Seismic reliability of electric power transmission systems

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Electric power transmission systems are networks of nodes (stations) connected by lines (power transmission lines), dedicated to the production, transformation and distribution of electric power to users. The network contains many seismically fragile elements, the stations being composed of slender steel-ceramic members, and is a complex system because it is capacitive and capable of insulating short-circuits. In the present work the functional logic of a generic electric network is analyzed and a model suitable for reliability assessment is established. The model is then applied to evaluate the seismic reliability of a realistic network comprising the central part of Italy, using simulation methods. Various measures can be adopted to assess the performance of a network: the one selected in this study is a global index related to the quantity and the quality of the power delivered.

1. ELEMENTS OF THE NETWORK: STATIONS AND POWER TRANSMISSION LINES

In fig.1 an example high-tension electric network (Rome compartment, central Italy) is shown. The two basic components of the network, i.e. stations (nodes) and power transmission lines (lines), are recognizable. Notice that in fig.1 each line may also represent two or more coincident lines. Stations are of three different types: 1) power plants: where electric energy is produced; different types of power plants exist, e.g. thermic, hydroelectric and nuclear power plants. 2) transformation stations: where electric voltage is transformed; high voltage is used for long-distance transmission; voltage is then transformed to lower values when approaching consumers; for reference, in Italy the following tensions are used: 380, 220, 150, 132, 66, 45, 30, 20, 15, 10, 6, 3, 0.380, 0.220 KV. 3) distribution stations: these deliver electricity to

fig. 1

Example high-tension electric network
(Rome compartment, central Italy)

consumers; they very often are at the same location as transformation stations. Power transmission lines are generally grouped into three categories, depending on the voltage of the transported electricity: 1) high voltage, 380 to 220 KV (AT); for long-distance transmission; there is little redundancy in AT transmission networks. 2) Medium voltage, 150 to 30 KV (MT); for regional transmission; more redundant than AT 3) Low voltage, below 30 KV (BT);

to final consumers; very redundant networks. Transmission lines are composed of steel towers (or wood poles for lower tension), carrying ceramic suspension insulators and copper or aluminium cables. They are much less fragile than the stations' components versus seismic actions, which allows to consider them as not vulnerable. Electric power transmission systems are complex systems since they are redundant, capacitive, with time-varying configuration (the latter is auto-adaptive to the demand of electric power) and *intelligent* because protected by mechanisms which isolate breakdowns, driven by electronic logic. The present work only deals with AT network and assumes that only transformation and distribution stations contain seismically fragile elements. The reason to restrain the study to the AT network is that its failures are much more important than lower tension networks' failures. Any major failure in the AT network implies, in fact, consequences on a national or even international scale. For example the italian and french AT electric networks have several links and are pretty sensitive to each other's problems. On the other hand, any failure in the MT or BT network would only have regional or local consequences.

2. FUNCTIONING OF THE NETWORK; PERFORMANCE INDEX

The components of an electric network are designed to produce, transform and distribute electric energy. Electric power originates from production stations usually at medium voltage; after transformation to higher voltage (320 or 220 KV) electric energy flows into the transportation network. The network (lines+stations) is a capacitive system, i.e. is capable of carrying a finite amount of power to the demand nodes which must be fed with electric power at prescribed tension. A global index of the quality of the functioning of the network in a specified condition has to account for the amount and quality (in terms of shift from the target voltage at the nodes) of the electric power delivered at the demand nodes, compared with the values of voltage and power in an optimal condition. The following form is proposed:

$$q(c) = \frac{\sum_d (P_r(c))_d \cdot \left(1 - \frac{\|V_d(c) - V_d(oc)\|}{|V_d(oc)|} \right) \cdot \text{step} \left[\left(\frac{\|V_d(c) - V_d(oc)\|}{|V_d(oc)|} \right) - \alpha \right]}{\sum_d (P_r(oc))_d} \quad (1)$$

with: q =global quality index; $P_r(*)$ =real part of the electric power in condition * (only the real part of P actually gives power to consumers); $|V_d(*)|$ =modulus of the tension in condition *; α =maximum allowed shift from the target voltage (we assume 10%); d =demand node; c =current condition; oc =optimal (reference) condition. In Equation (1) the delivered power in condition c is weighted using as weight the shift from the target voltage.

3. STATIONS

3.1 Description and logical model

The seismically fragile components are concentrated in the nodes (stations) of the network. The typical layout of a distribution-transformation station is shown in fig. 3; microcomponents are shown in fig. 2. The components may be grouped as follows: (i) measuring

instruments:TA,TV (ii) short-circuit and lightning protection instruments: switches, dischargers (iii) various supports and mechanical devices: horizontal and vertical sectionalising switches, coil support, bar support (iv) other components: line boxes, power supply to protection system, transformers. (i), (ii) and (iii) are slender, vertical and steel-ceramic members. The following aspects may be noted to help understanding and modeling the functioning of a distribution-transformation station: 1)two sides: high and low tension (380 and 132 KV) 2)symmetrical with respect to transformers 3)some macro-components may be identified: (1)*lines in-out* (montante di linea) : TV+ coil support+ sectionalising switch+ TA+ protection switch+ supports; (2)*bars-connecting line* (montante parallelo) : TA+ protection switch+ sectionalising switch+ supports; (3)*bars*: TV+ supports; (4)*line boxes*: containing measurement and electronic equipment; (5)*power supply to protection system*: small transformers+ building+ diesel engine+ batteries; (6)*autotransformer line* (montante ATR): transformer+ dischargers+ TA's+ protection switches+ supports; 4)power generally flows from high-voltage to low-voltage side but flow inversions and/or insulation of low or high tension side (hence no more transformation, only distribution) are possible;5)only active microcomponent: protection switches, driven by the corresponding line box *and* the station's power supply to protection system (chain system), which switch open to insulate short-circuits originating from collapses.

fig.2 macrocomponents

fig. 3 scheme of a trans.-distr. station

Macrocomponents are recognized by searching the longest and simple enough chain (i.e. series elements) of microcomponents.

fig.4 example of the functioning of a station

fig.5 example of the functioning of a station

The functioning of the protections and the interdependencies of the short-circuits and insulation of the stations in a network may be visualized considering the two examples of fig. 4 and 5 using a simplified 3 stations network. In the first one (fig.4) all of the macrocomponents in the stations are properly working apart from a short-circuit on a line of station C. The protection switches open and insulate the remaining parts of the stations. Notice that, while station B is fully functional, stations A and C are only partially working. Fig. 5 clarifies the central role of power supply to protections. In fact, with non-working protection switches, a single short-circuit similar to that of the previous case, makes the whole system to collapse (station C is directly involved in the short-circuit while stations A and B are insulated).

2.2 Fragilities of the macrocomponents

Most of the microelements of a reference distribution-transformation station have been recently subjected to shaking table tests (1/). These tests allowed the corresponding mechanical model to be calibrated, from which the fragilities have been evaluated using the standard FORM/ SORM methods. The intensity factor for the seismic motion is the peak ground acceleration. The generic macrocomponent (lines, boxes, bars, power supply to protection) is a series system composed of microelements. Assuming their failures are independent it is straightforward that :

$$P_s(Macro) = P\left(\bigcap_m S_m\right) = \prod_m P(S_m) = \prod_m [1 - P(F_m)]; \quad P_f(Macro) = 1 - \prod_m [1 - P(F_m)] \quad (2)$$

m = index for microcomponent in the Macro

Fig. 6 to 9 show the obtained fragilities for micro and, from (2), for macrocomponents.

fig. 6 Fragilities of microcomponents

fig. 7 Fragilities of macrocomponents

fig. 8 Fragilities of macrocomponents

fig. 9 Fragilities of macrocomponents

In short, the reliability model for the stations includes a number of fragile macrocomponents and the actual intelligent response of the stations both to element failures and to collapses and short-circuits. Clearly the station can be described as a multi-state component.

3. LOAD-FLOW ANALYSIS

The system is modeled as a capacitive network, i.e. is capable of transporting a finite amount of power from production to users, via the transportation lines. The elements of the network are the nodes (N stations, divided into C load, G supply and 1 balance stations) and the lines (L transportation lines). Boundary conditions are specified in terms of power at the C nodes (2xN conditions), real power and tension modulus at the G nodes (2xG conditions) and tension modulus and phase at the balance node (2 conditions). The electrical characteristics of the lines from node i to node j (i.e. longitudinal and transversal impedances, conceptually the power required by the line to let through a flow of electric energy) influence both the value of the elements (i,i), (j,j), and (i,j) of the *admittance matrix* Y (NxN complex matrix), which accounts for the state of the lines of the network, and the power at the nodes. In fact the relationships:

$$Y_{p,p} = \sum_q y_{p,q}^L + \sum_q \frac{y_{p,q}^T}{2}; \quad Y_{p,q} = -y_{p,q}^L; \quad P_n = E_n \cdot [\overline{Y \cdot E}]_n \quad (3)$$

with :

$y_{p,q}^L$ = longitudinal admittance of line p, q; $y_{p,q}^T$ = transversal admittance of line p, q

$Y_{p,q}$ = p, q element of Y matrix; E_n = complex tension at node n; P_n = complex power at node

hold. Unknowns of the load-flow problem are the 2xN real and complex tension values at the nodes. The problem is mathematically formulated as a system of 2N algebraic non linear equations in E_n , solved by trial and error procedure (which may not converge in the case of unstable conditions). Collapses of the macrocomponents of the station i imply insulation of one or more (i,j) lines; matrix Y and power flow along the network sides change and hence the network is in a varied condition.

4. AN EXAMPLE APPLICATION : CENTRAL ITALY

4.1 Electric network and earthquake model

As an example application the electric network of central Italy has been chosen. The network consists of 60 nodes (8 supply and 51 demand stations, plus one balance node) and 82 lines. This network is about one third

fig 10

of the italian AT network. It is located in a rather active seismogenetic region. Thirteen seismogenetic areas have been considered, which are shown in fig. 10. The Cornell model for the seismic hazard has been chosen.

In each seismogenetic 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 activity of the seismogenetic area is expressed via the doubly truncated Gutenberg- Richter expression :

$$\lambda(i) = \lambda(i_{MIN}) \cdot [1 - F_I(i)]; F_I(i) = 1 - \frac{\exp(-\beta \cdot i) - \exp(-\beta \cdot i_{MAX})}{\exp(-\beta \cdot i_{MIN}) - \exp(-\beta \cdot i_{MAX})} \quad (4)$$

β = severity parameter ; i_{MIN} [i_{MAX}] = lower [upper] bound for the earthquake's intensity

The parameters of the Gutenberg- Richter law are evaluated on the basis of the historical seismicity and are shown in table 1. The adopted attenuation law is (2/):
 $\Delta I_s(R) = a + b \cdot (R + R_0) + c \cdot \log(R + R_0) + \varepsilon$
 with parameters : $R_0 = 3$ Km; $a = -0.5$; $b = 4.43$; $c = 0.056$, $\varepsilon = N(0; \sigma_\varepsilon = 1.037)$.
 The law (3/)
 $a [cm/s^2] = 10^{MM \cdot 0.237 - 0.594} + \varepsilon$
 with $\varepsilon = N(0; \sigma_\varepsilon = 0.35)$ has been adopted to convert the earthquake intensity from MM to cm/s^2 , since the fragilities of the macrocomponents are expressed as a function of the soil acceleration.

region	β	λ	i_{min}	i_{max}
1	1.043	0.886	4.0	11.0
2	1.246	1.257	4.0	11.0
3	0.819	0.827	4.0	10.0
4	1.167	4.348	4.0	11.0
5	1.29	1.561	4.0	10.0
6	1.574	1.074	4.0	9.0
7	1.145	1.092	4.0	11.0
8	0.868	0.368	4.0	12.0
9	0.991	0.719	4.0	11.0
10	1.236	1.494	4.0	11.0
11	0.891	0.653	4.0	12.0
12	1.113	0.944	4.0	12.0
13	0.471	0.176	4.0	9.0

table 1 seism. areas

4.2 Montecarlo procedure

A Montecarlo procedure has been set up to assess the seismic reliability of the electric network. The steps may be listed as follows:

Cicle on all the seismogenetic areas

Generate (from G.R. law) a vaue for the intensity of the earthquake

Cicle on the N sites of the stations

Attenuate the intensity

Generate (from $N(0; \sigma_\varepsilon)$) a value for the error due to the attenuation

Convert to acceleration

Generate (from $N(0; \sigma_\varepsilon)$) a value for the error due to the conversion

Cicle on the M macroelements of the station

Generate (from the fragility/acc.) the state of M (surviv./failed)

Spread short-circuits and/or insulation of subareas of the station

Spread short-circuits and/or isolation of subareas of the network among the N stations

Load-Flow analysis---->q

Estimate $P[q \text{ belong to } q1; q2]$ and the c.o.v. of the estimator

If c.o.v. > maximum allowed error generate one more value for the intensity of the earthquake and repeat the analysis.

5. RESULTS

The results shown in figs.11 and 12 have been obtained. Fig.11 shows the cdf of the random variable q , as defined in paragraph 2, given an earthquake has occurred in the region being studied. The probability that q is equal to 100% (optimal functioning) is around 90%. The remaining probability mass (10%) is mainly concentrated in the range $q=[80,99]\%$. If an assumption is made about the repair time before optimal functioning after an earthquake, it is then possible to compute the moments of the random variable energy not distributed in 1 year. Fig. 12 shows the mean and standard deviation of this r.v. obtained with the assumption of repair time equal to 4 hours. Seismogenetic areas 3 and 4 have proven to be the most influential with respect to the other ones. The large values of standard deviations as compared to the mean values are due to the fact that the underlying pmf shows a clear bimodal shape with maximum at the nul value and second larger value of pmf at the largest value of the random variable.

fig. 11 cdf of quality index

6. CONCLUSIONS

The method developed allows to determine the global reliability of electric networks. fig. 12 means of energy not distributed

As a general remark on the model and results, one should notice the following points:

- important interactions exist between adjacent AT networks; on the other hand, when limiting the space extension of the electric network, neighborhooding systems are modeled via a few load or supply nodes with prescribed power.
The extension in space of the studied network is likely to be too small and the inclusion of the whole italian AT network is next programmed.
- the results are to a great extent dependent on the macrocomponents' fragilities. As for boxes and power supply system a more accurate analysis is desirable.
- the performance index should also take into account quantities like the number of broken pieces of equipment and the overload of some of them, the repair times, the economical and social difference in lack of power supply to big or small centers.
- the results obtained here only consider the AT network, which is the one containing the smaller number of fragile components with respect to MT and BT networks, and are dependent on the activity and severity of the seismogenetic areas. Central Italy seismogenetic areas are pretty active but only moderately severe with respect to the other italian ones (for instance the ones in Friuli, Irpinia and Calabria). An extension of the study is under progress.

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