earthquakes.

One of the most affected networks, especially in the first hours after the event, is the electrical distribution network. The first news that media report is that a considerable number of people is left without electric supply.

This aspect complicates situations that are already difficult by isolating communications from large parts of the cities, slowing down the rescue and making it harder for people to resume normal lives. It should not be forgotten that the quick restoration of such networks in critical conditions, for example by replacing key elements such as transformers, can have very high costs. Therefore, careful planning of the electricity grid is mandatory. In this paper the authors present some suggestions for dealing with this kind of problem.

This paper on electric network is part of a larger study on a virtual city called Ideal City (Zamani Noori et al. 2017) that is developed to be a resilience based designed community. This town is freely inspired to the city of Turin that is a town of about one million inhabitants in North-West Italy.

This study is related on the EPN (Electrical Power Network) but it is focused on the electrical distribution system. The electricity grid starts with generation stations located many kilometers far from urban centers. It continues with the transmission system that usually surrounds the cities and ends with the distribution network that carries power directly to consumers.

The network components in terms of fragility curves are studied. Repair costs and time are also estimated and, finally, the improvement of the network resilience is evaluated.

This network can be affected not only by earthquakes but also by tornadoes, which is the first cause of failure of electricity in USA in terms of MW lost. NIST-funded Center for Risk-Based Community Resilience Planning (Unnikrishnan & van de Lindt 2016) explains how the EPN of Centerville, a Virtual Community Testbed of approximately 50.000 people in a Midwestern State, can be studied in terms of network and losses analysis.

This type of approach is not present only in the American or European literature, but it is now a very actual theme in many countries. For example, an interesting work by Arghavani (2017) can be reported. This is a prototype model to analyze the seismic resilience of the transmission grid of the city of Qom, an Iranian center of quite a million citizen.

Iran is a high seismic zone and in this study the researchers have built a simplified model of the network and some scenarios are shown. It is a connectivity analysis, i.e. a binary statement 0 or 1, in which some lines fall, and it is represented the re-

sponse of the grid in terms of recovery time by using a gamma cumulative distribution function.
This type of investigation started years ago, from 2004 Professor Shinozuka (Shinozuka et al. 2004, Shinozuka et al. 2007) studied the resilience of integrated power and water system of the LADWP (Los Angeles Department of Water and Power). A database of effects of several previous events like the 1994 Northridge earthquake is used. In this research, the critical points of the distribution network are the transformers and the associated fragility curves. The correct spatial distribution of PGA is modelled within a Monte Carlo approach. Observing these results, the authors computed risk curves of power supply, households without power, economic losses and some system performance criteria.
Resilience of distribution network isn't only a university topic, but it is strictly regulated by law. This year, within the end of March, all Italian DSOs (Distribution System Operators) have been required to deliver a resiliency plan of their networks to national authority for electricity gas and water.

2 METHODOLOGY

2.1 *Model of the network*

The first problem of the present study consists in the limitation of available data. Information about distribution buses of an urban network is very difficult to be collected. Sensible data are usually not shared because some security standards or economic interest may be compromised. So, the idea is to try to find an electric grid compatible with the map of Ideal City. The approach selected is summarized in Figure 1.

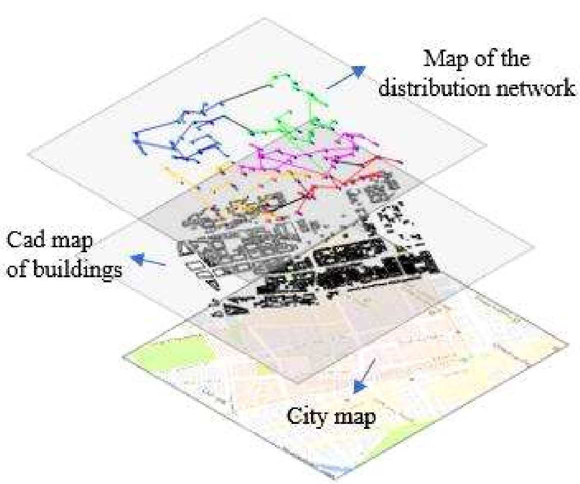

Figure 1. Summary of the approach

Building a power supply network for one million people cannot be developed immediately. Therefore, a literature review of existing case studies has been done. Then, the selected case has been adapted to an Ideal City sample.
The European Commission in collaboration with the Distribution System Operators Observatory of JRC (Joint Research Center) released a technical report (Prettico et al. 2016) about representative networks. They have collected data from 79 out of 190 European DSOs that are representative of the 70% of the electricity supplied by all DSOs serving over 100,000 customers. They distribute more than 2,000 TWh of electricity to over 200 million customers per year, covering a total area of more than 3 million square km.
This information has been used to build 36 indicators about network structure, network design and distributed generation. From 10 of these indicators representative distribution networks have been obtained using RNM (Reference Network Model). This is a useful software for large scale distribution planning developed by the Universidad Pontificia Comillas (Domingo et al. 2011).
In this paper, "urban" network from JRC database is used for the most densely populated districts and the "semi-urban" one for the surrounding areas.
The second step is to make this network independent from the map that JRC has used to realize the model. In these files, information about HV (high voltage), MV (medium voltage) and LV (low voltage) buses with coordinates, branches, electric parameters and protections are provided. In order to apply this realistic network to Ideal City, LV data are relevant only for defining the total amount of consumers, not for their real positions. So, only HV and MV buses are explicitly considered in the model. Finally, the network model is rebuilt writing a new description.
The network has not been freely projected, but it has been strictly controlled using Matpower6.0, a package of MATLAB M-files for solving power flow and optimal power flow problems developed by PSERC (Power Systems Engineering Research Center) at Cornell University (Zimmerman et al. 2011).
The method for the network performance analysis consists in the computation of the load flow on the entire damaged grid. In this way, a higher precision respect to a simpler and faster connectivity analysis (Arghavani 2017) is provided. Analyzes made by Matpower follow the Newton Raphson (NR) algorithm, which solves this nonlinear equation problem.
In the AC power flow problem (Zimmerman et al. 2011), the nodal bus injections are matched to the injections from loads and generators. The power balance equations are expressed in complex matrix form as

$$g_S\left(V,Sg\right)=S_{bus}\left(V\right)+S_d-C_gS_g=0 \tag{1}$$

where $S_{bus}(V)$ is the complex power injections as functions of the complex bus voltages V, S_d are constant power loads, S_g is the generator injections and the C_g is the connection matrix.
This problem can be split into its real P and reactive Q components:

$$g_P\left(\theta,V_m,P_g\right)=P_{bus}\left(\theta,V_m\right)+P_d-C_gP_g=0 \quad (2)$$

$$g_Q\left(\theta,V_m,Q_g\right)=Q_{bus}\left(\theta,V_m\right)+Q_d-C_gP_g=0 \quad (3)$$

where θ is the voltage angle and V_m is the voltage magnitude. The power flow problem could be a set of equations in the form

$$g\left(x\right)=0 \quad (4)$$

And in particular

$$g\left(x\right)=\begin{bmatrix} g_P\left(\theta,V_m,P_g\right) \text{ for PV and PQ buses} \\ g_Q\left(\theta,V_m,Q_g\right) \text{ for PQ buses} \end{bmatrix} \quad (5)$$

where PQ buses are pure load buses and they represent the major part of all of network buses. In these elements P and Q are defined, but θ and V_m must be calculated.
PV buses are connected to the generator and they are a small part of all buses. In these elements P and V_m are defined, but Q and must be calculated (Grainger & Stevenson 1994).
Is also important to specify the value of x, as:

$$x=\begin{bmatrix} \theta \text{ for all buses except Reference bus} \\ V_m \text{ for PQ buses} \end{bmatrix} \quad (6)$$

where the Reference bus is the slack bus and it is considered as the number one of the network. In this element, $\theta=0^o$, V_m is known but P and Q must be computed.
So, a nonlinear system (Dharamjit & Tanti 2012) with n_{pv} + n_{pq} equations and unknowns (n is the number of PV or PQ buses) results. Solving by x, it's possible to determine the generator real power injections at the reference bus and generator power injections.
These solutions are provided using the iterative NR's method. Starting from an initial trial solution, at each iteration, a tolerance must be smaller than a predetermined threshold. So, the passages are these:
It starts with

$$\left[g(x)\right]=\begin{bmatrix} \tilde{g} \end{bmatrix} \quad (7)$$

the solution at first iteration is

$$\left[x\right]=\left[x^{(0)}\right]=\left[x^{(k)}\right] \quad (8)$$

and the following ones in general are expressed as
The tolerance is computed as

$$\left[\varepsilon^{(k)}\right]=\begin{bmatrix} \tilde{g} \end{bmatrix}-\left[g(\left[x^{(k)}\right])\right] \quad (9)$$

If the tolerance doesn't become smaller than the threshold, the function $[g(x)]$ is represented as a series, involving the Jacobian matrix computed at $[x]=[x^{(k)}]$. They can be written as $[J^{(k)}]$.

Finally

$$\left[g(\left[x^{(k)}\right])\right]+\left[J^{(k)}\right]\cdot\left[\Delta x^{(k)}\right]=\begin{bmatrix} \tilde{g} \end{bmatrix} \quad (10)$$

and so

$$\left[J^{(k)}\right]\cdot\left[\Delta x^{(k)}\right]=\left[\varepsilon^{(k)}\right] \quad (11)$$

The NR's method linearizes the nonlinear system and, therefore, the Jacobian matrix is composed by constant values function of the unknows.
After the modelling of the network, the load flow is computed through the MATLAB code. If the NR's method converges (Figure 2) in few iterations and the power restraints are respected, the grid is properly designed.

```
Newton's method power flow converged in 5 iterations.

Converged in 0.78 seconds
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              166     Total Gen Capacity    1000.0       -1000.0 to 1000.0
Generators           1     On-line Capacity      1000.0       -1000.0 to 1000.0
Committed Gens       1     Generation (actual)     89.5              37.9
Loads              164     Load                    88.5              26.5
  Fixed            164       Fixed                 88.5              26.5
  Dispatchable       0       Dispatchable          -0.0 of -0.0      -0.0
Shunts               0     Shunt (inj)             -0.0               0.0
Branches           170     Losses (I^2 * Z)         1.00             11.35
Transformers         1     Branch Charging (inj)     -                0.0
Inter-ties           0     Total Inter-tie Flow     0.0               0.0
Areas                1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.984 p.u. @ bus 3192       1.002 p.u. @ bus 3160
Voltage Angle      -6.52 deg   @ bus 3192       0.00 deg   @ bus 1
P Losses (I^2*R)             -                  0.32 MW    @ line 1-3160
Q Losses (I^2*X)             -                 10.81 MVAr  @ line 1-3160
```

Figure 2. Example of convergence with the NR's method and restraints for a hypothetic network.

2.2 *Resilience Index*

The Italian Regulatory Authority for Electricity Gas and Water suggests to compute the resilience of an electric grid focus on the risk of disabling users in case of hazard or extreme weather conditions (The Italian Regulatory Authority for Electricity Gas and Water, 2017).
This index is called IRI and is calculated as

$$IRI = NUD \cdot PD \quad (12)$$

where NUD is the number of LV users disabled and PD is probability of disservice. This chance is

$$PD = 1 / TR \quad (13)$$

where TR is the return time of the event, calculated in accordance with the European standard CEI EN 50341 (EN 50341-2-13). For a safe calculation we will take 50-years as return time.
An assessment of resilience can be obtained by computing the inverse of the risk index, thus obtaining

$$IRE = TR / NUD \quad (14)$$

where IRE is the resilience index, or calculating the integer over time of the IRI index.
Another resilience rating can be given in term of ENS (Energy Not Supplied) to highlight the power delivered before the event and the time it takes to restore it.

2.3 *Fragility and Restoration*

The first assumption of this study is to concentrate the fragility of the network in medium voltage substations (Figure 3).

Figure 3. Typical indoor MV substation. Image taken from http://electrical-engineering-portal.com/

To model their fragility researchers have used the HAZUS®-MH MR5 (FEMA 2002) that provides sets of fragility curves for unanchored elements. This means that the components are assumed without any seismic protection and designed with normal requirements. This hypothesis is introduced because the goal is to estimate the worst-case scenario's probability of exceedance.
Medium voltage substations are composed by important equipment as transformers, switches, circuit breakers etc. Furthermore, they are assumed as installed in buildings, so they can be also affected by the structural damages. Table 1 reports the damage conditions.

Table 1. Description of damage states

Damage state	Description
Complete	component OR building 100% damaged
Extensive	component OR building 70% damaged
Moderate	component OR building 40% damaged
Minor	component OR building 5% damaged

Fragility curves of the components implement the PGA (Peak Ground Acceleration in [*g*]) as seismic intensity parameters. They are lognormal function defined through logarithmic mean λ and logarithmic standard deviation ß. Table 2 summarizes the implemented fragility curves parameters. Figure 4 depicts the resulting fragility functions.

Table 2. Fragility parameters for medium voltage substations with unanchored components (Cavalieri et al. 2014).

Damage state	λ	ß
Complete	-0.69	0.4
Extensive	-1.2	0.4
Moderate	-1.61	0.5
Minor	-2.3	0.6

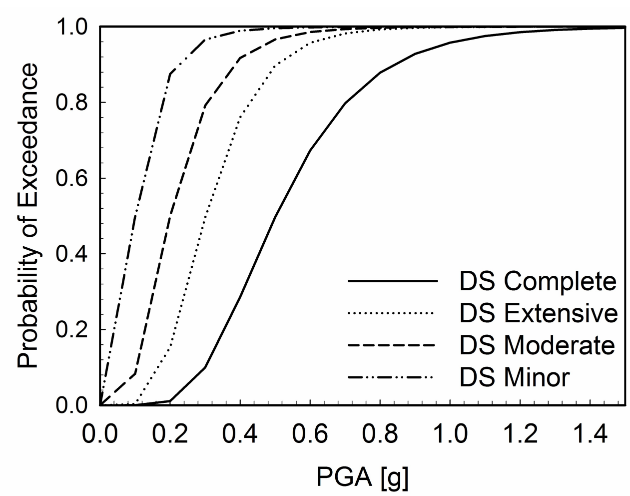

Figure 4. Fragility curves for medium voltage substations with standard components

The simulation considers an increasing set of PGAs and the resulting outcomes of the network are evaluated. In these scenarios, MV substations failed and consumers are without power.

The resilience of the system is evaluated in terms of MW lost due to people without electricity for a certain period, costs and time due to repair activities. About the restoration consequences, authors refer to HAZUS Technical Manual (FEMA 2002). Figure 5 reports the adopted restoration functions.

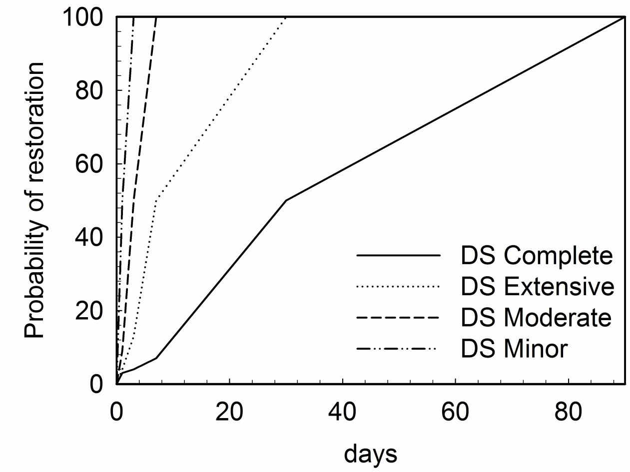

Figure 5. Discretized Restoration Functions for electric substations

In the restoration analyzes the focus is moved on transformers (Figure 6) because they can be considered the most critical substations components.

Figure 6. Typical MV/LV distribution transformer. Image taken from http://www.directindustry.it/

In general, (Cataliotti 1983-1999) they are electromagnetic induction static facilities, which modify power values from a primary circuit (receiver) to a secondary one (deliver)

Distribution transformers MV/LV have a three-column core, concentric windings, wire-wired conductors for small sections, flat for the major. They can be classified according to many parameters such as insulating material with which they are protected from high operating temperatures, depending on the service and cooling mode. In this case, however, they have been classified according to the nominal power that can be delivered. There are five classes of transformers (Prettico et al. 2016) as reported in Table 3.

Table 3. Classes of transformers and type of network in which are present

Transformers power (kVA)	Network
100	Semi-urban
250	Semi-urban
400	Semi-urban, Urban
630	Semi-urban, Urban
1000	Semi-urban, Urban

About transformers costs, authors refer to PACT, a FEMA tool to analyze the seismic performance assessment of structural and non-structural components (FEMA P-58-3 2016). Data are given in US dollar (USD) but they have been converted in euros (€) with 1.2 as exchange rate (Figure 7).

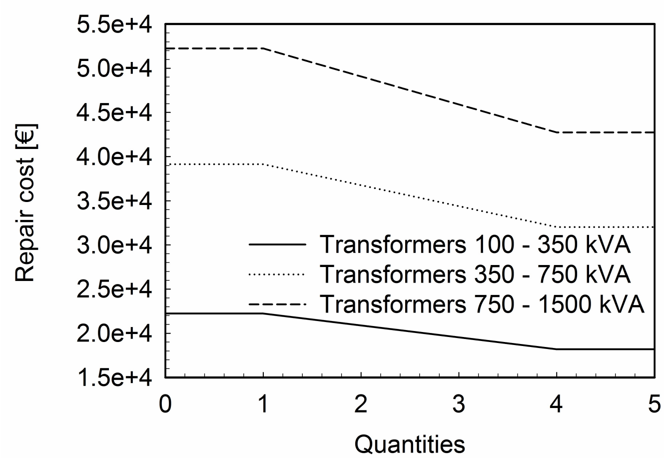

Figure 7. Repair cost of transformers related to their quantities

It is also important to take into account the correlation between the damage state and the transformers serviceability and power availability, as Table 4 summarizes.

Table 4. Relation damage state – power supply

Damage state	Serviceability	Power
Complete	Not repairable	No
Extensive	Operational after repairs	No
Moderate	Operational without repairs	Reduced
Minor	Operational without repairs	Reduced

3 APPLICATION

3.1 *Network description*

The case study employed for the application of the method consists in the Ideal City's district of Crocetta. It is a very central and urbanized area of Turin, full of residential buildings, offices and schools such as the university Politecnico di Torino. The population is about 40,000 people. During the day, such number of population increases.

So, the "urban" network from the JRC database is employed and adapted to the Crocetta's case, being suitable for about 50,000 users. Figure 8 shows the satellite image of the considered district.

Figure 8. Crocetta's picture from the satellite with its borders highlighted in red

The grid is composed by five feeders, which supply 12735 housing units (supposing a mean of 4 people per unit) and 38 MV consumers. There is only one HV/MV substation from 132 to 20 kV with 80 MVA of rated power and 126 MV/LV substations from 20 to 0.4 kV (Prettico et al. 2016). About the latter 126 MV/LV substations, they are detailed in Table 5.

Table 5. Number of transformers per each class

Rated power (kVA)	Number
1000	34
630	52
400	40

This distribution network is presented in Figure 9, while Figure 10 shows the overlap of the same grid with the district map, as obtained by some simplification from the real map of Turin (Zamani Noori et al. 2017).

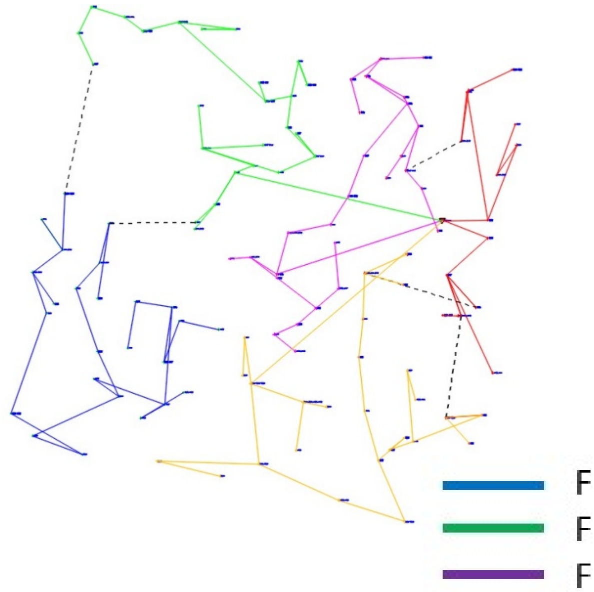

Figure 9. Urban network with MV buses in evidence

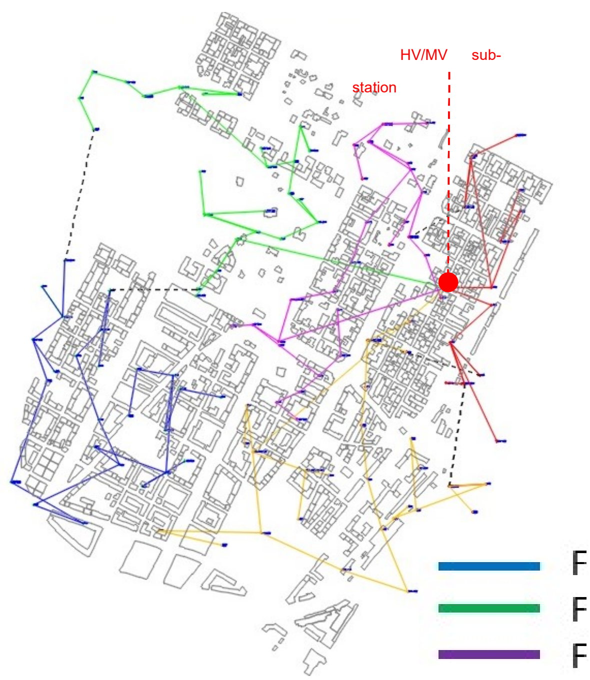

Figure 10. Overlap buildings-network

3.2 *Crocetta fragility and resilience*

In this work, repair costs and down time analysis are evaluated, so it is supposed to refer to a "damage state" situation for the network. In particular, "extensive" damage in Table 4 (with NO power and "Operational after repairs" conditions) for the network is considered. It is assumed that power can be feed only after grid restoration, which consists in components repairing. Indeed, resilience is studied for limited damage conditions, not for complete damage of components and buildings.

Looking at the correspondent fragility curve (Figure 4) it is clear that up to 0.2g the grid does not suffer

any damage. From 0.3g level, substations have the 50% probability of exceedance and with a 0.5g this percentage goes to about 90%.
So, an event with a magnitude between 0.3g-0.5g, can cause the power interruption and the steps until the complete restoration are considered for the present application.
Observing the repair time for MV buses, that is the substation (Figure 5), there is more than 50% chance of having the complete restoration in less than 10 days. In the following, the transformers case is analyzed in detail and the repairs specifications (FEMA P-58-3 2016) are shown is in steps (Table 6).

Table 6. Steps of repairs

After	Transformers repaired
4 days	400 kVA
6 days	400, 630 kVA
7 days	400, 630, 1000 kVA

To give an assessment of resilience we calculate the IRI risk index, if the event occurs at the hypothetic day 2 of a simulation. (Figure 11)

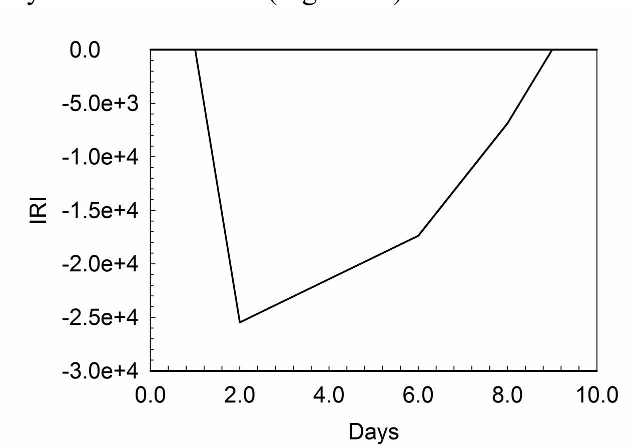

Figure 11. IRI index

A second evaluation can be given in terms of lost energy, the ENS trend is as follows (Figure 12).

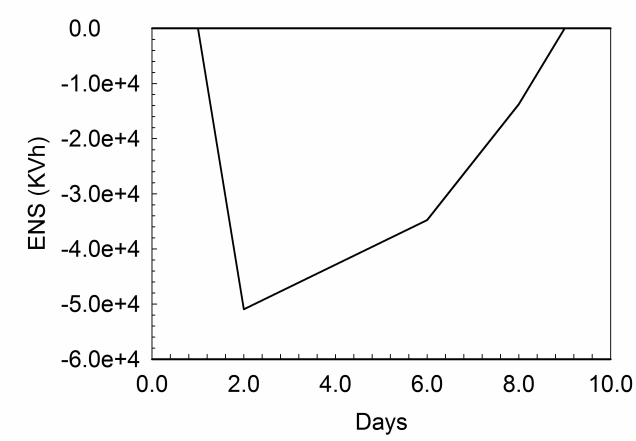

Figure 12. ENS per day

3.3 *Cost analysis and improvements*

As has been shown, a week is necessary for the complete restoration and this implying a huge loss of power. For an assignment of 4 kWh per user, the total amount for a district of the Ideal City, as the Crocetta case, consists in about 0.3 GWh. Considering the typical single-band price of 0.065€/kWh, the economic losses amount over 20,000 €. Accounting the repairs costs, losses further increase.

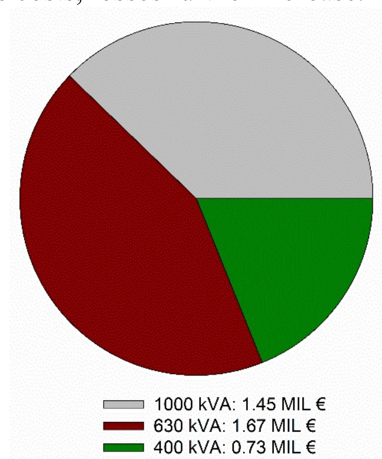

Figure 13. Transformers repair costs repartition

As reported in Figure 13, for the PGA in the range 0.3g-0.5g, the total amount of costs for the transformers consists of 3.85 million euros. Adding the ENS costs with those ones from the restoration of the electrical equipment, 4-5 million euros result.
To improve network resilience, it may be useful to employ substations specifically designed for seismic conditions. Indeed, they are characterized by different fragility curves (Figure 14) with respect to the standard case in Figure 2. Fixing 0.5g PGA, the standard case defines about 90% probability of failure while the seismic case 50%. So, an essential difference can be highlighted.

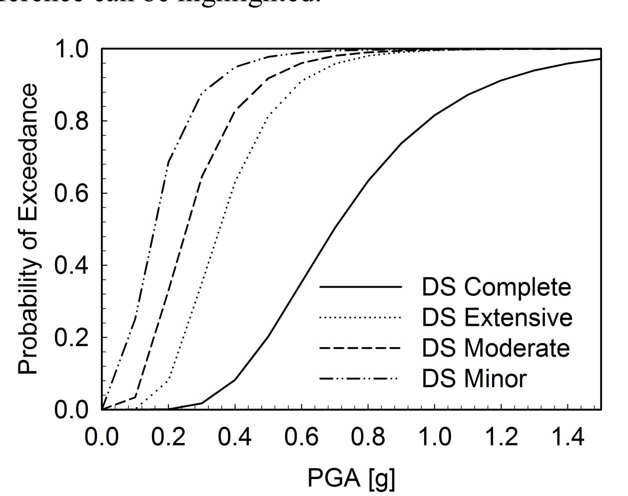

Figure 14. Fragility curves for medium voltage substations with seismic components

Finally, the networks interdependency has to be taken into account following the approach developed by Cimellaro et al. (2016). The fragility of electrical components is connected to failure's probability of buildings system in the district, where substations are installed. Besides, the electric network failure itself induces a series of cascading effects, as summarized in the scheme of Figure 15.
This research team (Cimellaro et al. 2016, Zamani Noori et al. 2017, Cimellaro et al. 2017) is deepening the cascading effects at the urban scale, creating a macroscale model through finite element (FE) analysis of buildings structures, debris and through connectivity matrices of the networks nodes.

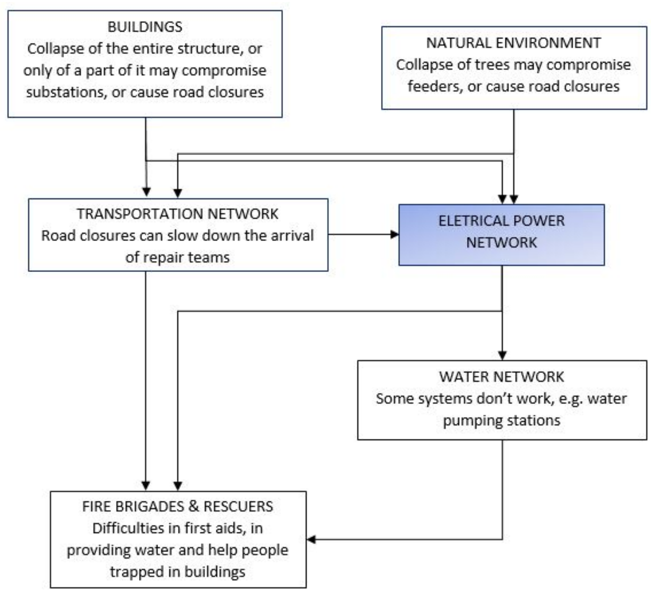

Figure 15. At the top of the figure is shown the indirect fragility of the power grid. At the bottom are presented some cascading effects triggered by blackouts or power reductions.

4 CONCLUSION

This paper is proposing a new methodology to estimate the performance and its inherent resilience of a power distribution network.
The steps are the following: (i) referring to electrical characteristics of urban representative network. (ii) Adapting the data to a specific map focusing on MV buses. (iii) Applying an earthquake hazard with a certain PGA. (iv) Estimating the grid response using fragility curves of MV substations and finally (v) determining the economic losses with repair costs and time curves.
Furthermore, measures for improving resilience are suggested by employing seismic retrofits in substations. The interaction of EPN with other networks is also mentioned and will be studied in further researches in the future.

5 AKNOWLEDGMENT

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