SEISMIC RELIABILITY OF ELECTRIC NETWORKS AND INTERACTION WITH OTHER DAMAGE INDICATORS

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SUMMARY

The paper illustrates a procedure to assess the territorial risk of electric power black – out when it is most needed because of high damage, in case of a seismic event. In order to do so, both the electric power network (EPN) and the local damage are separately modelled. The statistics of the simultaneous event lack of electric power at a point on the territory and high local damage are computed via a sampling technique. The model of EPN used herein has been already presented and is briefly recalled in the text. The procedure is applied to an example case; the results allow individuation of the points on the territory with the highest risk . These deserve priority in upgrading of the means of electric networks' components.

INTRODUCTION

A high level of seismic performance for lifelines is increasingly recognised as a key factor to minimise the effects of a major earthquake. Recent surveys after strong-motion events [Schiff 1988, O' Rourke and Palmer, 1994, Lund, 1996, O' Rourke, 1996] have shown that direct damage to such systems is considerable and that it often causes further undesired events, e.g. fire for gas pipe-lines.

Electric networks are extremely vulnerable lifelines since they contain a large number of vulnerable pieces of equipment, not designed to withstand lateral actions. These are concentrated in the stations, nodes of the network, lines's vulnerability being negligible with respect to the stations's one. EPN's weaknesses include a strong network-type behaviour (malfunctioning originating from any station may spread to significant parts of the system and cause black-out on national scale), and a lengthy procedure, up to some days, for re-start of the power flow after a major black-out.

On the other hand, electric power in post-disaster situations is essential, a minimum level of protection being the feeding of important installations like hospitals, civil protection buildings, telecommunication and information broadcasting centers. This is not generally achieved even for moderate earthquakes and the passive redundancy given by electrogenous groups is present only at some of these installations and often unable to feed all of the functions in the important buildings. The need for upgrading the existing EPN's in seismic areas shows up clearly. The present study is therefore devoted to the assessment of the seismic risk at all the EPN nodes, individuation of the most important ones through the value of suitable indicators.

Although seismic damage to EPN is a key topic for civil protection, little research has been devoted to its assessment. State-of-the-art procedures use numerical simulation, sampling both the actions and the componental resistances; the electric network is analyzed with steady-state power flow equations. Differences in the procedures arise in the stations's models, which include simpler two states (Failure/Safe) assumptions [Ang et al., 1992, Ang et al., 1995, Shinozuka and Tanaka, 1996], or more complex ones, considering interactions between failures of the components of a station1-3; this way, stations are modeled as multi-states components, capable of spreading short-circuits also at the exterior, as it really happens. The latter model has exploited the

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results of an experimental [Ismes, 1993] research program started in 1993 by the Italian State Electricity Board, E.N.E.L.; the experimental data, obtained with shaking table tests on the fragile components of the networks, have been used to calibrate the reliability structural models with standard form/sorm methods.

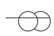
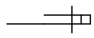
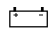
In what follows, this model is first briefly recalled; then the procedure to individuate the important nodes is proposed and tested using the data of a real EPN, the one of Sicily in Italy.

MODELS IN THE PROCEDURE

Structural and electric model of EPN's

The reader is referred to previous studies [Vanzi, 1995a, Vanzi et al., 1995b, Vanzi, 1996] for a more detailed description of electric networks; for the sake of completeness some recalls will be made herein. The vulnerable elements of EPN's are contained in the stations and consist of a large number of slender steel-ceramic elements, with a considerable mass on top, together with electronic pieces of equipment whose correct functioning is sensitive to imposed accelerations. The electronic equipment allows to continuously monitor the state of the network and to insulate short-circuits in case of need. All these components, herein referred to as microcomponents, are listed in table1, together with the symbols commonly used in electric engineering to indicate them. Table 1 also shows the parameters (λ, ζ= natural log of the mean and standard deviation) of their lognormal fragility curve expressed as a function of the local peak ground acceleration in m/s^2.

Table1: microcomponents

Name	Coil bearing	Switch A	TA	TV	Horiz. Section	Vertic. Section	Dis-charger	Bar bearing	Trans-former	Box	Power supply
#	1	2	3	4	5	6	7	8	9	10	11
Symbol											
λ	1.364	1.662	1.428	1.792	1.746	1.690	2.265	1.476	3.157	2.925	1.399
ζ	0.338	0.328	0.269	0.269	0.223	0.340	0.315	0.438	0.287	0.519	0.162

The HT, MT and LT electric networks of Sicily is shown in figure1. A distribution – transformation station is organized as in fig. 2, with power flowing from high to low tension; a distribution station contains only the components on the low tension side. Stations are protected from spread of short – circuits via the switches which open and insulate malfunctionings; proper functioning of switches depend on proper functioning of both power supply and boxes.

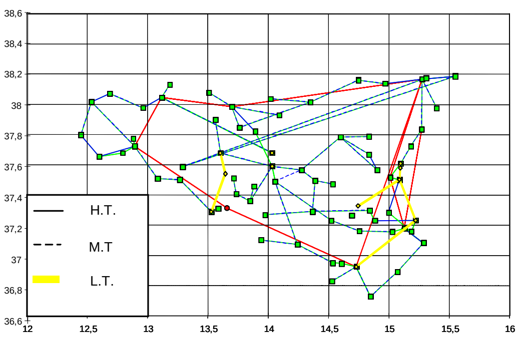


Figure 1: HT, MT and LT EPN of Sicily

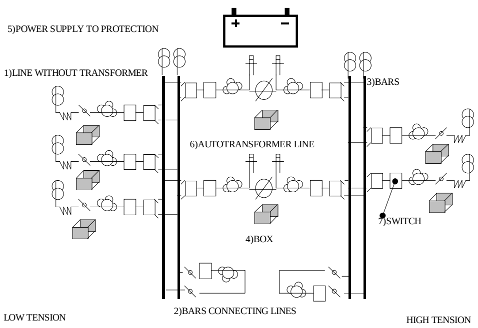


Figure 2: components in a station

To simplify the model of the station, serial arrangement of microcomponents have been grouped in macrocomponents; these are shown in figure 2, numbered from 1 to 7. Assuming that failures of microcomponents in each macrocomponent are independent events, it is straightforward that :

$$P_S(\text{Macro}) = \prod_{\text{micro}} P_S(\text{micro}) \qquad (1)$$

where P_S is the probability of survival, Macro indicates each macrocomponent and micro is an index varying over all the microcomponents in a macrocomponent. Hence the grouping in macrocomponents simplifies the stations's model while allowing to evaluate the fragilities in a simple way through (1).

The EPN electric model used is capacitive, i.e. accounts for the power transport capability of each link between two generic nodes and takes into account failure at the stations. The reader is referred to [Vanzi, 1995a, Vanzi et al., 1995b, Vanzi, 1996] for a detailed description of this feature.

Performance indexes of epn's

The importance of electric power feeding in post – earthquake operations grows with the extension of local damage. In fact, power cut – off being always an undesired event, it may have dramatic consequences in case damages are important, e.g. with hospitals full but no electric power.

In this study, the indicator of local damage chosen is the number of casualties at municipalities, c(m) already used in previous works [Nuti and Vanzi, 1998a, Nuti and Vanzi, 1998b] and illustrated in the next chapter.

Together with a local indicator of damage, a local indicator of the EPN performance is necessary. Since the exploitable part of energy is the real part of power at a node, EPN performance has been quantified with the value of r(n), ratio of the real part of electric power at the node n in post – earthquake conditions to the same quantity in ordinary conditions. r(n) is a continuos variable ranging from 0, no power delivered, to 100%, normal operating conditions.

In the simulations that follow it has been assumed that municipalities, where casualties are computed, are served by the closest EPN station, where r is computed; it has been hence possible to compute the indexes c and r relative to either municipalities or EPN nodes.

The information contained in both r and c have been summed in the index cr(.),(.) being either a municipality or a node; cr(.) is the number of casualties who are not served by electricity:

$$cr(.)=c(.)[1- r(.)] \qquad (2)$$

The mean value of this indicator is the expected number of casualties not served by electric power, given an earthquake. It is anticipated that important nodes will be individuated via the index cr.

Correlation between local earthquake intensity and number of casualties

Among the possible alternatives of indicators of local damage, the number of casualties was chosen because it was felt to give more direct understanding of the consequences of power cut – off. For simplicity, the number of casualties at a site was considered a function only of the local earthquake intensity; the functional form retained is taken from [Coburn and Spence, 1992] and reads:

$$\begin{aligned} &\bar{C}(I) = \alpha \cdot (I - I_{min})^{\beta} \quad && I \geq I_{min} \\ &\bar{C}(I) = 0 && \text{otherwise} \end{aligned} \qquad (3)$$

where I is the Modified Mercalli intensity, $\bar{C}(I)$ the mean value of the ratio of casualties to population, α, β and I_{min} are coefficients depending on buildings fragility and coefficient of occupation. For the region of Abruzzo, Italy, these parameters have been estimated [Giannini et al., 1984, Decanini et al., 1994] on the basis of available data to be worth:

$$\alpha = 0.00048 \qquad (4)$$
$$\beta = 4$$
$$I_{\min} = 7MM$$

Both the law (3) and its parameters (4) have been retained in the application made in this paper to a real case, Sicily, because of the similarity, in an average sense, of the buildings fragility and coefficient of occupation, in the two regions. The ratio of casualties to population C(I) has then been modeled as a lognormal random variable with mean value and coefficient of variation equal to 15%. The data on the population, drawn from the census [ISTAT, 1991], allow computation of the number of casualties c at the municipality m as:

$$c(m,I)=population(m).\ C(I)$$

Model of the seismic action

The classical Cornell model, with diffused seismicity, has been assumed for earthquake generation. In each seismogenic area, the coordinates of the epicenter are independent random variables with constant distribution between the minimum and maximum values of the coordinates of the points of the area. The time succession of earthquakes was modeled with the Poisson distribution; distribution of intensities given an event is modeled via the doubly truncated Gutenberg- Richter law. For each area, the parameters of the Gutenberg- Richter law are evaluated on the basis of the historical seismicity. A circular attenuation law:

$$\Delta I_s(R)=a+b(R+Ro)+c\ \log(R+Ro) \qquad (5)$$

has been adopted. The (deterministic) attenuation value in (5), has been considered as the mean value of a lognormal random variable with c.o.v. δ_I. The parameters in (5) are worth [Decanini et al., 1994]:

$$Ro=3\ Km;\ a=-4.43;\ b=0.0056;\ c=1.8833;\ \delta_I=15\% \qquad (6)$$

Since the fragilities of the macro components are expressed as a function of the soil acceleration, conversion from MM intensity to acceleration in cm/s^2 has been performed; the empirical law:

$$a(cm/s2)=10^{I\alpha+\beta} \qquad (7)$$

has been used. The (deterministic) attenuation value in (5), has again been considered as the mean value of a lognormal random variable with coefficient of variation δ_a . The parameters in (7) are worth:

$$\alpha=0.237;\ \beta=0.594;\ \delta_a=15\% \qquad (8)$$

Both (6) and (7) have been calibrated using registration of events in Italy.

Computational procedure

A MonteCarlo scheme has been adopted to assess the statistics of the network performance. The flow-chart of the procedure is shown in figure 3.

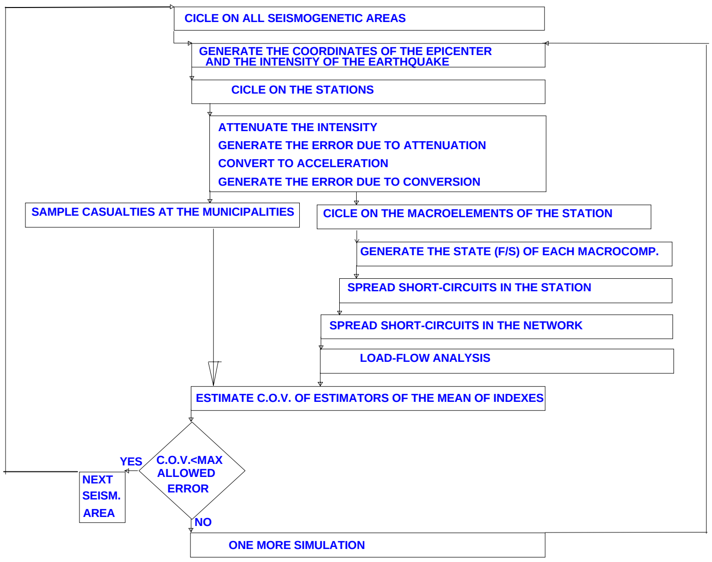


figure 3: flow-chart of the procedure

This procedure has been implemented in a computer program [Giannini and Vanzi, 1999a, Giannini and Vanzi, 1999b) which has been used for the case study presented in chapter 2. In the example applications, an average value of 2,000 simulations per seismogenic area have been sufficient in order to have the c.o.v. of the estimators of the mean value of performance indexes lower than 10%.

APPLICATION TO THE EPN OF SICILY

The procedure has been applied to the region of Sicily, Italy, which presents elevated values of seismicity and population density. The EPN considered, fig. 1, contains the high, medium and low tension distribution networks and basically consists in a ring from which depart the sides feeding the internal regions. In the following, the EPN performance in its present state is assessed and discussed.

Effects of earthquakes on the EPN of Sicily

The network chosen consists in 181 nodes (5 supply and 175 demand stations, plus one balance node) and 220 lines and is located among the seismogenic regions of figure 4. The Gutenberg – Richter parameters of the law are in table 2. Figure 3 shows the population distribution in the region (maximum is 700,000) and is useful to understand the results that follow.

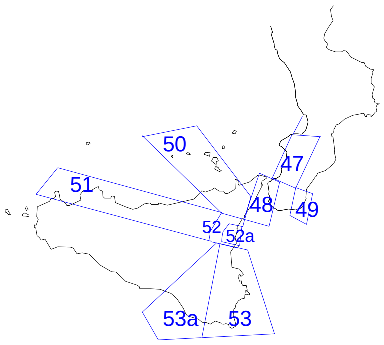


Figure 4: seismogenic areas in Sicily

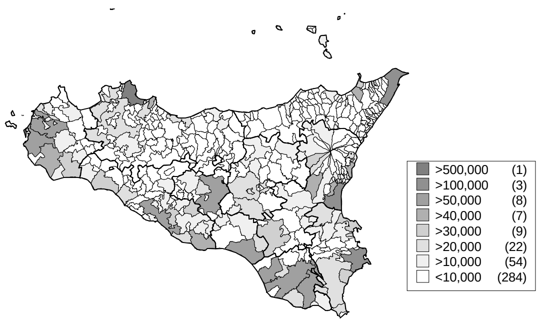


Figure 5: population distribution in Sicily

Table 2: Gutenberg – Richter parameters of the seismogenic areas

region	iMIN	iMAX	λ	β
47	4.5	11	1.105	0.682
48	4.5	11	1.114	0.916
49	4.5	9	0.703	0.099
50	4.5	10	0.789	0.79
51	4.5	9	1.001	0.741
52 + 52a	4.5	10	0.851	1.255
53	4.5	11	1.081	0.524
53a	4.5	9	1.305	0.585

Under a scenario scheme, with earthquakes conditioned to a seismic area and intensities corresponding to a return period of 500 years, the most critical situation has been identified. This corresponds to the seismogenic area 52+52a, which encloses the town of Catania (population 330,000), the other seismogenic areas yielding sensibly minor damages. The event with the prescribed return period has a 9.8 IMM intensity and causes an average value of 5,524 casualties, concentrated in Catania boundaries. Figures 6 and 7 show the results obtained for the indexes c and r computed at electric nodes.

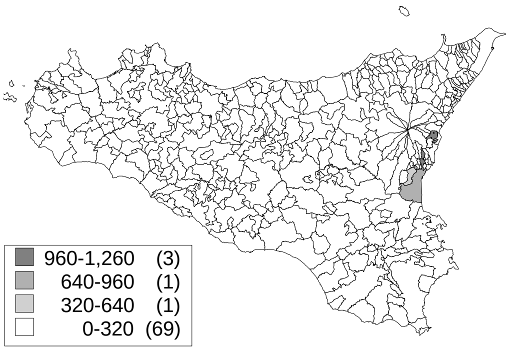


figure 6: seismogenic area 52+52a; mean of c at nodes

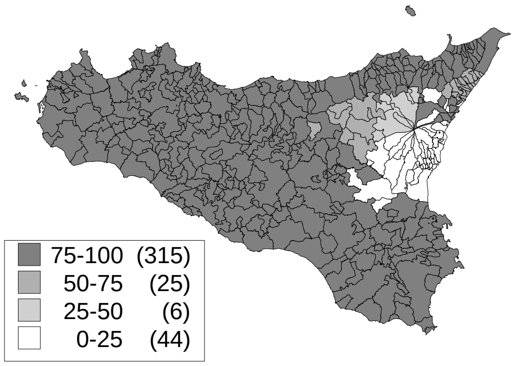


figure 7: seismogenic area 52+52a; mean of r at nodes

The results for the index cr, not shown here, coincide with those in fig. 6 signaling the fact that, in emergency conditions, the electric power network is always out of order. The behavior of the electric system confirms this (fig. 7). The analyses with events with 50 years return period, not shown here, have proved that also under moderate earthquakes the probabilities of out of order of the EPN are high.

CONCLUSIONS

The proposed procedure has shown capability of individuating the points at highest risk on the territory. This piece of information should be used to upgrade the stations of the EPN which show highest value of the proposed indexes.

The results from this study will be used within a broader research, which will be published soon, aimed at upgrading the EPN components with an economic optimization; the performance indexes described herein will then be used to individuate the critical EPN nodes.

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