D 3.3

DELIVERABLE

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SEVENTH FRAMEWORK PROGRAMME

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Abstract

This report presents a survey of the technical literature on fragility models for the components of Electric power networks (EPNs). This work has been carried out with the purpose of producing a state-of-the-art of available models and indicating those that are most suited for use in the European context. The selection has been based both on the data supporting the models, when possible, and on the envisaged systemic approach to the simulation of EPN within the SYNER-G general methodology for infrastructural systems vulnerability assessment. The latter adopts a capacitive, detailed flow-based modelling with propagation of short-circuits over the network and requires internal modelling of the sub-station logic.

The report also identifies research needs to improve on the currently available fragility models.

Keywords: Sub-station logic, micro-component, macro-component, empirical fragility, analytical fragility, model selection.

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1 Description of an EPN

A modern EPN (Electric Power Network) is a complex interconnected system that can be subdivided into four major parts:

1.1.1 Generation

- Transformation
- Transmission and Distribution
- Loads

These are briefly described in the following sections. A more detailed treatment can be found in deliverable D5.2 "Systemic vulnerability and loss for electric power systems". The interested reader can also see Saadi, H. 2002. *Power system analysis - second edition*. McGraw-Hill Primis Custom Publishing.

1.2 FUNCTIONS WITHIN AN EPN

1.2.1 Generation

Generation of electric power is carried out in power plants. A power plant (Fig. 1.1) is composed of several three-phase AC (Alternate Current) generators known as synchronous generators or alternators. Synchronous generators have two synchronously rotating fields, one of which is produced by the rotor driven at synchronous speed and excited by DC (Direct Current), while the second one is produced in the stator windings by the three-phase armature currents. The DC current for the rotor windings is provided by the excitation systems, which maintain generator voltage and control the reactive power flow. Because of the absence of the commutator, AC generators can generate high power at high voltage, typically 30 kV. In a power plant, the size of generators can vary from 50 MW to 1500 MW.

At the time when the first EPNs were established in the world, individual electric companies were operating at different frequencies anywhere, in US ranging from 25 Hz to 133 Hz. As the need for interconnection and parallel operation became evident, a standard frequency of 60 Hz was adopted throughout the US and Canada, while most European countries selected the 50 Hz system. These two AC frequencies are still in use at the present time.

The source of the mechanical power, commonly named "prime mover", may be hydraulic turbines at waterfalls, steam turbines whose energy comes from the burning of coal, gas and nuclear fuel, gas turbines or occasionally internal combustion engines burning oil. Many alternative energy sources, like solar power, geothermal power, wind power, tidal power and biomass, are also employed.

Fig. 1.1 Power plant

1.2.2 Transformation

One of the major components of a power system is the transformer (Fig. 1.2), which transfers power with very high efficiency from one level of voltage to another level. The power transferred to the secondary winding is almost the same as the primary, except for losses in the transformer. Therefore, using a *step-up* transformer of voltage ratio *a* will reduce the secondary current of a ratio 1/*a*, reducing losses in the line, which are inversely proportional to voltage and directly proportional to distance. This makes the transmission of power over long distances possible. At the receiving end of the transmission lines *step-down* transformers are used to reduce the voltage to suitable values for distribution or utilization.

Fig. 1.2 High voltage transformer

1.2.3 Transmission and distribution

The purpose of a *power delivery system* (simple sketch in Fig. 1.3), also known as *transmission and distribution (T&D) system*, is to transfer electric energy from generating units at various locations to the customers demanding the loads.

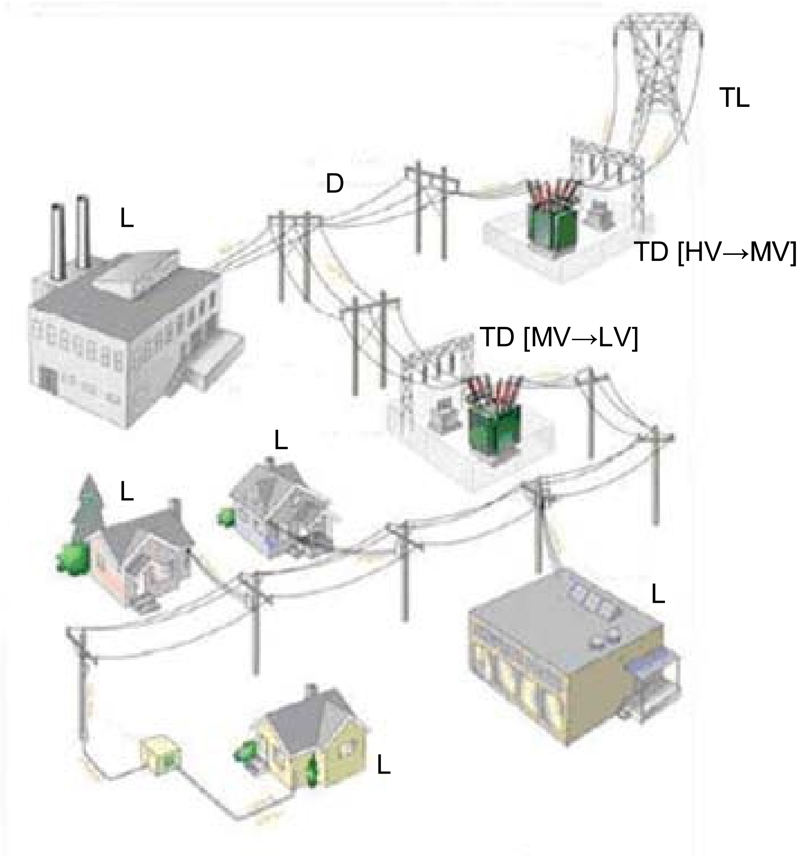


Fig. 1.3 Sketch of a T&D system for an EPN (TL = Transmission Lines, D = Distribution lines, TD [HV→MV] = Transformation (from high to medium voltage) and Distribution station, TD [MV→LV] = Transformation (from medium to low voltage) and Distribution station, L = Load)

A T&D system is divided into two general tiers: a *transmission system* that spans long distances at high voltages on the order of hundred of kilovolts (kV), usually between 60 and 750 kV, and a more local *distribution system* at intermediate voltages. The latter is further divided into a medium voltage distribution system, at voltages in the low tens of kV, and a low voltage distribution system, which consists of the wires that directly connect most domestic and small commercial customers, at voltages in the 220-240 V range for Europe. The distribution system can be both overhead and underground.

The transmission and distribution systems are generally characterised by two different topological structures: the transmission system is an interconnected redundant grid, composed of stations as nodes and transmission lines as edges, while the distribution system is a tree-like network, following the main streets in a city and reaching the end users. Fig. 1.4 shows the two topological structures.

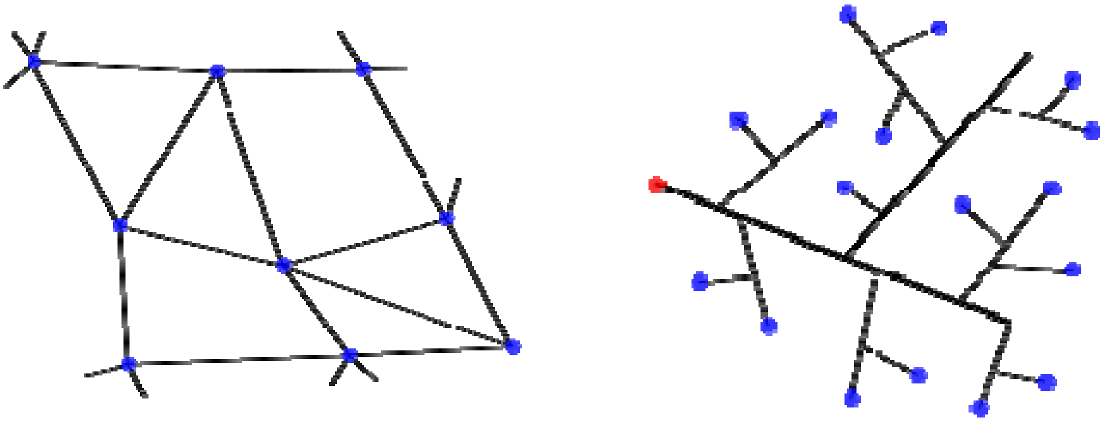


Fig. 1.4 Typical topological structures, grid-like (on the left) and tree-like (on the right), respectively for transmission and distribution systems

The European high voltage transmission grid, composed of lines with a voltage greater or equal to 220 kV, is displayed in Fig. 1.5. The image has been taken from Poljanšek, K., Bono, F. and Gutiérrez, E. 2010. *GIS-BASED METHOD TO ASSESS SEISMIC VULNERABILITY OF INTERCONNECTED INFRASTRUCTURE. A case of EU gas and electricity networks*. JRC Scientific and Technical Reports.

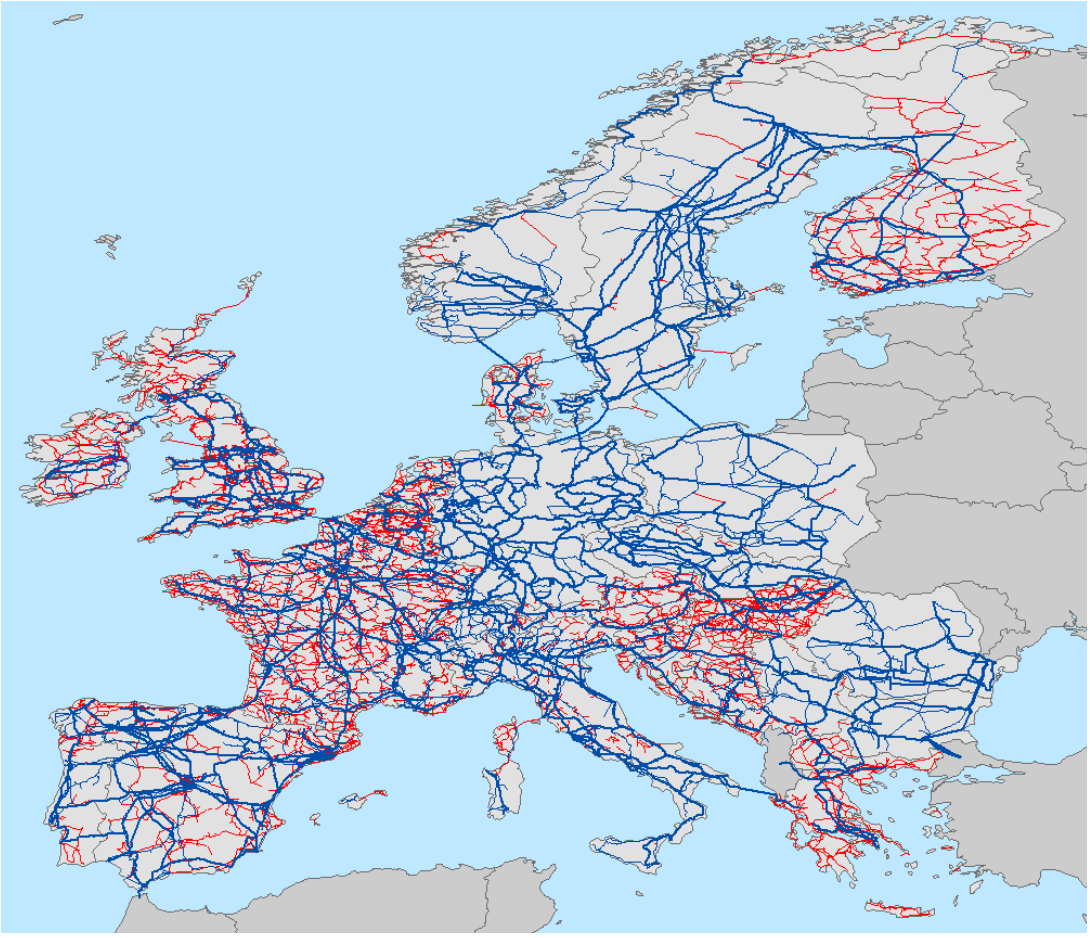


Fig. 1.5 European high voltage transmission grid (V ≥ 220 kV). Higher voltage lines in blue, lower voltage lines in red. Line thickness is proportional to voltage.

The lines at different voltages are terminated in *substations*.

An electric substation (Fig. 1.6) is a facility that serves as a source of energy supply for the local distribution area in which it is located, and has the following main functions:

- Changing or switching voltage from one level to another, by means of transformers.
- Providing points where safety devices such as disconnect switches, circuit breakers, and other equipment can be installed.
- Regulating voltage to compensate for system voltage changes.
- Eliminating lightning and switching surges from the system.
- Converting AC to DC and DC to AC, as needed.
- Changing frequency, as needed.

Substations can be entirely enclosed in buildings where all the equipment is assembled into one metal clad unit. Other substations have step-down transformers, high voltage switches, oil circuit breakers, and lightning arresters located outside the substation building.

The electric power is delivered to the single customers through distribution circuits, that include poles, wires, in-line equipment, utility-owned equipment at customer sites, above ground and underground conductors. Distribution circuits either consist of anchored or unanchored components.

Fig. 1.6 Substation

1.2.4 Loads

Loads of power systems are divided into *industrial*, *commercial* and *residential*.

Industrial loads are served directly from the high voltage transmission system or medium voltage distribution system. Commercial and residential loads consist largely of lighting, heating and cooling. These loads are independent of frequency and consume negligibly small reactive power. The real power of loads is expressed in terms of kilowatts (kW) or megawatts (MW).

The magnitude of load varies throughout the day and power must be available to consumers on demand. The greatest value of load during a 24-hr period is called *peak demand*. Smaller peaking generators may be commissioned to meet the peak load that occurs for only a few hours. In order to assess the usefulness of the generating plant the load factor is defined, which is the ratio of average load over a designated period of time to the peak load occurring in that period. Load factors may be given for a day, a month or a year.

1.3 ANALYSIS OF AN EPN

Analysis of an EPN in a seismically active environment can be carried out, as for other lifeline systems, at two different levels. The first basic one focuses on connectivity only and can only lead to a binary statement on whether any given node is connected with another node and, specifically, whether it is connected to a generation node through the network. This level of analysis is particularly inadequate for a system such as the EPN since the tolerance on the amount and quality, in terms of voltage and frequency, of the power fed to any demand node for maintaining serviceability is very low. The actual power flow in the node must be determined to make any meaningful statement on the satisfaction of the power demand at the node, not just its state of continued connectivity. The latter is an intrinsically systemic problem since it depends on the determination of the flows on the entire (damaged) network. Further, before being able to evaluate flows it is necessary to determine what is the EPN portion still up and running after an event. This does not simply mean what components are damaged since damage to components has non-local consequences. Indeed, damage to the components of a sub-station can lead to a short-circuit that may or may not propagate further away from that sub-station to adjacent others, generating in extreme cases very large black-outs. Hence power-flow analysis follows the analysis of short-circuit propagation. This is the modelling approach adopted within the SYNER-G general methodology. These issues are explained and dealt with in deliverable report D5.2.

Finally, this deliverables reports fragility models for components. In the literature one can find also models for the repair of these components, namely those contained in the HAZUS library. These models are not reported herein since the problem is regarded as a systemic one whereby repair can only be undertaken under the condition that both repair teams and spare parts are available. This condition cannot be checked without considering the actual extent and type of damage, the accessibility of sites, etc. Hence models for repair that do not account for these factors cannot be included within the framework of the SYNER-G general methodology.

2 Identification of the main typologies for electric power system components in Europe

The electric power systems components can be grouped on the base of four different analysis levels of the network. The main typologies, with particular reference to the European context, are listed in Table 2.1.

Table 2.1 Main typologies of EPN components in Europe

Typology		Analysis level	Element code
Electric power grid		Network	EPN01
Generation plant		Station	EPN02
Substation		Station	EPN03
Distribution circuits		Distribution-system	EPN04
Macro-components		Substation’s component	
	Autotransformer line	Substation’s component	EPN05
	Line without transformer	Substation’s component	EPN06
	Bars-connecting line	Substation’s component	EPN07
	Bars	Substation’s component	EPN08
	Cluster	Substation’s component	EPN09
Micro-components		Substation’s component	
	Circuit breaker	Substation’s component	EPN10
	Lightning arrester or Discharger	Substation’s component	EPN11
	Horizontal disconnect switch or Horizontal sectionalizing switch	Substation’s component	EPN12
	Vertical disconnect switch or Vertical sectionalizing switch	Substation’s component	EPN13
	Transformer or Autotransformer	Substation’s component	EPN14
	Current transformer	Substation’s component	EPN15
	Voltage transformer	Substation’s component	EPN16
	Box or Control house	Substation’s component	EPN17
	Power supply to protection system	Substation’s component	EPN18
	Coil support	Substation’s component	EPN19
	Bar support or Pothead	Substation’s component	EPN20
	Regulator	Substation’s component	EPN21
	Bus	Substation’s component	EPN22
	Capacitor bank	Substation’s component	EPN23

It has been noted from the literature review that authors often assign different names to the same micro-component.

It has to be remarked that most authors do not explicitly distinguish between micro- and macro-components. This distinction is useful in terms of reliability analysis when the approach to network modelling is capacitive (i.e. power flows are computed) and the internal logic of substations is modelled, i.e., partial functioning (continued service with reduced power flow) is accounted for. In this latter case the modelling effort, which is much higher than when a substation is considered as a single component with a binary state (fail/safe), can be reduced by assembling sub-sets of micro-components that are serially arranged within the substation in order to reduce them to a single element characterised by a single fragility: the macro-component. The substation layout is then composed of general (non-serial) arrangement of macro-components which can lead to partial functioning states, depending on the distribution of damage.

Looking again to Table 2.1, it should be now clear how some of the components listed, for which a fragility curve/model could be retrieved in the literature and is reported in chapter 3, are not of interest within the SYNER-G analysis framework where the level of detail/ resolution in the description of the EPN, and in general of lifelines, is higher. In particular, a fragility model for the whole network (EPN01) cannot be used, and a fragility model for an entire substation (EPN03) can only be used in preliminary simplified connectivity-only analyses.

3 Identification of existing fragility functions for electric power system components

Table 3.1 reports the main recent works on fragility functions of electric power system components, with the indication of the methodology used to evaluate the curves, the components classification, the considered intensity measure, as well as damage states and indices.

Table 3.1 Main works about EPN components fragilities

Reference	Methodology	Elements classification	Earthquake descriptor	Damage States and Indices
Anagnos, T. 1999	Empirical, with two normal functions	6 electric microcomponents	Peak Ground Acceleration	Failure with different failure modes depending on the considered component
Anagnos, T., and D. K. Ostrom. 2000.	Empirical, with two normal functions	500 kV circuit breaker and 230 kV horizontal disconnect switch	Peak Ground Acceleration	Failure with different failure modes depending on the considered component
Ang, A. H.-S., J. A. Pires, and R. Villaverde. 1996	Empirical, with lognormal function	6 electric microcomponents and 500 kV-230 kV substations	Peak Ground Acceleration	Failure based on power imbalance, abnormal voltage, unstable condition and operational power interruption
Bettinali, F., A. Rasulo, I. Vanzi, S. Imperatore, and S. Evangelista. 2004	Numerical	11 electric microcomponents	Peak Ground Acceleration	Failure
Dueñas-Osorio, L., J. I. Craig, and B. J. Goodno. 2007	Empirical, with lognormal function	Electric power grid	Peak Ground Acceleration	Failure based on substation functionality; *CL* = 20, 50 and 80%
FEMA – HAZUS^{MH} Technical Manual. 2003	Numerical, Boolean approach	Substation, distribution circuits, generation plant and 4 microcomponents	Peak Ground Acceleration	Slight/minor; Moderate; Extensive; Complete

Giovinazzi S., and A. King. 2009	Empirical (lognormal function)/ Numerical	Medium voltage substation	Peak Ground Acceleration	Slight/minor; Moderate; Extensive; Complete
Hwang, H. H. M., and J. R. Huo. 1998	Empirical (lognormal function)/ Numerical	9 electric microcomponents, pothead structure and 115/12 kV transformer	Peak Ground Acceleration	Failure
Hwang, H. H. M., and T. Chou. 1998	Numerical, dynamic analyses, fault tree	6 electric microcomponents, 1 macrocomponent and substation	Peak Ground Acceleration	Failure
Liu, G.-Y., C.-W. Liu, and Y. J. Wang. 2003	Empirical, with two normal functions	500 kV- 230 kV three-phase transformers	Peak Ground Acceleration	Failure
Rasulo, A., A. Goretti, and C. Nuti. 2004	Numerical	11 electric microcomponents and substation	Peak Ground Acceleration	Failure
Shinozuka, M., X. Dong, T. C. Chen, and X. Jin. 2007	Empirical, with lognormal function	Transformer, circuit breaker, disconnect switch and bus	Peak Ground Acceleration	Failure based on imbalance of power and abnormal voltage
Straub, D., and A. Der Kiureghian. 2008	Empirical (lognormal function)/ Bayesian analysis	1-phase 230 kV transformer, 230 kV live tank circuit breaker and systems of these components	Peak Ground Acceleration	Failure
Vanzi, I. 1996	Numerical, FORM/SORM methods	11 electric microcomponents and 4 macrocomponents	Peak Ground Acceleration	Failure
Vanzi, I. 2000	Numerical, optimization problem	Distribution substation	Peak Ground Acceleration	Failure
Vanzi, I., A. Rasulo, and S. Sigismondo. 2004	Numerical, Cornell method	420 kV circuit breaker	Spectral acceleration	Failure

3.1 DETAILED TABLES ON FRAGILITY FUNCTIONS

For each EPN components' typology, the following tables report the details about the fragility functions, extracted from the works listed in Table 3.1. The tables are grouped in three sections, the first of which is related to the whole network and the stations, while the remaining two sections deal with macro- and microcomponents fragility curves. It has to be remarked here that the fragility curves for electric power grids are not of interest for SYNER-G, since the aim is to perform a fragility assessment of lifelines, and in particular of an EPN at a lower analysis level, from the microcomponent up to the station, including also the distribution circuits.

Several of the surveyed works do not report numerical parameters for the fragility curves. Given the importance of having the parameters for using these models in an infrastructure simulation analysis, in this report these have been approximately determined from quantile values graphically retrieved from the curves. In particular this has been done in different ways.

Tables from Table 3.17 to Table 3.24, as well as Table 3.35, report the UWG (*Utilities Working Group*) fragility curves. These are defined by four parameters: minimum peak ground acceleration for the onset of damage and PGA at the 16th, 50th (corresponding to the median m) and 84th damage percentiles. Fragility curves are created by combining two normal distributions: N(m, σ_1) for probabilities less than 0.5 and N(m, σ_2) for values greater than 0.5. The values of σ_1 and σ_2 are determined by assuming that $m - \sigma_1$ = 16th percentile and $m + \sigma_2$ = 84th percentile. Damage probabilities are set to zero for all PGA values less than the assumed minimum needed for the onset of damage.

All the remaining curves in this report are lognormal functions, LN(λ, β).

Where possible, i.e. for those curves reaching values from 0 to more the 0.75 in the selected *intensity measure* (IM) range, the 25th, 50th (corresponding to the median m) and 75th damage percentiles have been graphically retrieved from the curves. Given these three values, λ and β were determined from Eq. (3.1) and Eq. (3.2),

$$\lambda = \ln(m) \tag{3.1}$$

$$\beta = 0.74 * \left[\ln\left(75^{\text{th}}\text{percentile}\right) - \ln\left(25^{\text{th}}\text{percentile}\right)\right] = 0.74 * IQR \tag{3.2}$$

where IQR is the interquartile range of the associated normal distribution.

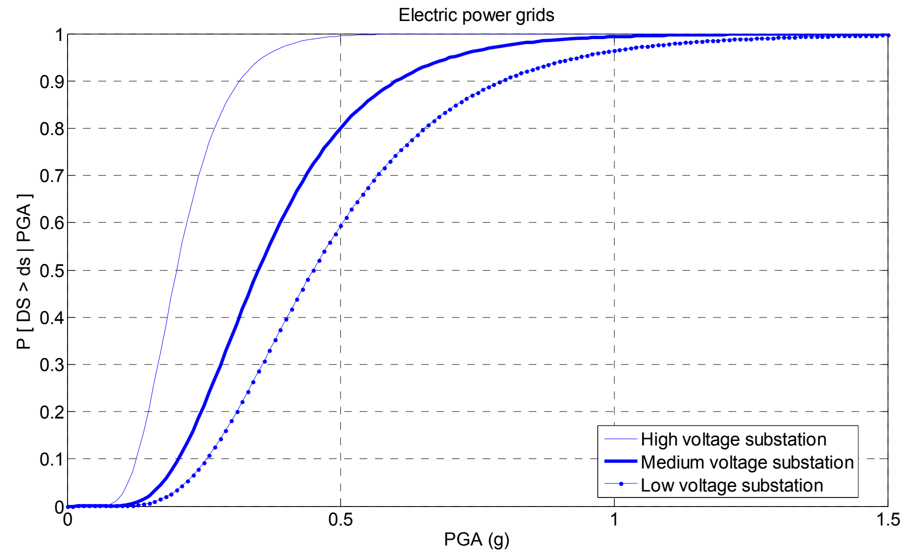
For the few remaining curves, β was computed with different expressions depending on the case. These are all similar to Eq. (3.2), in which the 25th and 75th damage percentiles were replaced by two available percentile values, while 0.74 was replaced by a coefficient numerically obtained from normal random sampling. The λ parameter was determined as in Eq. (3.1), with the m value read from the curve if possible, otherwise assumed in a way that the approximate curve, with a fixed value of the β parameter, was as close as possible to the original one.

Finally, the “Method” entry in the tables reports the method employed to derive the fragility curves:

- Empirical: statistical regression on data from damage surveys in actual events, or test from laboratory.
- Numerical: uses response data from numerical simulations of the component under earthquake input.

3.1.1 Fragility models for the whole network or for stations

Table 3.2 Detailed table on EPN01

Element at risk	Electric power grid	**Element Code**	EPN01
Reference	Dueñas-Osorio, L., J. I. Craig, and B. J. Goodno. 2007		
Method	Empirical	**Function**	Lognormal, LN(*λ*, *β*)
Typology	Three typologies: 1) High voltage substation (V > 350 kV) 2) Medium voltage substation (150 kV < V < 350 kV) 3) Low voltage substation (V < 150 kV)		
Damage states	Failure (Collapse)	**Seismic intensity parameter**	PGA (g)
Background	Empirical data from US west coast earthquakes		
Figures			

Parameters (graphically retrieved from the curves)

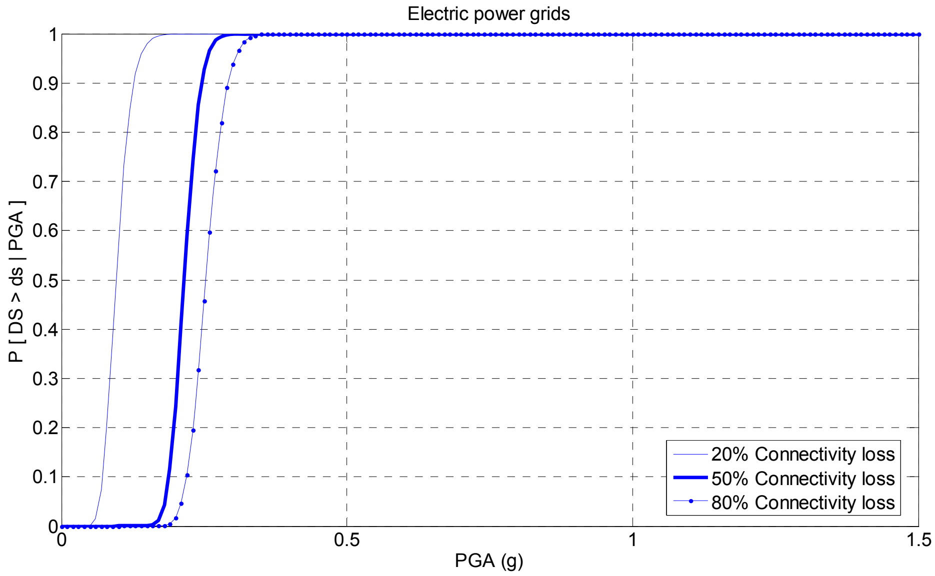
Substation's voltage	**25th perc. (g)**	**Median (g)**	**75th perc. (g)**	***λ* (g)**	***β***
Low	0.33	0.45	0.6	-0.8	0.44
Medium	0.26	0.35	0.46	-1.05	0.42
High	0.155	0.2	0.25	-1.61	0.35

Comments	The figure represents the fragility of the systems to exceed an *extensive damage* state. This limit state implies damage beyond short-term repair, leaving the network systems under consideration as completely non-functional

Table 3.3 Detailed table on EPN01

Element at risk	Electric power grid	**Element Code**	EPN01
Reference	Dueñas-Osorio, L., J. I. Craig, and B. J. Goodno. 2007		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Damage states	20% *CL*	50% *CL*	80% *CL*
Seismic intensity parameter	PGA (g)		
Background	Empirical data from US west coast earthquakes		

Figures



Parameters (graphically retrieved from the curves)

Connectivity loss level (%)	**25th perc. (g)**	**Median (g)**	**75th perc. (g)**	**λ (g)**	**β**
20	0.082	0.096	0.11	-2.34	0.22
50	0.2	0.215	0.23	-1.54	0.1
80	0.235	0.253	0.273	-1.37	0.11

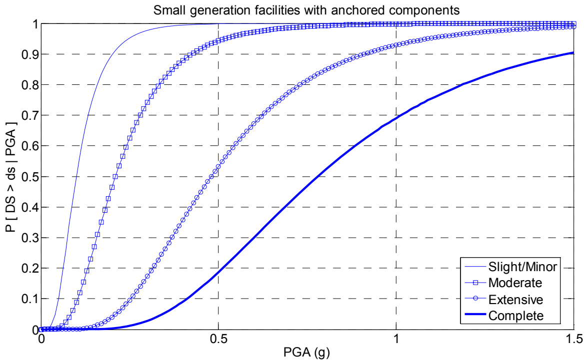
Comments

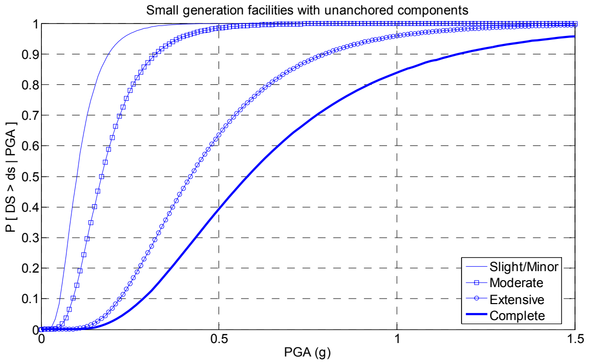
Connectivity Loss (*CL*) levels of = 20*,* 50 and 80% represent three limiting states to measure the ability of the network to function properly; more precisely, they quantify the likelihood of the distribution nodes to decrease their capacity to be connected to generation nodes given a particular seismic hazard

Table 3.4 Detailed table on EPN02

Element at risk	Small generation plant (less than 200 MW)		**Element Code**	EPN02
Reference	FEMA – HAZUS^{MH} Technical Manual. 2003			
Method	Numerical			
Function	Lognormal, LN(λ, β)			
Typology	Two typologies: 1) Anchored/Seismic Components 2) Unanchored/Standard Components			
Damage states	Slight/Minor	Moderate	Extensive	Complete
Seismic intensity parameter		PGA (g)		
Background	The curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationships of subcomponents.			

Figures





Parameters

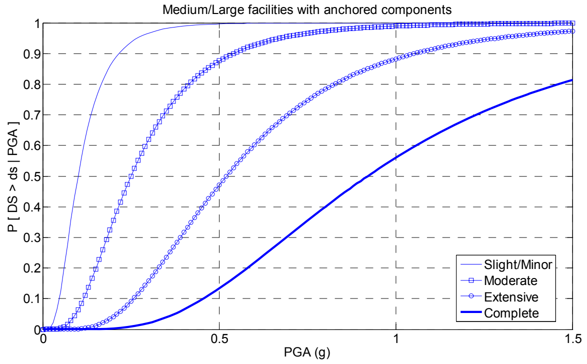
	Damage State	Median (g)	λ (g)	β
Anchored	Slight/Minor	0.1	-2.3	0.55
	Moderate	0.21	-1.56	0.55
	Extensive	0.48	-0.73	0.5
	Complete	0.78	-0.25	0.5
Unanchored	**Damage State**	**Median (g)**	**λ (g)**	**β**
	Slight/Minor	0.1	-2.3	0.5
	Moderate	0.17	-1.77	0.5
	Extensive	0.42	-0.87	0.5
	Complete	0.58	-0.54	0.55

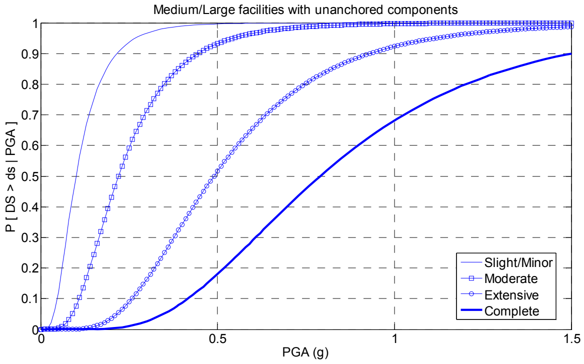
Comments In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically

Table 3.5 Detailed table on EPN02

Element at risk	Medium/large generation plant (more than 200 MW)		**Element Code**	EPN02
Reference	FEMA – HAZUS^{MH} Technical Manual. 2003			
Method	Numerical			
Function	Lognormal, LN(λ, β)			
Typology	Two typologies: 1) Anchored/Seismic Components 2) Unanchored/Standard Components			
Damage states	Slight/Minor	Moderate	Extensive	Complete
Seismic intensity parameter	PGA (g)			
Background	The curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationships of subcomponents.			

Figures



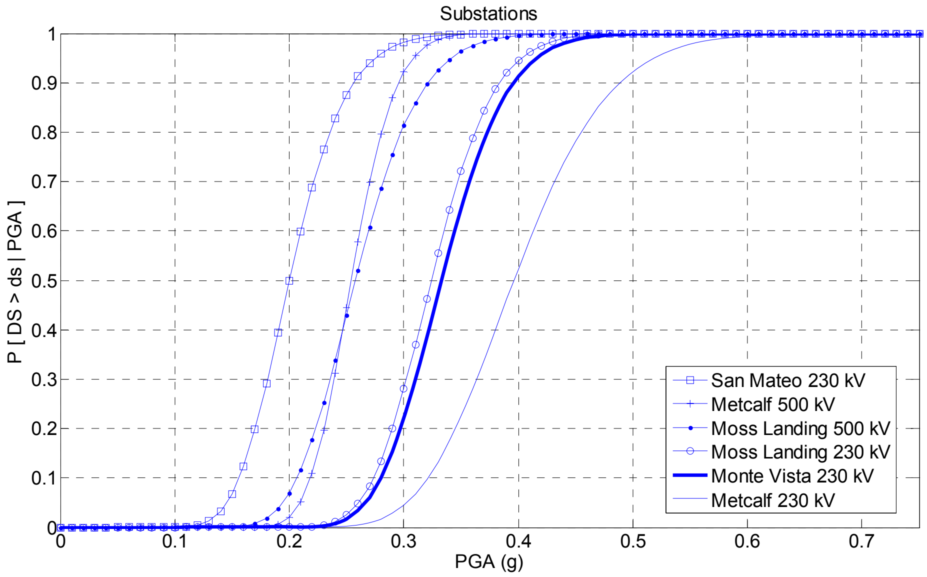


		Damage State	Median (g)	λ (g)	β
Parameters	Anchored	Slight/Minor	0.1	-2.3	0.6
		Moderate	0.25	-1.39	0.6
		Extensive	0.52	-0.65	0.55
		Complete	0.92	-0.08	0.55
	Unanchored	**Damage State**	**Median (g)**	**λ (g)**	**β**
		Slight/Minor	0.1	-2.3	0.6
		Moderate	0.22	-1.51	0.55
		Extensive	0.49	-0.71	0.5
		Complete	0.79	-0.24	0.5
Comments	In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically				

Table 3.6 Detailed table on EPN03

Element at risk	Substation	**Element Code**	EPN03
Reference	Ang, A. H.-S., J. A. Pires, and R. Villaverde. 1996		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Typology	Two typologies: 1) 500 kV substations 2) 230 kV substations		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Empirical data from the 1989 Loma Prieta earthquake		

Figures



Parameters

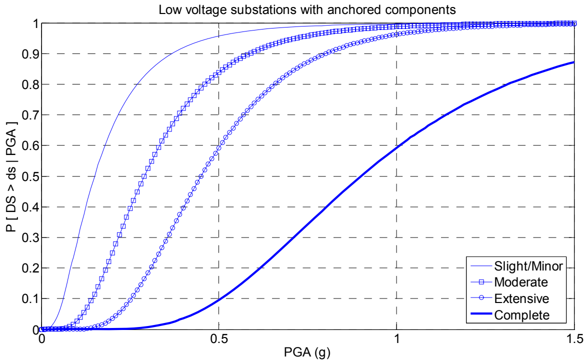
Substation	λ (g)	β
San Mateo, 230 kV	0.35	0.45
Metcalf, 500 kV	0.45	0.55
Moss Landing, 500 kV	0.55	0.75
Moss Landing, 230 kV	0.65	0.85
Monte Vista, 230 kV	0.8	1
Metcalf, 230 kV	0.85	1.05

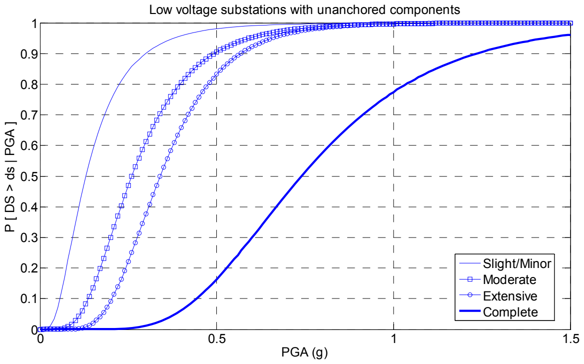
Comments

A sensitivity analysis is conducted to investigate the sensitivity of the results to the form of probability density function adopted for the capacity and fundamental frequency of the equipment

Table 3.7 Detailed table on EPN03

<table>
<tr><td>Element at risk</td><td colspan="3">Low voltage substation
(34.5 to 150 kV)</td><td>Element Code</td><td colspan="2">EPN03</td></tr>
<tr><td>Reference</td><td colspan="6">FEMA – HAZUS^{MH} Technical Manual. 2003</td></tr>
<tr><td>Method</td><td colspan="6">Numerical</td></tr>
<tr><td>Function</td><td colspan="6">Lognormal, LN(λ, β)</td></tr>
<tr><td>Typology</td><td colspan="6">Two typologies:
1) Anchored/Seismic Components
2) Unanchored/Standard Components</td></tr>
<tr><td>Damage states</td><td colspan="2">Slight/Minor</td><td colspan="2">Moderate</td><td>Extensive</td><td>Complete</td></tr>
<tr><td colspan="3">Seismic intensity parameter</td><td colspan="4">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="6">The curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationships of subcomponents.</td></tr>
<tr><td colspan="7">Figures

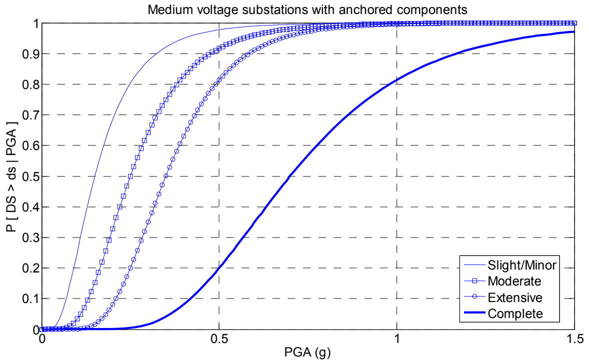


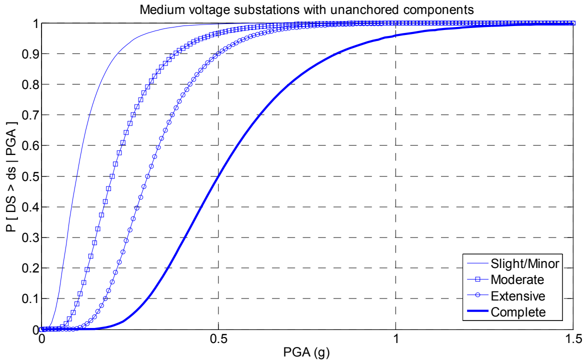


</td></tr>
<tr><td rowspan="10">Parameters</td><td rowspan="5">Anchored</td><td>Damage State</td><td>Median (g)</td><td>λ (g)</td><td colspan="2">β</td></tr>
<tr><td>Slight/Minor</td><td>0.15</td><td>-1.9</td><td colspan="2">0.7</td></tr>
<tr><td>Moderate</td><td>0.29</td><td>-1.24</td><td colspan="2">0.55</td></tr>
<tr><td>Extensive</td><td>0.45</td><td>-0.8</td><td colspan="2">0.45</td></tr>
<tr><td>Complete</td><td>0.9</td><td>-0.1</td><td colspan="2">0.45</td></tr>
<tr><td rowspan="5">Unanchored</td><td>Damage State</td><td>Median (g)</td><td>λ (g)</td><td colspan="2">β</td></tr>
<tr><td>Slight/Minor</td><td>0.13</td><td>-2.04</td><td colspan="2">0.65</td></tr>
<tr><td>Moderate</td><td>0.26</td><td>-1.35</td><td colspan="2">0.5</td></tr>
<tr><td>Extensive</td><td>0.34</td><td>-1.08</td><td colspan="2">0.4</td></tr>
<tr><td>Complete</td><td>0.74</td><td>-0.3</td><td colspan="2">0.4</td></tr>
<tr><td>Comments</td><td colspan="6">In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically</td></tr>
</table>

Table 3.8 Detailed table on EPN03

<table>
<tr><td>Element at risk</td><td colspan="3">Medium voltage substation (150 to 350 kV)</td><td>Element Code</td><td>EPN03</td></tr>
<tr><td>Reference</td><td colspan="5">FEMA – HAZUS^{MH} Technical Manual. 2003</td></tr>
<tr><td>Method</td><td colspan="5">Numerical</td></tr>
<tr><td>Function</td><td colspan="5">Lognormal, LN(λ, β)</td></tr>
<tr><td>Typology</td><td colspan="5">Two typologies:
1) Anchored/Seismic Components
2) Unanchored/Standard Components</td></tr>
<tr><td>Damage states</td><td colspan="2">Slight/Minor</td><td>Moderate</td><td>Extensive</td><td>Complete</td></tr>
<tr><td colspan="3">Seismic intensity parameter</td><td colspan="3">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="5">The curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationships of subcomponents.</td></tr>
<tr><td colspan="6">Figures

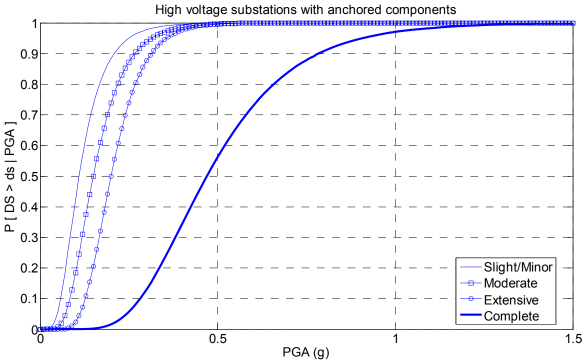




</td></tr>
<tr><td rowspan="10">Parameters</td><td rowspan="5">Anchored</td><td>Damage State</td><td>Median (g)</td><td>λ (g)</td><td>β</td></tr>
<tr><td>Slight/Minor</td><td>0.15</td><td>-1.9</td><td>0.6</td></tr>
<tr><td>Moderate</td><td>0.25</td><td>-1.39</td><td>0.5</td></tr>
<tr><td>Extensive</td><td>0.35</td><td>-1.05</td><td>0.4</td></tr>
<tr><td>Complete</td><td>0.7</td><td>-0.36</td><td>0.4</td></tr>
<tr><td rowspan="5">Unanchored</td><td>Damage State</td><td>Median (g)</td><td>λ (g)</td><td>β</td></tr>
<tr><td>Slight/Minor</td><td>0.1</td><td>-2.3</td><td>0.6</td></tr>
<tr><td>Moderate</td><td>0.2</td><td>-1.61</td><td>0.5</td></tr>
<tr><td>Extensive</td><td>0.3</td><td>-1.2</td><td>0.4</td></tr>
<tr><td>Complete</td><td>0.5</td><td>-0.69</td><td>0.4</td></tr>
<tr><td>Comments</td><td colspan="5">In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically</td></tr>
</table>

Table 3.9 Detailed table on EPN03

<table>
<tr><td>Element at risk</td><td colspan="2">High voltage substation
(350 kV and above)</td><td>Element Code</td><td colspan="2">EPN03</td></tr>
<tr><td>Reference</td><td colspan="5">FEMA – HAZUS^{MH} Technical Manual. 2003</td></tr>
<tr><td>Method</td><td colspan="5">Numerical</td></tr>
<tr><td>Function</td><td colspan="5">Lognormal, LN(λ, β)</td></tr>
<tr><td>Typology</td><td colspan="5">Two typologies:
1) Anchored/Seismic Components
2) Unanchored/Standard Components</td></tr>
<tr><td>Damage states</td><td>Slight/Minor</td><td>Moderate</td><td>Extensive</td><td colspan="2">Complete</td></tr>
<tr><td colspan="2">Seismic intensity parameter</td><td colspan="4">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="5">The curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationships of subcomponents.</td></tr>
<tr><td colspan="6">Figures



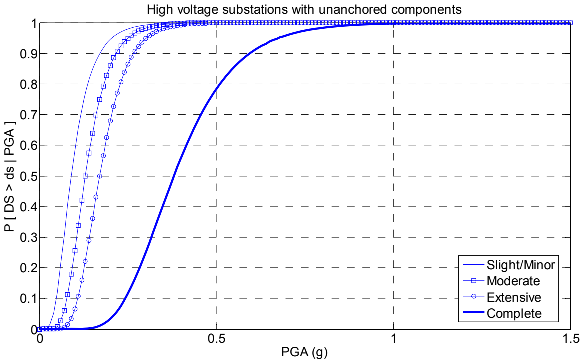

</td></tr>
<tr><td rowspan="10">Parameters</td><td rowspan="5">Anchored</td><td>Damage State</td><td>Median (g)</td><td>λ (g)</td><td>β</td></tr>
<tr><td>Slight/Minor</td><td>0.11</td><td>-2.21</td><td>0.5</td></tr>
<tr><td>Moderate</td><td>0.15</td><td>-1.9</td><td>0.45</td></tr>
<tr><td>Extensive</td><td>0.2</td><td>-1.61</td><td>0.35</td></tr>
<tr><td>Complete</td><td>0.47</td><td>-0.76</td><td>0.4</td></tr>
<tr><td rowspan="5">Unanchored</td><td>Damage State</td><td>Median (g)</td><td>λ (g)</td><td>β</td></tr>
<tr><td>Slight/Minor</td><td>0.09</td><td>-2.41</td><td>0.5</td></tr>
<tr><td>Moderate</td><td>0.13</td><td>-2.04</td><td>0.4</td></tr>
<tr><td>Extensive</td><td>0.17</td><td>-1.77</td><td>0.35</td></tr>
<tr><td>Complete</td><td>0.38</td><td>-0.97</td><td>0.35</td></tr>
<tr><td>Comments</td><td colspan="5">In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically</td></tr>
</table>

Table 3.10 Detailed table on EPN03

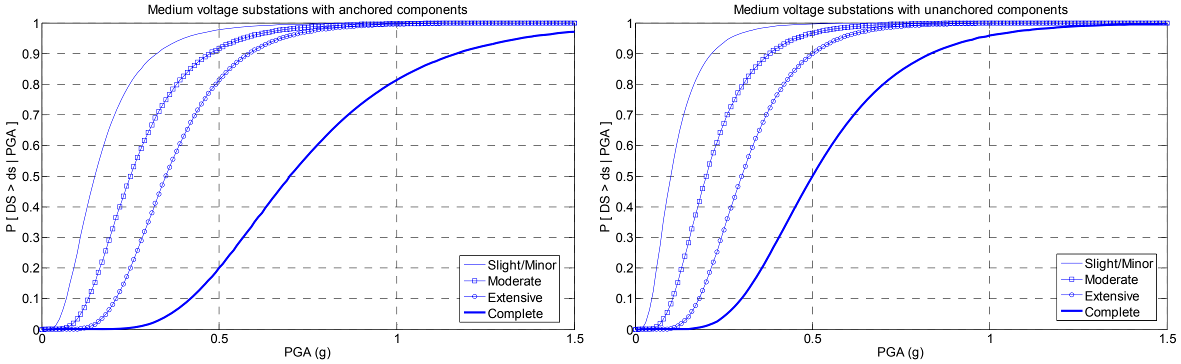
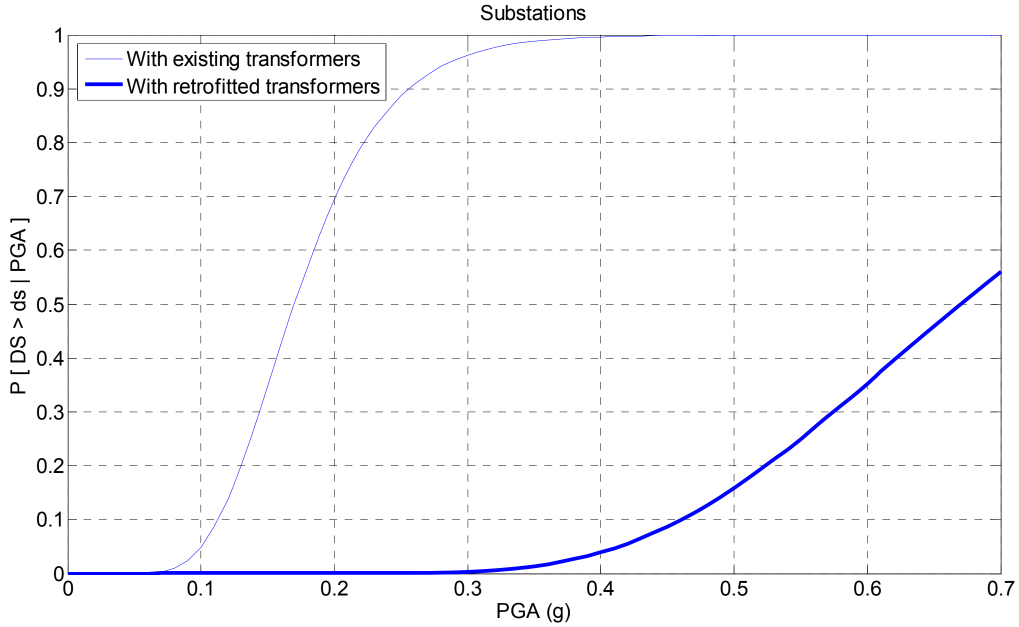
Element at risk	Medium voltage substation	**Element Code**	EPN03	
Reference	Giovinazzi S., and A. King. 2009			
Method	Empirical/Numerical			
Function	Lognormal, LN(λ, β)			
Typology	Two typologies: 1) Anchored/Seismic Components 2) Unanchored/Standard Components			
Damage states	Slight/Minor	Moderate	Extensive	Complete
Seismic intensity parameter	PGA (g)			
Background	HAZUS^{MH} model, combination of expert judgement models and empirical models based on statistical analysis of damage data from previous events			
Figures 				
Parameters	Listed in Table 3.8			
Comments	HAZUS^{MH} fragility curves account for the probabilistic combination of subcomponent damage functions, using Boolean expressions to describe the relationship between components and subcomponents			

Table 3.11 Detailed table on EPN03

Element at risk	Substation	**Element Code**	EPN03
Reference	Hwang, H. H. M., and T. Chou. 1998		
Method	Numerical		
Function	Lognormal, LN(λ, β)		
Typology	Two typologies: 1) Substation with existing transformers 2) Substation with retrofitted transformers		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Fragility data of individual components in substation 21 in Memphis		

Figures



Parameters (graphically retrieved from the curves)

Typology of substation	**25th perc. (g)**	**Median (g)**	**75th perc. (g)**	**λ (g)**	**β**
With existing transformers	0.13	0.17	0.2	-1.77	0.32
With retrofitted transformers	0.55	0.67	-	-0.4	0.29

Comments

Regarding the retrofitting, it is assumed that the transformers can be anchored so that they are prevented from sliding or overturning at any level of ground shaking;

For the 2nd typology, β = 1.4826 * [ln(median) - ln(25th percentile)]

Table 3.12 Detailed table on EPN03

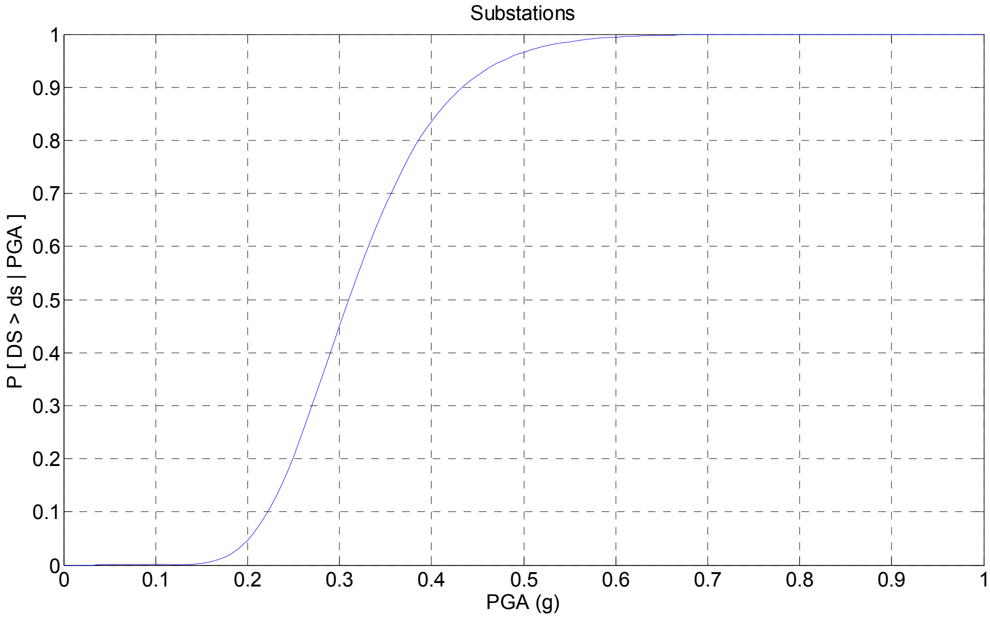
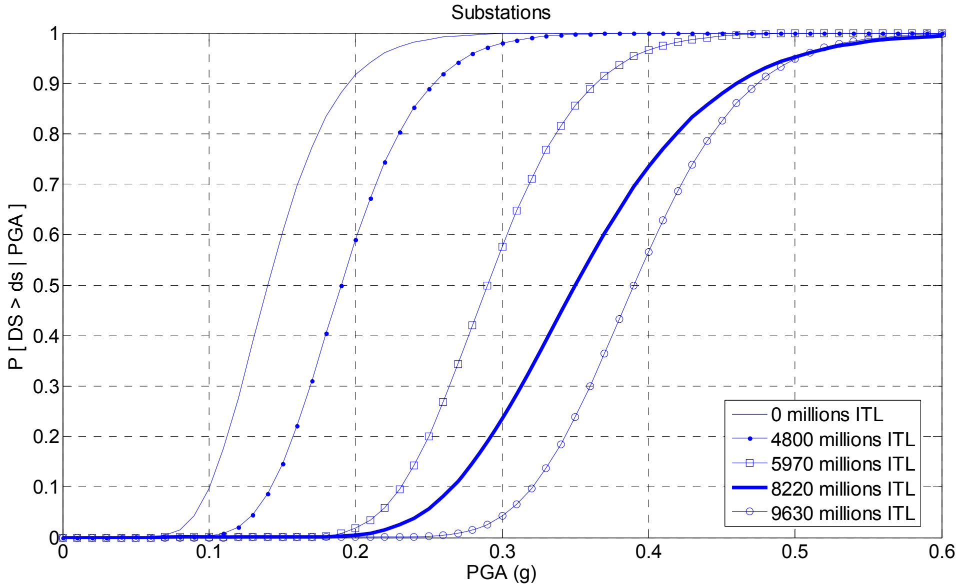
<table>
<tr><td>Element at risk</td><td colspan="2">Substation</td><td>Element Code EPN03</td></tr>
<tr><td>Reference</td><td colspan="3">Rasulo, A., A. Goretti, and C. Nuti</td></tr>
<tr><td>Method</td><td colspan="3">Numerical</td></tr>
<tr><td>Function</td><td colspan="3">Lognormal, LN(λ, β)</td></tr>
<tr><td>Damage states</td><td colspan="3">Failure (Collapse)</td></tr>
<tr><td colspan="2">Seismic intensity parameter</td><td colspan="2">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="3">Fragility curves for typical Italian electrical components</td></tr>
<tr><td colspan="4">Figures

</td></tr>
<tr><td>Parameters (graphically retrieved from the curve)</td><td colspan="3">Median = 0.31 g
λ = -1.17 g
25th percentile = 0.26 g
75th percentile = 0.37 g
β = 0.26</td></tr>
<tr><td>Comments</td><td colspan="3">The substation fragility curve has been derived from the substation equipment identifying the minimal cut-sets necessary to interrupt the electric flow and then combining the component fragilities for a serial system</td></tr>
</table>

Table 3.13 Detailed table on EPN03

Element at risk	Distribution substation	**Element Code**	EPN03
Reference	Vanzi, I. 2000		
Method	Numerical, optimization problem conditioned to PGA = 0.25 g		
Function	Lognormal, LN(λ, β)		
Typology	12 cases based on the upgrading cost		
Damage states	Failure (Collapse)	**Seismic intensity parameter**	PGA (g)
Background	Information on the HV, MV and LV EPNs (Electric Power Networks) of Sicily		

Figures



Parameters (graphically retrieved from the curves)

Upgrading cost (millions ITL)	25th perc. (g)	Median (g)	75th perc. (g)	λ (g)	β
0	0.12	0.14	0.17	-1.97	0.26
4800 (2.479 MLN €)	0.17	0.19	0.23	-1.66	0.22
5970 (3.083 MLN €)	0.26	0.29	0.33	-1.24	0.18
8220 (4.245 MLN €)	0.3	0.35	0.4	-1.05	0.21
9630 (4.973 MLN €)	0.35	0.39	0.43	-0.94	0.15

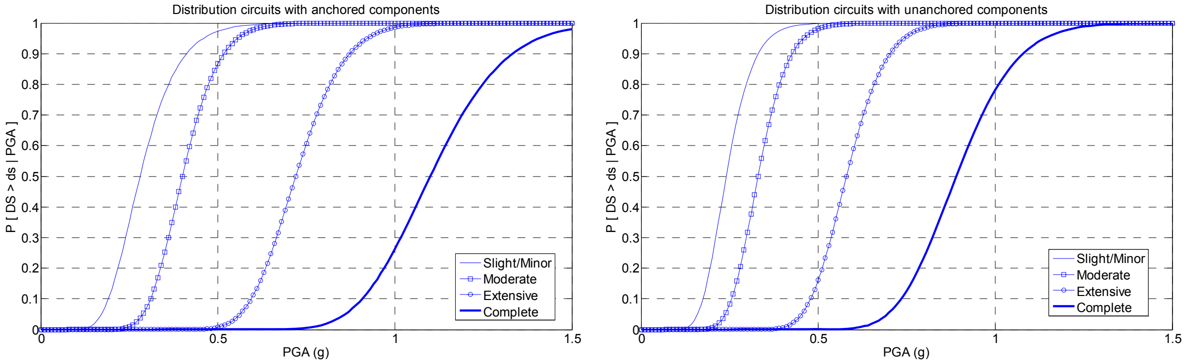
(only the main 5 curves are reported, ITL = Italian Lire)

Comments

If the optimization problem is solved conditioned to a different value of PGA, the same results are obtained;

The independence of the result of the optimization problem from PGA applies to any station type

Table 3.14 Detailed table on EPN04

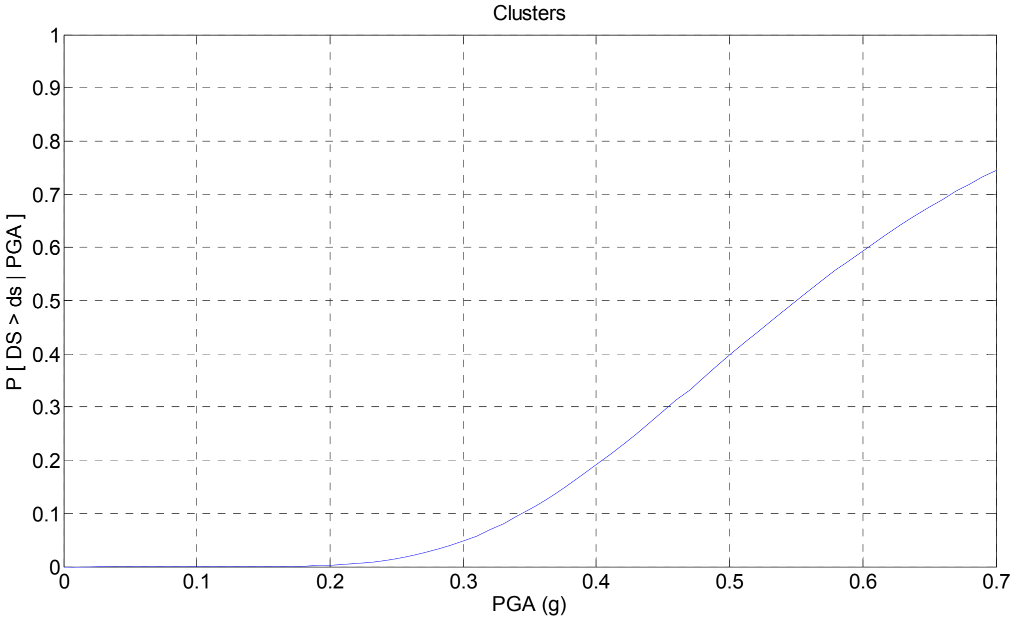
Element at risk	Distribution circuits		**Element Code**	EPN04	
Reference	FEMA – HAZUS^{MH} Technical Manual. 2003				
Method	Numerical				
Function	Lognormal, LN(λ, β)				
Typology	Two typologies: 1) Anchored/Seismic Components 2) Unanchored/Standard Components				
Damage states	Slight/Minor	Moderate	Extensive	Complete	
Seismic intensity parameter		PGA (g)			
Background	The curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationships of subcomponents.				
Figures					
Parameters	Anchored	**Damage State**	**Median (g)**	**λ (g)**	**β**
		Slight/Minor	0.28	-1.27	0.3
		Moderate	0.4	-0.92	0.2
		Extensive	0.72	-0.33	0.15
		Complete	1.1	0.1	0.15
	Unanchored	**Damage State**	**Median (g)**	**λ (g)**	**β**
		Slight/Minor	0.24	-1.43	0.25
		Moderate	0.33	-1.11	0.20
		Extensive	0.58	-0.54	0.15
		Complete	0.89	-0.12	0.15
Comments	In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically				

3.1.2 Fragility models for macrocomponents

Table 3.15 Detailed table on EPN09

Element at risk	1 electric macrocomponent (cluster)	**Element Code**	EPN09
Reference	Hwang, H. H. M., and T. Chou. 1998		
Method	Numerical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Information on substation 21 in Memphis		

Figures



Parameters (graphically retrieved from the curve)

Component	25th percentile (g)	Median (g)	λ (g)	β
Cluster	0.43	0.55	-0.6	0.36

Comments

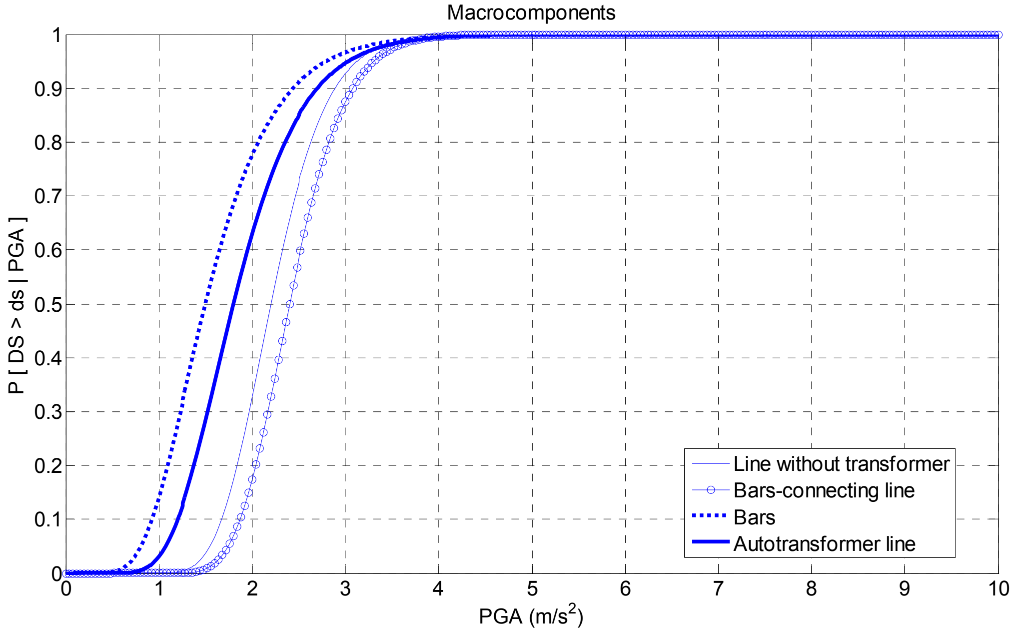
The fragility curves have been obtained by performing dynamic analyses on appropriate models of the components;

The cluster is composed of a bus, a pothead and six lightning arresters;

β = 1.4826 * [ln(median) - ln(25th percentile)]

Table 3.16 Detailed table on EPN05 to 08

<table>
<tr><td>Element at risk</td><td>4 electric macrocomponents</td><td>Element Code</td><td>EPN05 to 08</td></tr>
<tr><td>Reference</td><td colspan="3">Vanzi, I. 1996</td></tr>
<tr><td>Method</td><td colspan="3">Numerical, FORM/SORM methods</td></tr>
<tr><td>Function</td><td colspan="3">Lognormal, LN(λ, β)</td></tr>
<tr><td>Damage states</td><td colspan="3">Failure (Collapse)</td></tr>
<tr><td>Seismic intensity parameter</td><td colspan="3">PGA (m/s^2)</td></tr>
<tr><td>Background</td><td colspan="3">Fragilities of microcomponents considered by the same author</td></tr>
<tr><td colspan="4">Figures


</td></tr>
<tr><td>Parameters (graphically retrieved from the curves)</td><td colspan="3">
<table>
<tr><th>Macrocomponent</th><th>25th perc. (m/s^2)</th><th>Median (m/s^2)</th><th>75th perc. (m/s^2)</th><th>λ (m/s^2)</th><th>β</th></tr>
<tr><td>Line without transformer</td><td>1.8</td><td>2.2</td><td>2.4</td><td>0.79</td><td>0.21</td></tr>
<tr><td>Bars-connecting line</td><td>2</td><td>2.4</td><td>2.6</td><td>0.88</td><td>0.19</td></tr>
<tr><td>Bars</td><td>1.2</td><td>1.5</td><td>2</td><td>0.41</td><td>0.38</td></tr>
<tr><td>Autotransformer line</td><td>1.5</td><td>1.8</td><td>2.3</td><td>0.59</td><td>0.32</td></tr>
</table>
</td></tr>
<tr><td>Comments</td><td colspan="3">The considered macrocomponents are: (1) Line without transformer, (2) Bars-connecting line, (3) Bars, (4) Autotransformer line;
The failures of interconnected vulnerable microelements are assumed as independent events</td></tr>
</table>

3.1.3 Fragility models for microcomponents

Table 3.17 Detailed table on EPN10

<table>
<tr><td>**Element at risk**</td><td colspan="3">230 kV circuit breaker</td><td>**Element Code**</td><td>EPN10</td></tr>
<tr><td>**Reference**</td><td colspan="5">Anagnos, T. 1999</td></tr>
<tr><td>**Method**</td><td>Empirical</td><td>**Function**</td><td colspan="3">Two normal functions, N(m, σ_1) and N(m, σ_2)</td></tr>
<tr><td>**Typology**</td><td colspan="5">General Electric ATB4, ATB5 and ATB6 circuit breakers (same curve)</td></tr>
<tr><td>**Failure modes**</td><td colspan="2">Column Base Gasket Leak</td><td>1 Porcelain Column Fails</td><td colspan="2">2 Porcelain Columns Fail</td></tr>
<tr><td colspan="3">**Seismic intensity parameter**</td><td colspan="3">PGA (g)</td></tr>
<tr><td>**Background**</td><td colspan="5">UWG fragility curves and empirical damage data from 12 US earthquakes</td></tr>
<tr><td colspan="6">**Figures**

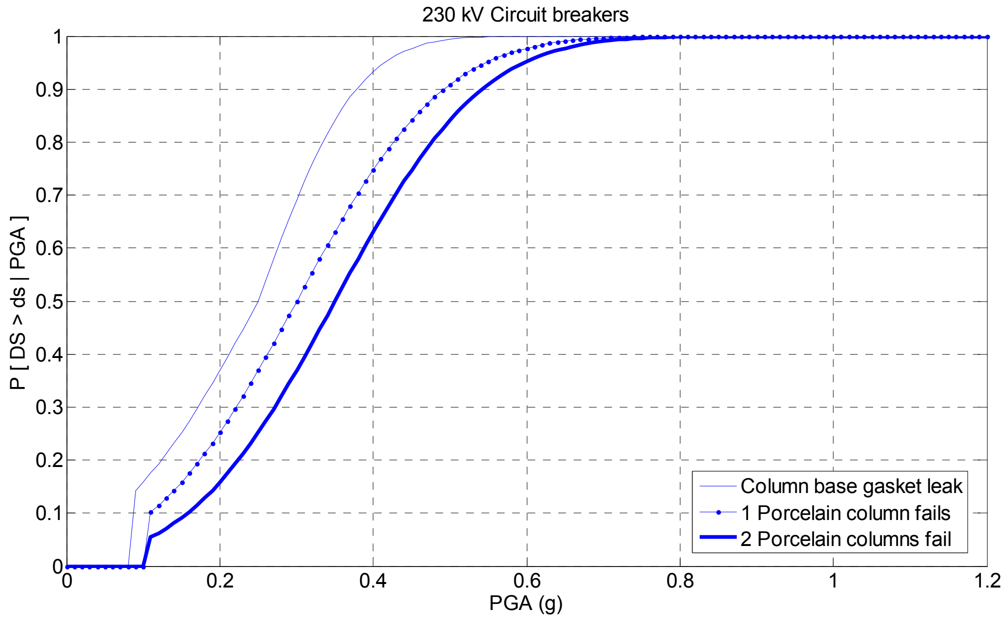
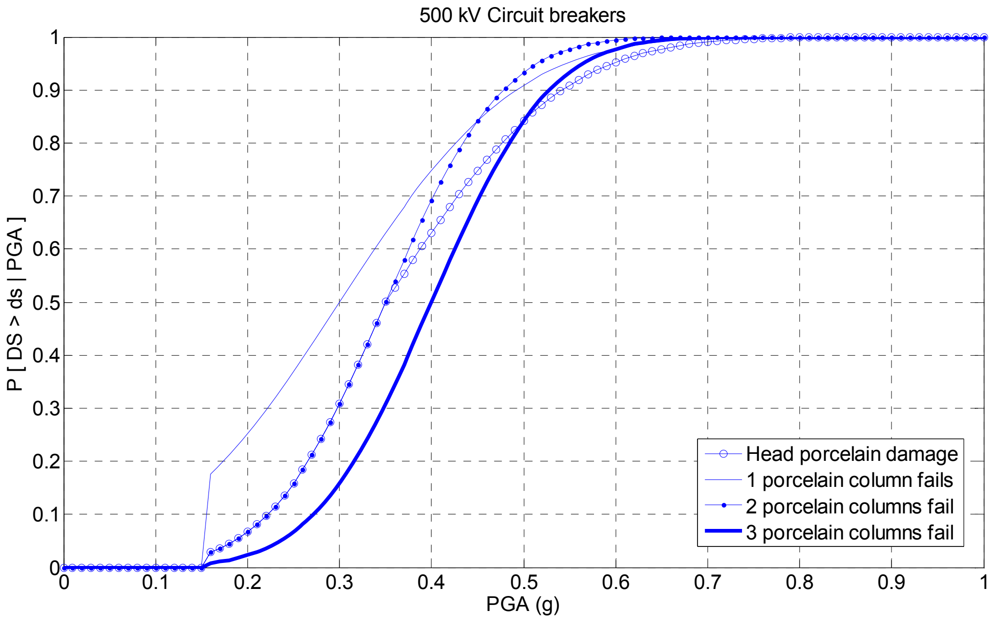

</td></tr>
<tr><td>**Parameters (graphically retrieved from the curves)**</td><td colspan="5"><table>
<tr><th>Failure mode</th><th>Minimum (g)</th><th>16th perc. (g)</th><th>Median (g)</th><th>84th perc. (g)</th><th>σ_1</th><th>σ_2</th></tr>
<tr><td>Column base gasket leak</td><td>0.08</td><td>0.1</td><td>0.25</td><td>0.35</td><td>0.15</td><td>0.1</td></tr>
<tr><td>1 porcelain column fails</td><td>0.1</td><td>0.15</td><td>0.3</td><td>0.45</td><td>0.15</td><td>0.15</td></tr>
<tr><td>2 porcelain columns fail</td><td>0.1</td><td>0.2</td><td>0.35</td><td>0.5</td><td>0.15</td><td>0.15</td></tr>
</table></td></tr>
<tr><td>**Comments**</td><td colspan="5"></td></tr>
</table>

Table 3.18 Detailed table on EPN10

Element at risk	500 kV circuit breaker		**Element Code**	EPN10
Reference	Anagnos, T. 1999			
Method	Empirical			
Function	Two normal functions, N(m, σ_1) and N(m, σ_2)			
Failure modes	Head Porcelain Damage	1 Porcelain Column Fails	2 Porcelain Columns Fail	3 Porcelain Columns Fail
Seismic intensity parameter	PGA (g)			
Background	UWG fragility curves and empirical damage data from 12 US earthquakes			
Figures				

Parameters (extracted from a different reference)

Failure mode	Minimum (g)	16th perc. (g)	Median (g)	84th perc. (g)	σ_1	σ_2
Head porcelain damage	0.15	0.25	0.35	0.5	0.1	0.15
1 porcelain column fails	0.15	0.15	0.3	0.45	0.15	0.15
2 porcelain columns fail	0.15	0.25	0.35	0.45	0.1	0.1
3 porcelain columns fail	0.15	0.3	0.4	0.5	0.1	0.1

Comments

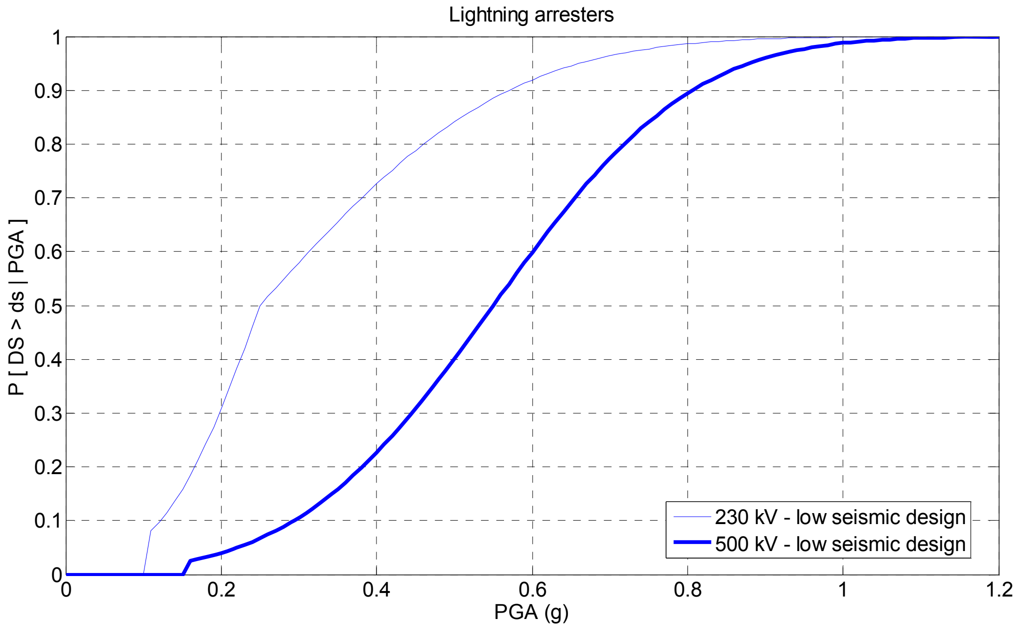
Two types of damage data are present:

1) Damage Data - Non-Seismic; 2) Damage Data - Seismically Retrofitted

Table 3.19 Detailed table on EPN11

Element at risk	Lightning arrester	**Element Code**	EPN11
Reference	Anagnos, T. 1999		
Method	Empirical		
Function	Two normal functions, N(m, σ_1) and N(m, σ_2)		
Typology	Two typologies: 1) 230 kV lightning arresters 2) 500 kV lightning arresters		
Damage states	Failure (Collapse) Failure mode: Failure of Porcelain Column		
Seismic intensity parameter	PGA (g)		
Background	UWG fragility curves and empirical damage data from 12 US earthquakes		

Figures



Parameters (graphically retrieved from the curves)

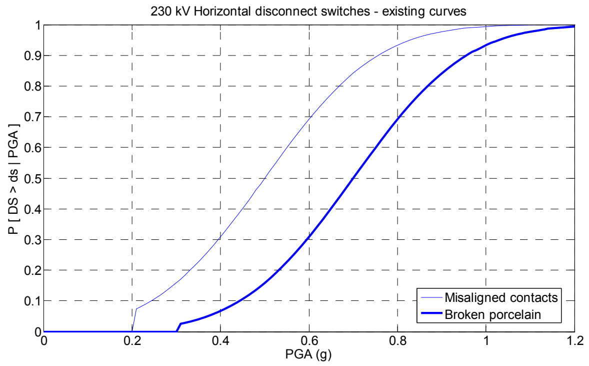
Typology	Minimum (g)	16th perc. (g)	Median (g)	84th perc. (g)	σ_1	σ_2
230 kV	0.1	0.15	0.25	0.5	0.1	0.25
500 kV	0.15	0.35	0.55	0.75	0.2	0.2

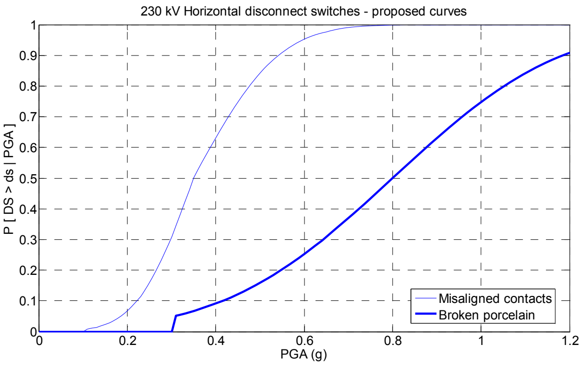
Comments

Table 3.20 Detailed table on EPN12

Element at risk	230 kV horizontal disconnect switch	**Element Code**	EPN12
Reference	Anagnos, T. 1999		
Method	Empirical		
Function	Two normal functions, N(m, σ_1) and N(m, σ_2)		
Typology	Two typologies: 1) older disconnect switches with no seismic design requirements 2) new disconnect switches, shake table tested		
Failure modes	Misaligned Contacts	Broken Porcelain	
Seismic intensity parameter	PGA (g)		
Background	UWG fragility curves and empirical damage data from 12 US earthquakes		

Figures





Parameters (extracted from a different reference)

Failure mode	**Minimum (g)**	**16th perc. (g)**	**Median (g)**	**84th perc. (g)**	σ_1	σ_2
Existing parameters						
Misaligned contacts	0.2	0.3	0.5	0.7	0.2	0.2
Broken porcelain	0.3	0.5	0.7	0.9	0.2	0.2
Proposed parameters						
Misaligned contacts	0.1	0.25	0.35	0.5	0.1	0.15
Broken porcelain	0.3	0.5	0.8	1.1	0.3	0.3

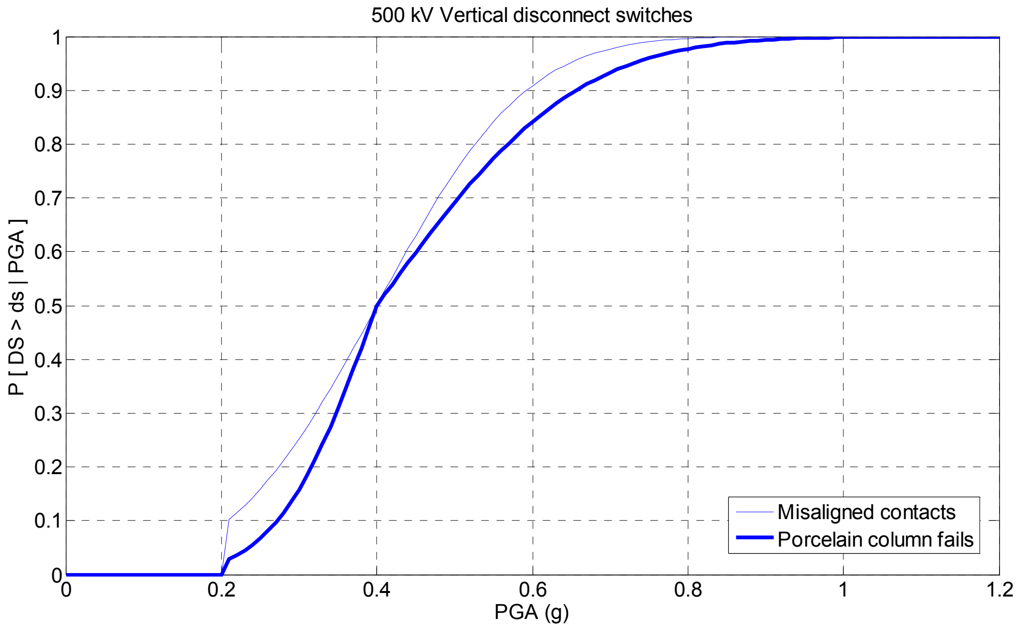
Comments

- Existing parameters refer to existing UWG fragility curves;
- Proposed parameters refer to the UWG curves as updated since 1993, through additional information available due to observations from more recent earthquakes or from modelling and testing programs

Table 3.21 Detailed table on EPN13

Element at risk	500 kV vertical disconnect switch	**Element Code**	EPN13
Reference	Anagnos, T. 1999		
Method	Empirical		
Function	Two normal functions, N(m, σ_1) and N(m, σ_2)		
Failure modes	Misaligned Contacts	Porcelain Column Fails	
Seismic intensity parameter	PGA (g)		
Background	UWG fragility curves and empirical damage data from 12 US earthquakes		

Figures



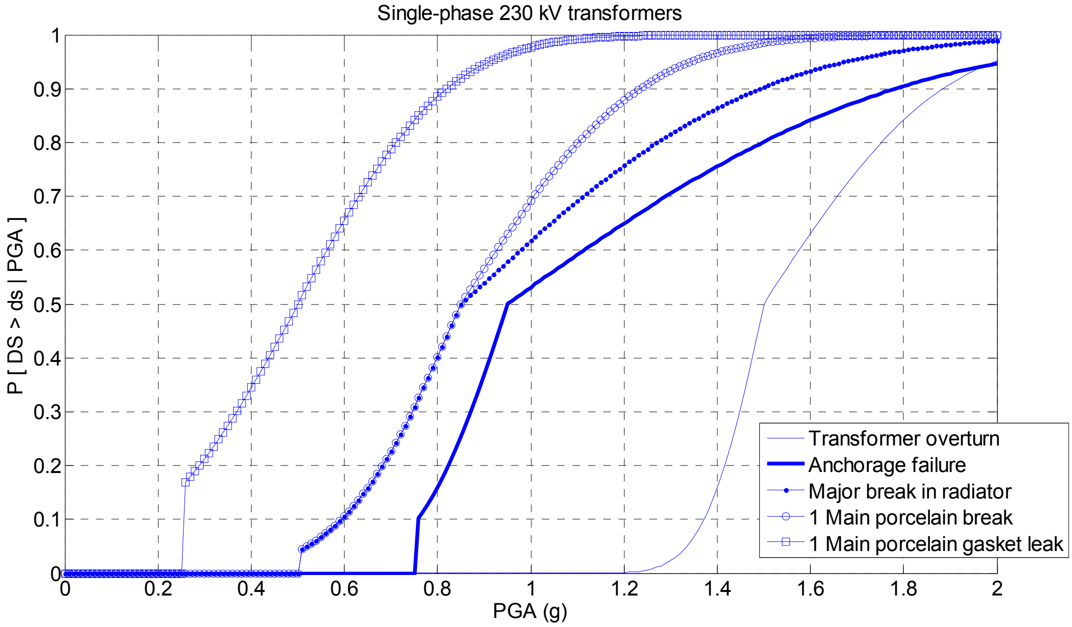
Parameters (graphically retrieved from the curves)

Failure mode	**Minimum (g)**	**16th perc. (g)**	**Median (g)**	**84th perc. (g)**	σ_1	σ_2
Misaligned contacts	0.2	0.25	0.4	0.55	0.15	0.15
Porcelain column fails	0.2	0.3	0.4	0.6	0.1	0.2

Comments	There are very few data for this equipment class and no clear trends are evident

Table 3.22 Detailed table on EPN14

Element at risk	Single-phase 230 kV transformer		**Element Code**	EPN14	
Reference	Anagnos, T. 1999				
Method	Empirical	**Function**	Two normal functions, N(m, σ_1) and N(m, σ_2)		
Failure modes	1 Main Porcelain Gasket Leak	1 Main Porcelain Break	Major Break in Radiator	Anchorage Failure	Transformer Overturn
Seismic intensity parameter		PGA (g)			
Background	UWG fragility curves and empirical damage data from 12 US earthquakes				
Figures					



Parameters (graphically retrieved from the curves)

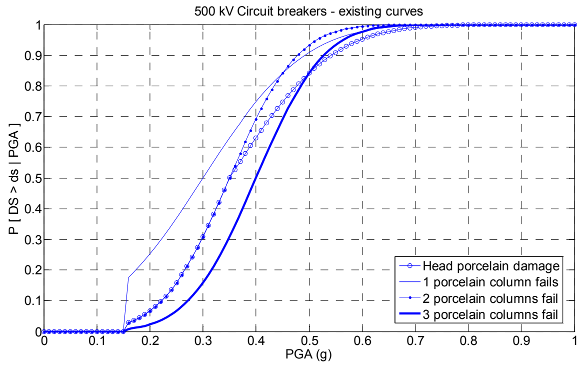
Failure mode	Minimum (g)	16th perc. (g)	Median (g)	84th perc. (g)	σ_1	σ_2
Transformer overturn	0	1.4	1.5	1.8	0.1	0.3
Anchorage failure	0.75	0.8	0.95	1.6	0.15	0.65
Major break in radiator	0.5	0.65	0.85	1.35	0.2	0.5
1 main porcelain break	0.5	0.65	0.85	1.15	0.2	0.3
1 main porcelain gasket leak	0.25	0.25	0.5	0.75	0.25	0.25

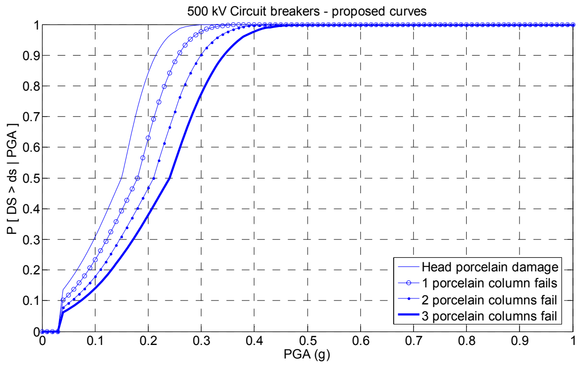
Comments	Transformers can have many different configurations and the data in the figure do not discriminate between different configurations

Table 3.23 Detailed table on EPN10

Element at risk	500 kV circuit breaker		**Element Code**	EPN10
Reference	Anagnos, T., and D. K. Ostrom. 2000			
Method	Empirical	**Function**	Two normal functions, N(m, σ_1) and N(m, σ_2)	
Failure modes	Head Porcelain Damage	1 Porcelain Column Fails	2 Porcelain Columns Fail	3 Porcelain Columns Fail
Seismic intensity parameter		PGA (g)		
Background	UWG fragility curves and empirical damage data from 12 US earthquakes			

Figures





Parameters

Failure mode	Min. (g)	16th perc. (g)	Median (g)	84th perc. (g)	σ_1	σ_2
Existing parameters						
Head porcelain damage	0.15	0.25	0.35	0.5	0.1	0.15
1 porcelain column fails	0.15	0.15	0.3	0.45	0.15	0.15
2 porcelain columns fail	0.15	0.25	0.35	0.45	0.1	0.1
3 porcelain columns fail	0.15	0.3	0.4	0.5	0.1	0.1
Proposed parameters						
Head porcelain damage	0.03	0.05	0.15	0.2	0.1	0.05
1 porcelain column fails	0.03	0.07	0.18	0.24	0.11	0.06
2 porcelain columns fail	0.03	0.09	0.21	0.28	0.12	0.07
3 porcelain columns fail	0.03	0.11	0.24	0.32	0.13	0.08

Comments

All curves have been developed using two types of damage data:

1) Damage Data - Non-Seismic;

2) Damage Data - Seismically Retrofitted;

- Existing parameters refer to existing UWG fragility curves;
- Proposed parameters refer to the UWG curves as updated since 1993, through additional information available due to observations from more recent earthquakes or from modelling and testing programs

Table 3.24 Detailed table on EPN12

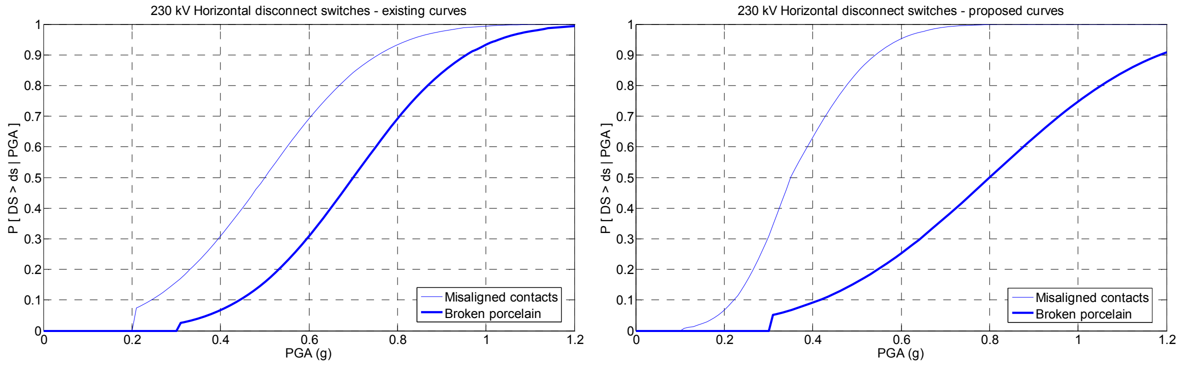
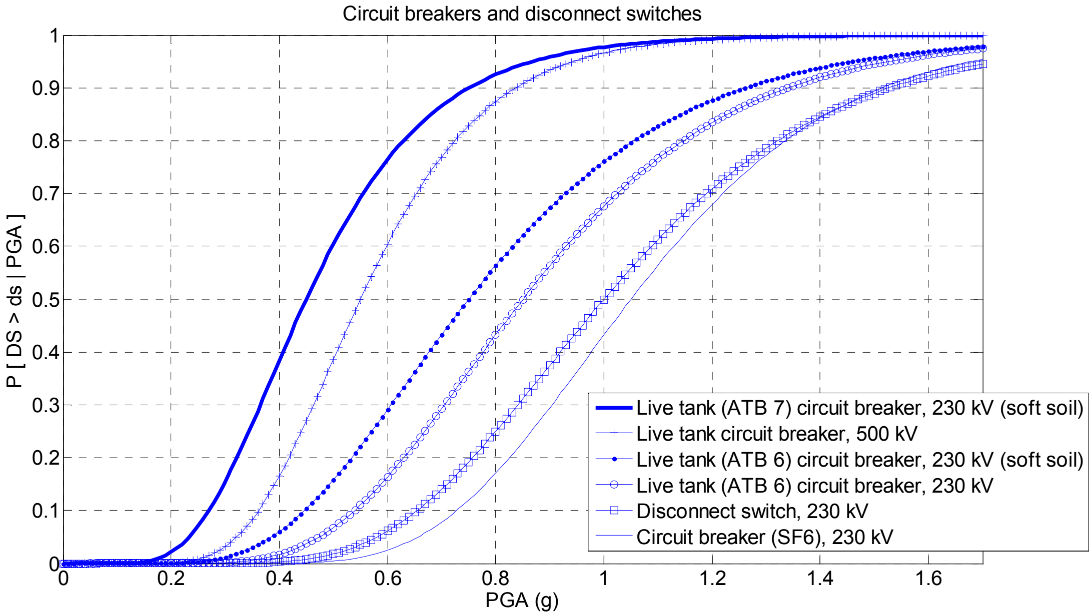
<table>
<tr><td>Element at risk</td><td>230 kV horizontal disconnect switch</td><td>Element Code</td><td>EPN12</td></tr>
<tr><td>Reference</td><td colspan="3">Anagnos, T., and D. K. Ostrom. 2000</td></tr>
<tr><td>Method</td><td colspan="3">Empirical</td></tr>
<tr><td>Function</td><td colspan="3">Two normal functions, N(m, σ_1) and N(m, σ_2)</td></tr>
<tr><td>Failure modes</td><td>Misaligned Contacts</td><td colspan="2">Broken Porcelain</td></tr>
<tr><td>Seismic intensity parameter</td><td colspan="3">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="3">UWG fragility curves and empirical damage data from 12 US earthquakes</td></tr>
<tr><td colspan="4">Figures
 </td></tr>
<tr><td>Parameters</td><td colspan="3">Listed in Table 3.20</td></tr>
<tr><td>Comments</td><td colspan="3">- Existing parameters refer to existing UWG fragility curves;
- Proposed parameters refer to the UWG curves as updated since 1993, through additional information available due to observations from more recent earthquakes or from modelling and testing programs</td></tr>
</table>

Table 3.25 Detailed table on EPN10 & EPN12/13

Element at risk	6 electric microcomponents	**Element Code**	EPN10 & EPN12/13
Reference	Ang, A. H.-S., J. A. Pires, and R. Villaverde. 1996		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Empirical data from the 1989 Loma Prieta earthquake		

Figures



Parameters (graphically retrieved from the curves)

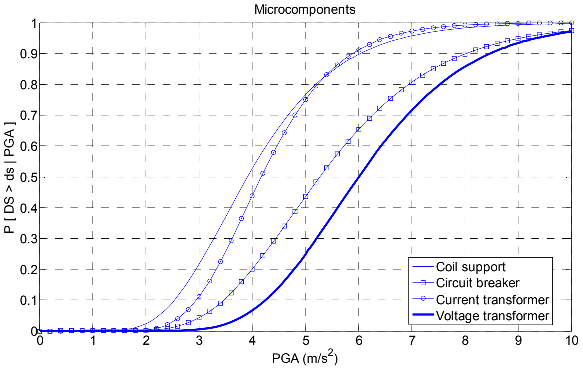
Component	25th perc. (g)	Median (g)	75th perc. (g)	λ (g)	β
Live tank (ATB 7) circuit breaker, 230 kV (soft soil)	0.35	0.45	0.6	-0.8	0.4
Live tank circuit breaker, 500 kV	0.45	0.55	0.7	-0.6	0.33
Live tank (ATB 6) circuit breaker, 230 kV (soft soil)	0.55	0.75	0.95	-0.29	0.41
Live tank (ATB 6) circuit breaker, 230 kV	0.65	0.85	1.05	-0.16	0.36
Disconnect switch, 230 kV	0.8	1	1.25	0	0.33
Circuit breaker (SF6), 230 kV	0.85	1.05	1.25	0.05	0.29

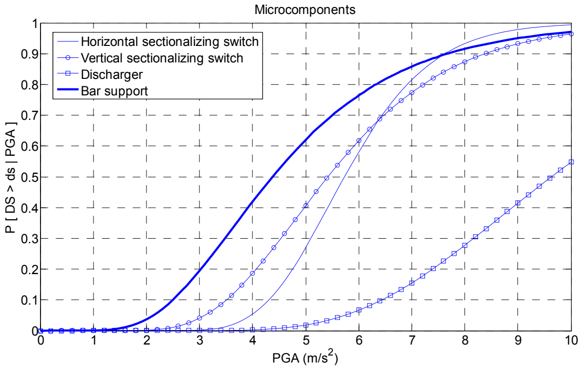
Comments	A sensitivity analysis is conducted to investigate the sensitivity of the results to the form of probability density function adopted for the capacity and fundamental frequency of the equipment

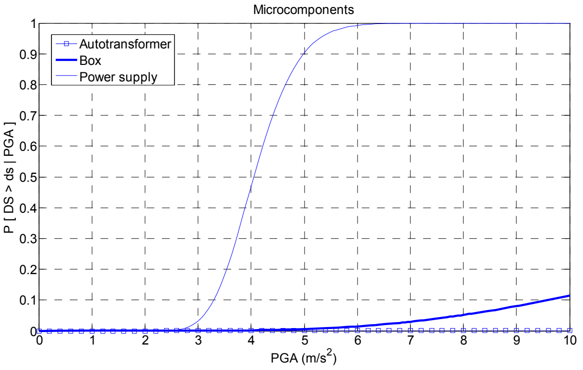
Table 3.26 Detailed table on EPN10 to EPN20

Element at risk	11 electric microcomponents	**Element Code**	EPN10 to EPN20
Reference	Bettinali, F., A. Rasulo, I. Vanzi, S. Imperatore, and S. Evangelista. 2004		
Method	Numerical	**Function**	Lognormal, LN(λ, β)
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (m/s^2)	**Background**	Cornell method

Figures







The considered microcomponents are: (1) Coil support, (2) Circuit breaker, (3) Current transformer, (4) Voltage transformer, (5) Horizontal sectionalizing switch, (6) Vertical sectionalizing switch, (7) Discharger, (8) Bar support, (9) Autotransformer, (10) Box, (11) Power supply to protection system.

Parameters (extracted from a different reference)

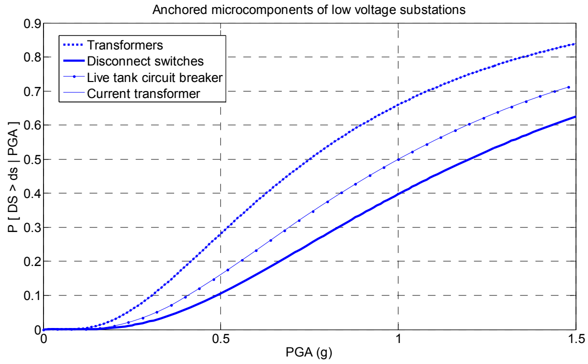
Component	**λ (m/s^2)**	**β**	**Component**	**λ (m/s^2)**	**β**
Coil support	1.36	0.34	Discharger	2.27	0.32
Circuit breaker	1.66	0.33	Bar support	1.48	0.44
Current transformer	1.43	0.27	Autotransformer	3.16	0.29
Voltage transformer	1.79	0.27	Box	2.93	0.52
Horiz. sectionalizing switch	1.75	0.22	Power supply to protection system	1.4	0.16
Vert. sectionalizing switch	1.69	0.34			

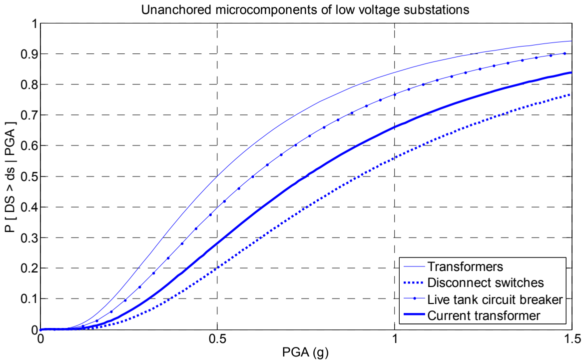
Comments	The retrieved fragility curves take into account the uncertainties about both the mechanical properties and the dynamic input

Table 3.27 Detailed table on EPN10, 12/13, 14, 15

Element at risk	4 microcomponents of low voltage substations	**Element Code**	EPN10, EPN12/13, EPN14, EPN15
Reference	FEMA – HAZUS^{MH} Technical Manual. 2003		
Method	Numerical		
Function	Lognormal, LN(λ, β)		
Typology	Two typologies: 1) Anchored/Seismic Components 2) Unanchored/Standard Components		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		

Figures





Parameters

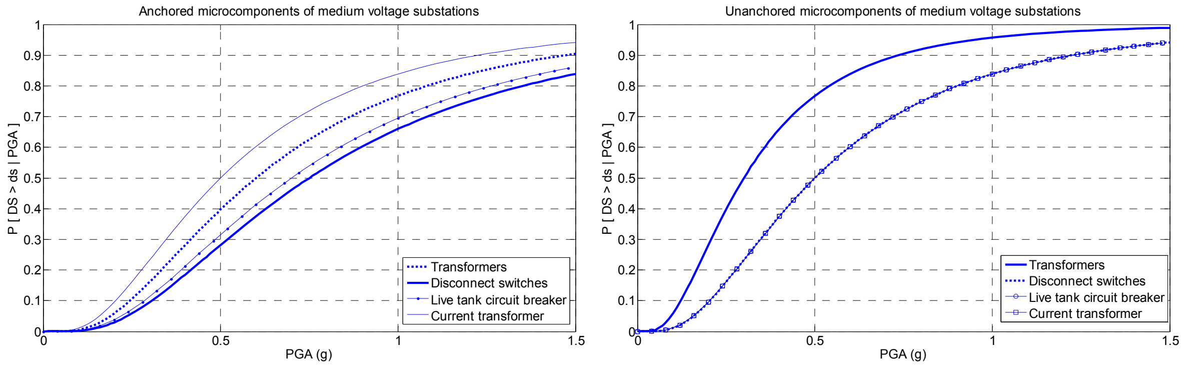
Anchored				Unanchored			
Component	**Median (g)**	**λ (g)**	**β**	**Component**	**Median (g)**	**λ (g)**	**β**
Transformer	0.75	-0.29	0.7	Transformer	0.5	-0.69	0.7
Disconnect switch	1.2	0.18	0.7	Disconnect switch	0.9	-0.11	0.7
Live tank circuit breaker	1	0	0.7	Live tank circuit breaker	0.6	-0.51	0.7
Current transformer	0.75	-0.29	0.7	Current transformer	0.75	-0.29	0.7

Comments	The considered microcomponents are: (1) Transformer, (2) Disconnect switch, (3) Live tank circuit breaker, (4) Current transformer

Table 3.28 Detailed table on EPN10, 12/13, 14, 15

Element at risk	4 microcomponents of medium voltage substations	**Element Code**	EPN10, EPN12/13, EPN14, EPN15
Reference	FEMA – HAZUS^{MH} Technical Manual. 2003		
Method	Numerical		
Function	Lognormal, LN(λ, β)		
Typology	Two typologies: 1) Anchored/Seismic Components 2) Unanchored/Standard Components		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		

Figures



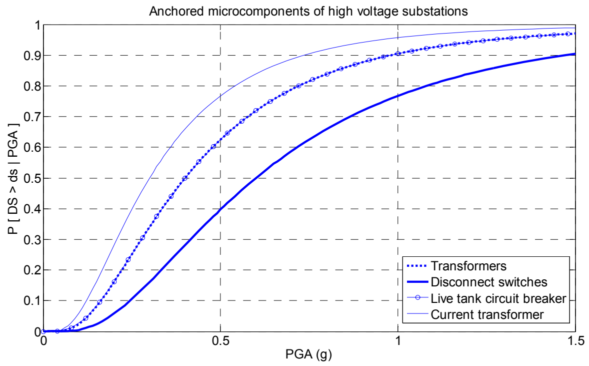
Parameters	Anchored				Unanchored			
	Component	**Median (g)**	**λ (g)**	**β**	**Component**	**Median (g)**	**λ (g)**	**β**
	Transformer	0.6	-0.51	0.7	Transformer	0.3	-1.2	0.7
	Disconnect switch	0.75	-0.29	0.7	Disconnect switch	0.5	-0.69	0.7
	Live tank circuit breaker	0.7	-0.36	0.7	Live tank circuit breaker	0.5	-0.69	0.7
	Current transformer	0.5	-0.69	0.7	Current transformer	0.5	-0.69	0.7

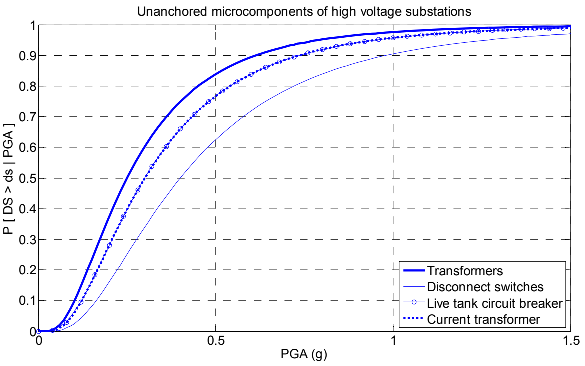
Comments	The considered microcomponents are: (1) Transformer, (2) Disconnect switch, (3) Live tank circuit breaker, (4) Current transformer

Table 3.29 Detailed table on EPN10, 12/13, 14, 15

Element at risk	4 microcomponents of high voltage substations	**Element Code**	EPN10, EPN12/13, EPN14, EPN15
Reference	FEMA – HAZUS^{MH} Technical Manual. 2003		
Method	Numerical		
Function	Lognormal, LN(λ, β)		
Typology	Two typologies: 1) Anchored/Seismic Components 2) Unanchored/Standard Components		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		

Figures





Parameters

Anchored				Unanchored			
Component	**Median (g)**	**λ (g)**	**β**	**Component**	**Median (g)**	**λ (g)**	**β**
Transformer	0.4	-0.92	0.7	Transformer	0.25	-1.39	0.7
Disconnect switch	0.6	-0.51	0.7	Disconnect switch	0.4	-0.92	0.7
Live tank circuit breaker	0.4	-0.92	0.7	Live tank circuit breaker	0.3	-1.2	0.7
Current transformer	0.3	-1.2	0.7	Current transformer	0.3	-1.2	0.7

Comments	The considered microcomponents are: (1) Transformer, (2) Disconnect switch, (3) Live tank circuit breaker, (4) Current transformer

Table 3.30 Detailed table on EPN20

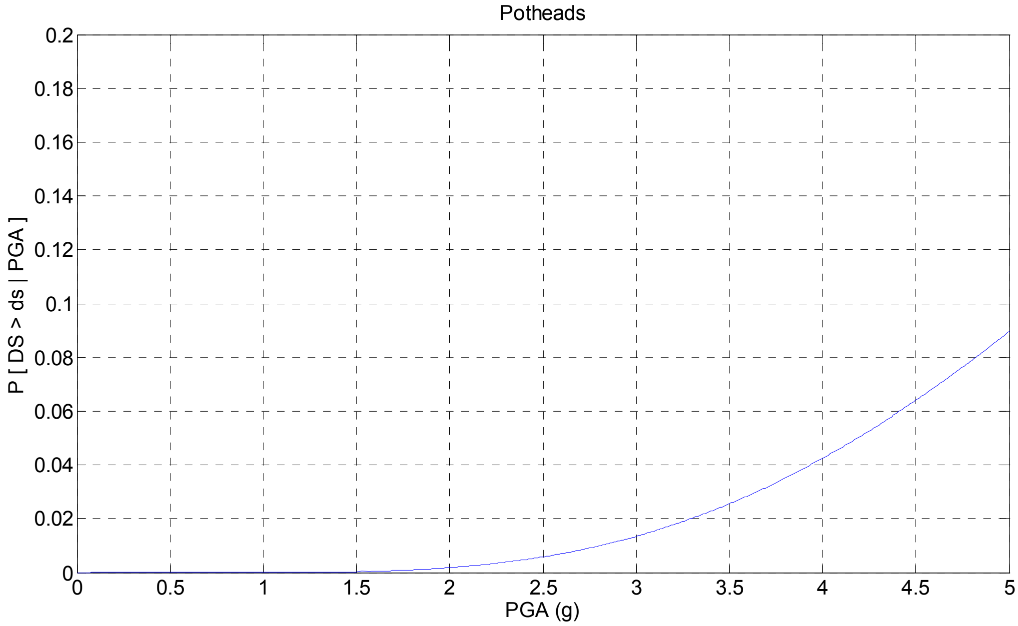
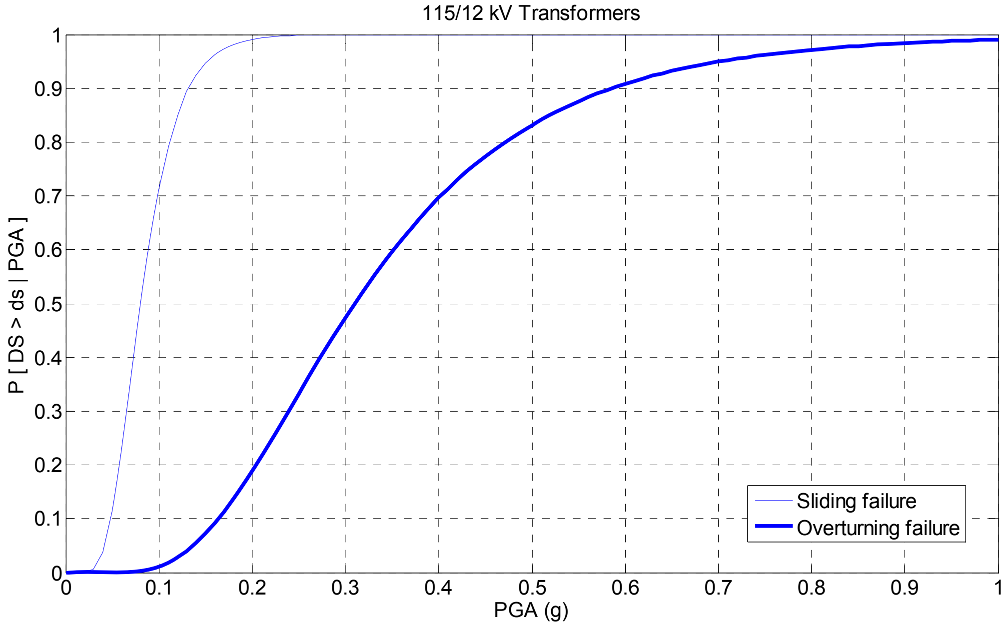
Element at risk	Pothead structure	**Element Code**	EPN20
Reference	Hwang, H. H. M., and J. R. Huo. 1998		
Method	Empirical/Numerical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Response spectrum analysis using the SAP software and data of tensile strength of porcelain in one substation located in the Memphis area		
Figures  			
Parameters (graphically retrieved from the curves)	Median = 11 g λ = 2.4 g 5th percentile = 4.2 g 10th percentile = 5.2 g β = 0.59		
Comments	Both the response and strength are considered as lognormal variables. The tensile strength of porcelain is considered as a lognormal variable with a mean value of 48 MPa and the COV taken as 0.3; the COV of the maximum tensile stress in porcelain is set as 0.5; β = 2.75 * [ln(10th percentile) - ln(5th percentile)]		

Table 3.31 Detailed table on EPN14

Element at risk	115/12 kV transformer	**Element Code**	EPN14
Reference	Hwang, H. H. M., and J. R. Huo. 1998		
Method	Empirical/Numerical		
Function	Lognormal, LN(λ, β)		
Failure modes	Overturning	Sliding	
Seismic intensity parameter	PGA (g)		
Background	Numerical expressions and data related to one substation located in the Memphis area and to ground motions recorded from past earthquakes		

Figures



Parameters (graphically retrieved from the curves)

Failure mode	25th perc. (g)	Median (g)	75th perc. (g)	λ (g)	β
Sliding failure	0.065	0.08	0.11	-2.53	0.39
Overturning failure	0.22	0.31	0.43	-1.17	0.5

Comments

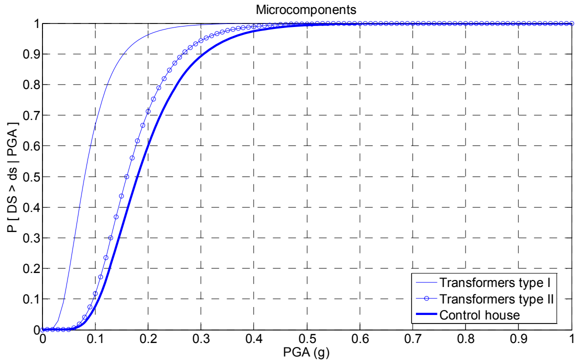
The overturning capacity is considered as a deterministic variable, while the PGA value is considered as a lognormal variable;

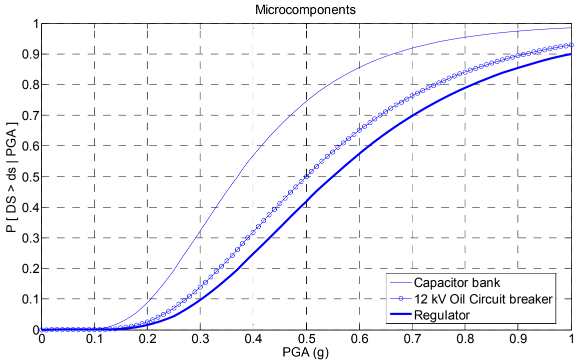
Both the capacity and the shear force of the bolt are considered as lognormal variables. The COV of the PGA value is set as 0.5; the COV of the capacity of the bolt is set as 0.11; the COV of the shear force in the bolt is set as 0.5

Table 3.32 Detailed table on EPN10, 14, 17, 21, 23

Element at risk	6 electric microcomponents	**Elem. Code**	EPN10, 14, 17, 21, 23
Reference	Hwang, H. H. M., and J. R. Huo. 1998		
Method	Empirical/Numerical		
Function	Lognormal, LN(*λ*, *β*)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Numerical expressions and data related to one substation located in the Memphis area and to ground motions recorded from past earthquakes		

Figures





The considered microcomponents are: (1) Transformer type I, (2) Transformer type II, (3) Control house, (4) Capacitor bank, (5) 12 kV Oil Circuit breaker, (6) Regulator.

Parameters (graphically retrieved from the curves)

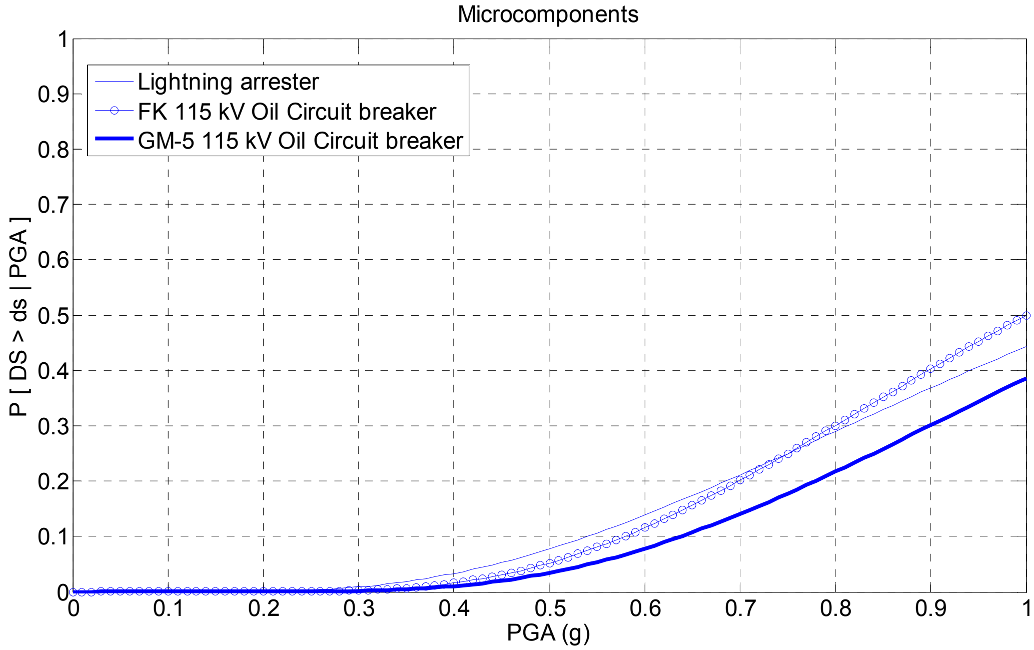
Component	25th perc. (g)	Median (g)	75th perc. (g)	*λ* (g)	*β*
Transformer type I	0.06	0.08	0.12	-2.53	0.51
Transformer type II	0.12	0.16	0.21	-1.83	0.4
Control house	0.14	0.18	0.24	-1.71	0.41
Capacitor bank	0.27	0.37	0.5	-0.99	0.46
12 kV Oil circuit breaker	0.36	0.5	0.68	-0.69	0.47
Regulator	0.4	0.55	0.75	-0.6	0.47

Comments

Table 3.33 Detailed table on EPN10, 11

Element at risk	3 electric microcomponents	**Element Code**	EPN10, 11
Reference	Hwang, H. H. M., and J. R. Huo. 1998		
Method	Empirical/Numerical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Numerical expressions and data related to one substation located in the Memphis area and to ground motions recorded from past earthquakes		

Figures



Parameters (graphically retrieved from the curves)

Component	25th perc. (g)	Median (g)	λ (g)	β
Lightning arrester	0.75	1.08	0.08	0.54
FK 115 kV Oil Circuit breaker	0.75	1	0	0.43
GM-5 115 kV Oil Circuit breaker	0.84	1.14	0.13	0.45

Comments

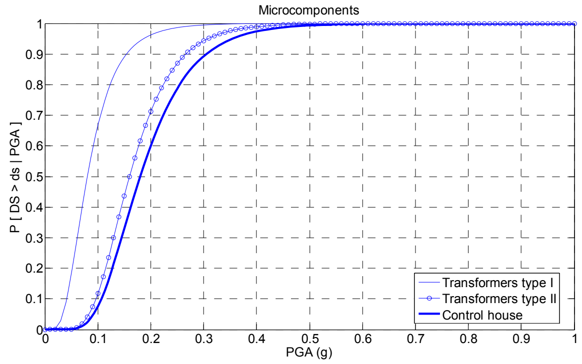
The considered microcomponents are: (1) Lightning arrester, (2) FK 115 kV Oil Circuit breaker, (3) GM-5 115 kV Oil Circuit breaker;

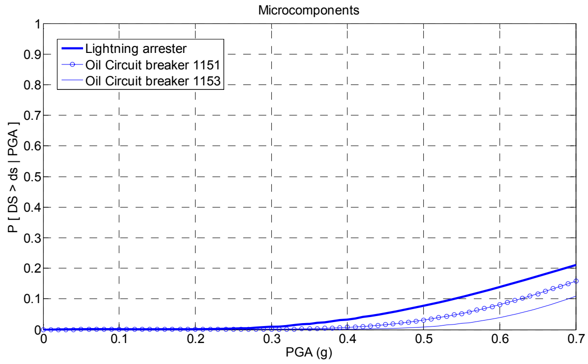
β = 1.4826 * [ln(median) - ln(25th percentile)]

Table 3.34 Detailed table on EPN10, 11, 14, 17

Element at risk	6 electric microcomponents	**Element Code**	EPN10, 11, 14, 17
Reference	Hwang, H. H. M., and T. Chou. 1998		
Method	Numerical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Information on substation 21 in Memphis		

Figures





Parameters (graphically retrieved from the curves)

Component	5th perc. (g)	Median (g)	10th perc. (g)	λ (g)	β
Oil circuit breaker 1151	0.53	1.03	0.61	0.03	0.39
Oil circuit breaker 1153	0.63	1	0.7	0	0.29

For microcomponents (1), (2), (3), (4), the parameters are listed in Table 3.32 and Table 3.33

Comments

The considered microcomponents are: (1) Transformer type I, (2) Transformer type II, (3) Control house, (4) Lightning arrester, (5) Oil Circuit breaker 1151, (6) Oil Circuit breaker 1153;

The fragility curves have been obtained by performing dynamic analyses on appropriate models of the components;

For microcomponents (5), (6), β = 2.75 * [ln(10th perc.) - ln(5th perc.)]

Table 3.35 Detailed table on EPN14

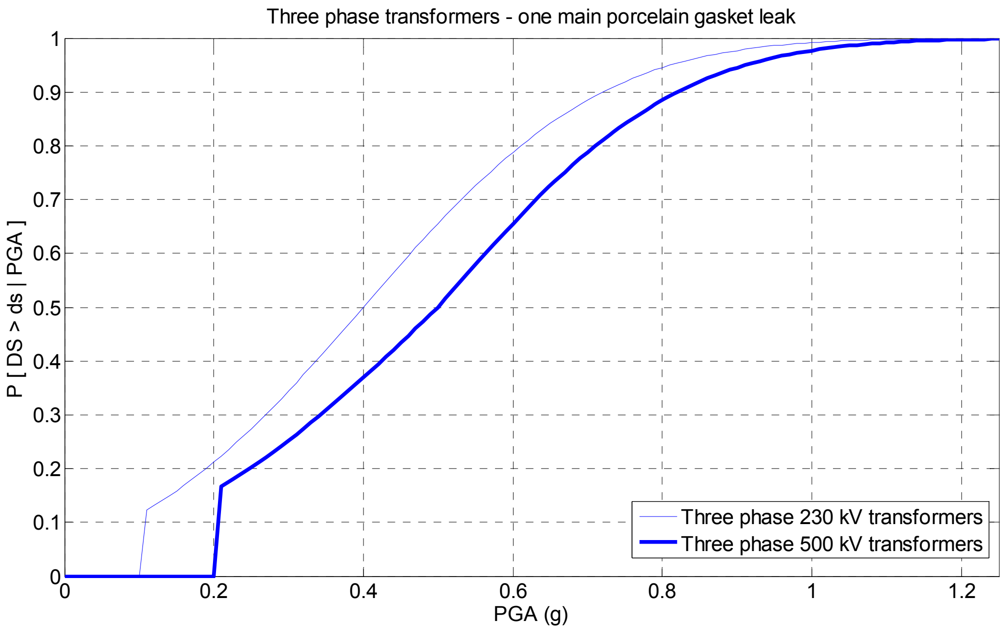
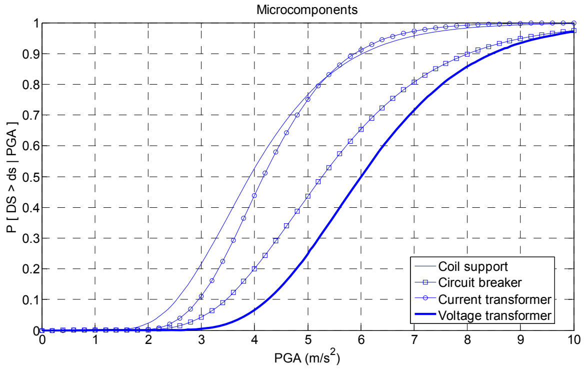
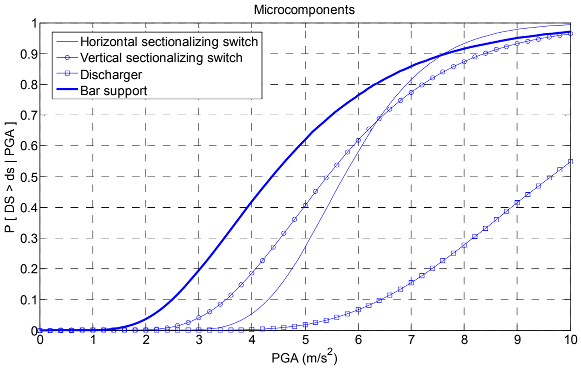
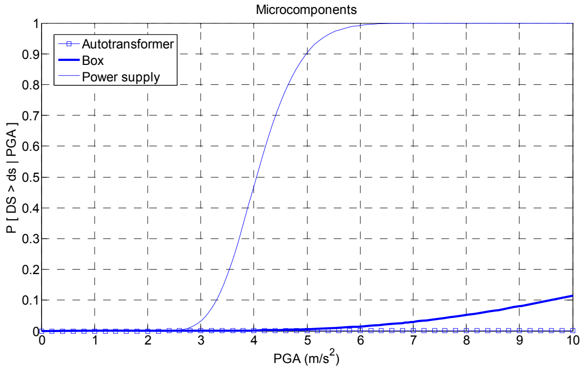
<table>
<tr><td>Element at risk</td><td colspan="2">Three-phase transformer</td><td>Element Code</td><td>EPN14</td></tr>
<tr><td>Reference</td><td colspan="4">Liu, G.-Y., C.-W. Liu, and Y. J. Wang. 2003</td></tr>
<tr><td>Method</td><td colspan="4">Empirical</td></tr>
<tr><td>Function</td><td colspan="4">Two normal functions, N(m, σ_1) and N(m, σ_2)</td></tr>
<tr><td>Typology</td><td colspan="4">Two typologies:
1) 230 kV three-phase transformers
2) 500 kV three-phase transformers</td></tr>
<tr><td>Damage states</td><td colspan="4">Failure (Collapse)
Failure mode: one main porcelain gasket leak</td></tr>
<tr><td colspan="2">Seismic intensity parameter</td><td colspan="3">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="4">UWG fragility curves</td></tr>
<tr><td colspan="5">Figures

</td></tr>
<tr><td>Parameters (graphically retrieved from the curves)</td><td colspan="4">
<table>
<tr><th>Typology</th><th>Minimum (g)</th><th>16th perc. (g)</th><th>Median (g)</th><th>84th perc. (g)</th><th>σ_1</th><th>σ_2</th></tr>
<tr><td>230 kV</td><td>0.1</td><td>0.15</td><td>0.4</td><td>0.65</td><td>0.25</td><td>0.25</td></tr>
<tr><td>500 kV</td><td>0.2</td><td>0.2</td><td>0.5</td><td>0.75</td><td>0.3</td><td>0.25</td></tr>
</table></td></tr>
<tr><td>Comments</td><td colspan="4">The two fragility curves, which were proposed by UWG for the minimal failure mode (one main porcelain gasket leak) of equipment categorized as TR2 Class (three-phase 230 kV transformers) and TR4 Class (three-phase 500 kV transformers), could be applied to the 161/69 and 345/161 kV transformers, respectively</td></tr>
</table>

Table 3.36 Detailed table on EPN10 to EPN20

<table>
<tr><td>Element at risk</td><td colspan="2">11 electric microcomponents</td><td rowspan="2">Element Code
EPN10 to EPN20</td></tr>
<tr><td>Reference</td><td colspan="2">Rasulo, A., A. Goretti, and C. Nuti. 2004</td></tr>
<tr><td>Method</td><td colspan="3">Numerical</td></tr>
<tr><td>Function</td><td colspan="3">Lognormal, LN(λ, β)</td></tr>
<tr><td>Damage states</td><td colspan="3">Failure (Collapse)</td></tr>
<tr><td colspan="2">Seismic intensity parameter</td><td colspan="2">PGA (m/s^2)</td></tr>
<tr><td>Background</td><td colspan="3">Fragility curves for typical Italian electrical components</td></tr>
<tr><td colspan="4">Figures







The considered microcomponents are: (1) Coil support, (2) Circuit breaker, (3) Current transformer, (4) Voltage transformer, (5) Horizontal sectionalizing switch, (6) Vertical sectionalizing switch, (7) Discharger, (8) Bar support, (9) Autotransformer, (10) Box, (11) Power supply to protection system.</td></tr>
<tr><td>Parameters (graphically retrieved from the curves)</td><td colspan="3">Listed in Table 3.26</td></tr>
<tr><td>Comments</td><td colspan="3">No specific information on the Larino substation equipment characteristics have been provided; however some conclusions have been derived on the basis of fragility curves for typical Italian electrical components</td></tr>
</table>

Table 3.37 Detailed table on EPN14

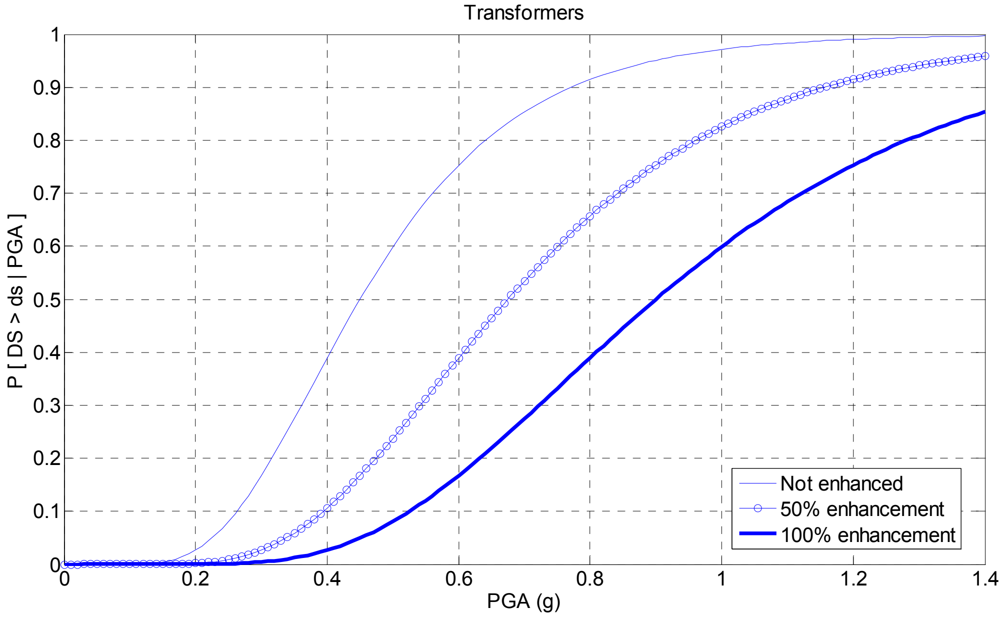
Element at risk	Transformer	**Element Code**	EPN14
Reference	Shinozuka, M., X. Dong, T. C. Chen, and X. Jin. 2007		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Typology	Three cases: 1) Not Enhanced 2) 50% Enhancement 3) 100% Enhancement		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Empirical data from the 1994 Northridge earthquake		
Figures 			
Parameters	Median = 0.45 g, λ = -0.8 g, β = 0.42		
Comments	Case 1 curve is obtained empirically from the Northridge earthquake damage data; Case 2 curve represents improvement on Case 1 curve by 50% (in terms of median value, no change in log-normal standard deviation); Case 3 curve represents improvement on Case 1 curve by 100% (in terms of median value, no change in log-normal standard deviation); These improvements are deemed possible on the basis of the analytical and experimental study carried out by Feng and Saadeghvaziri		

Table 3.38 Detailed table on EPN10

<table>
<tr><td>Element at risk</td><td>Circuit breaker</td><td>Element Code</td><td>EPN10</td></tr>
<tr><td>Reference</td><td colspan="3">Shinozuka, M., X. Dong, T. C. Chen, and X. Jin. 2007</td></tr>
<tr><td>Method</td><td colspan="3">Empirical</td></tr>
<tr><td>Function</td><td colspan="3">Lognormal, LN(<i>λ</i>, <i>β</i>)</td></tr>
<tr><td>Damage states</td><td colspan="3">Failure (Collapse)</td></tr>
<tr><td>Seismic intensity parameter</td><td colspan="3">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="3">Empirical data from the 1994 Northridge earthquake</td></tr>
<tr><td colspan="4">Figures

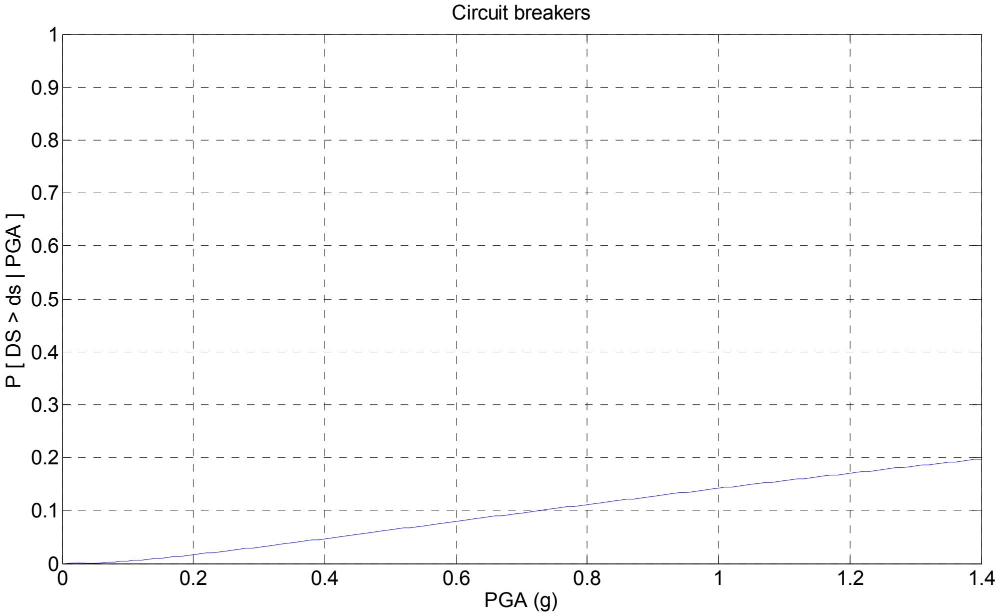

</td></tr>
<tr><td>Parameters</td><td colspan="3">Median = 5.10 g
<i>λ</i> = 1.63 g
<i>β</i> = 1.52</td></tr>
<tr><td>Comments</td><td colspan="3">This fragility curve for circuit breakers indicates their high seismic robustness reflecting LADWP’s (Los Angeles Department of Water and Power’s) retrofit effort for circuit breakers implemented closely before the Northridge earthquake</td></tr>
</table>

Table 3.39 Detailed table on EPN12/13

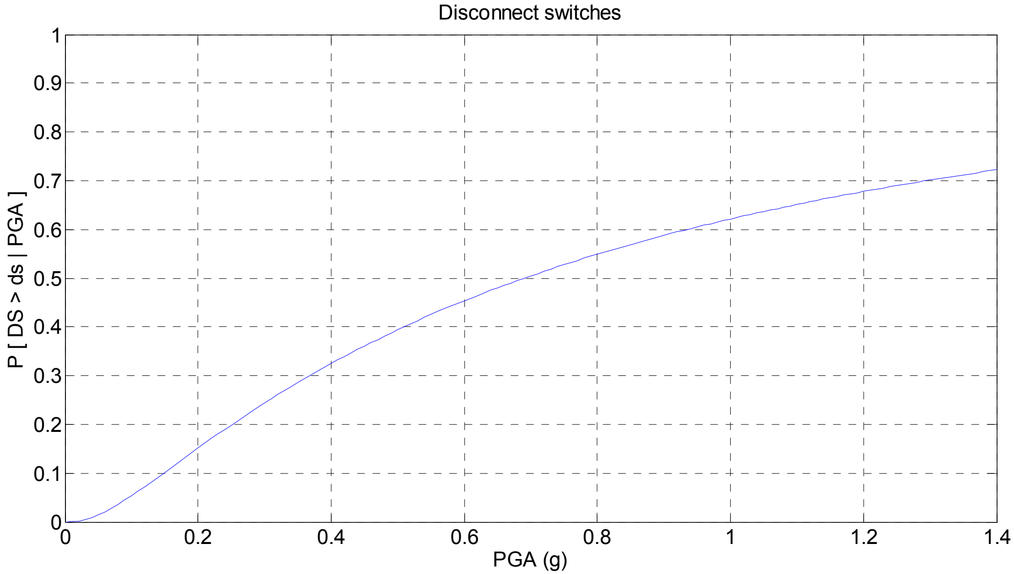
Element at risk	Disconnect switch	**Element Code**	EPN12/13
Reference	Shinozuka, M., X. Dong, T. C. Chen, and X. Jin. 2007		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Empirical data from the 1994 Northridge earthquake		
Figures 			
Parameters	Median = 0.69 g λ = -0.37 g β = 1.20		
Comments			

Table 3.40 Detailed table on EPN22

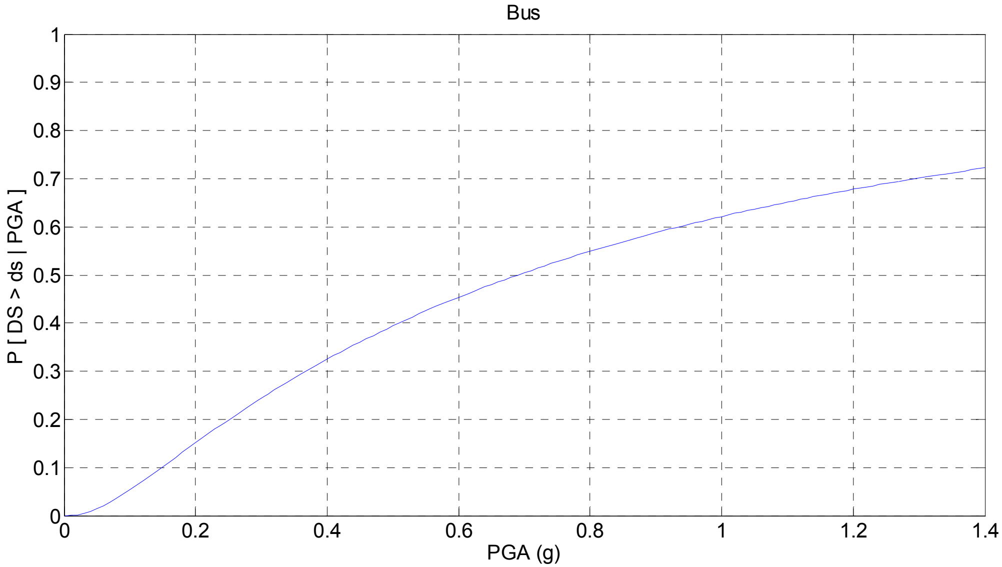
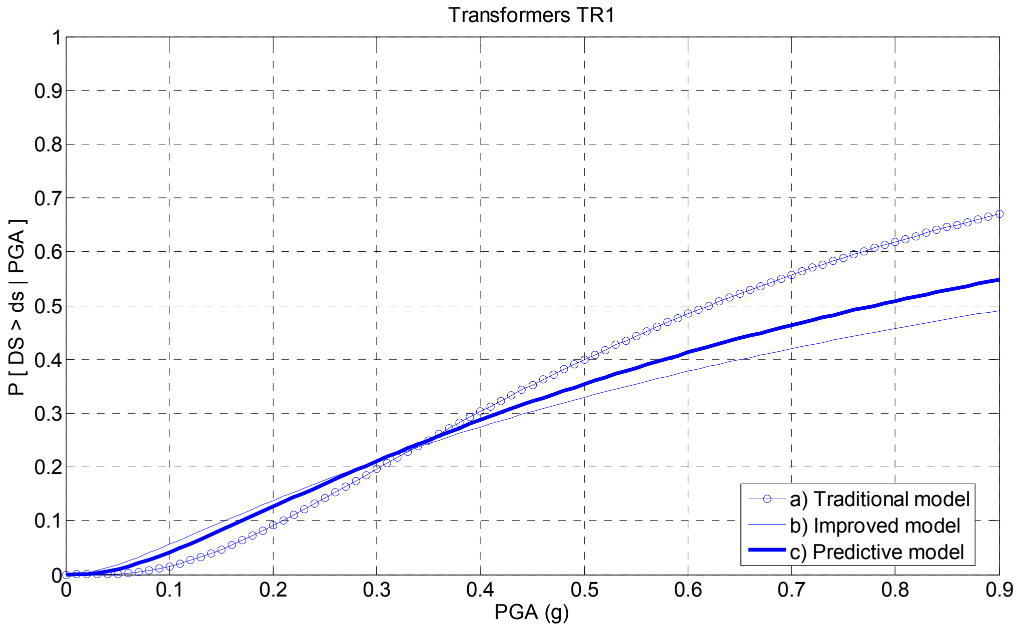
Element at risk	Bus	**Element Code**	EPN22
Reference	Shinozuka, M., X. Dong, T. C. Chen, and X. Jin. 2007		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Empirical data from the 1994 Northridge earthquake		
Figures 			
Parameters	Median = 0.69 g λ = -0.37 g β = 1.20		
Comments	The fragility curve for buses is assumed to be identical to that for the disconnect switches in the face of no damage data available		

Table 3.41 Detailed table on EPN14

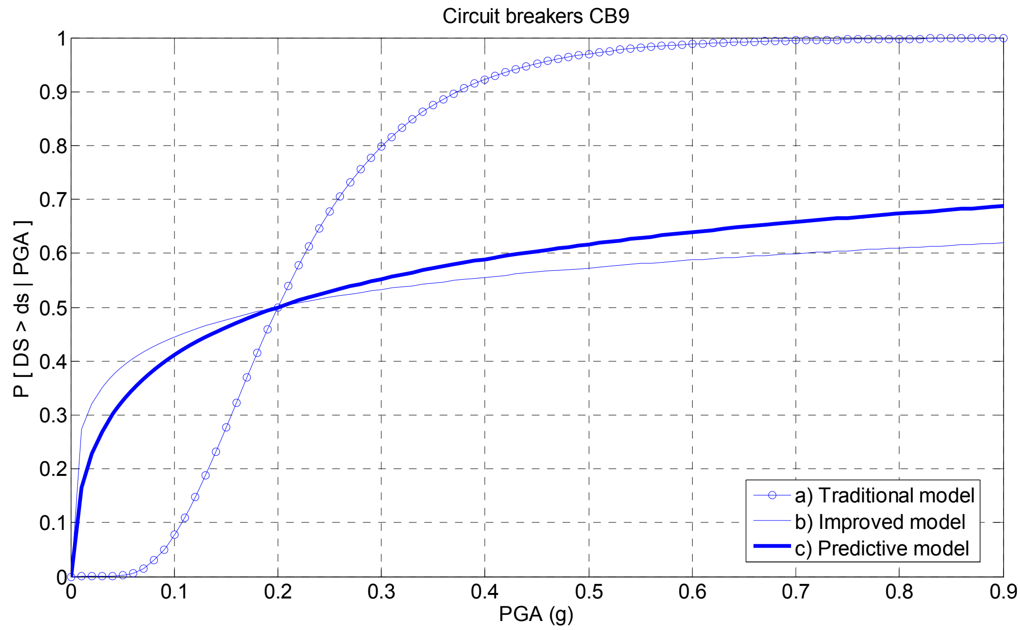
<table>
<tr><td>Element at risk</td><td>1-phase 230 kV transformer</td><td>Element Code</td><td>EPN14</td></tr>
<tr><td>Reference</td><td colspan="3">Straub, D., and A. Der Kiureghian. 2008</td></tr>
<tr><td>Method</td><td colspan="3">Empirical</td></tr>
<tr><td>Function</td><td colspan="3">Lognormal, LN(λ, β)</td></tr>
<tr><td>Damage states</td><td colspan="3">Failure (Collapse)</td></tr>
<tr><td>Seismic intensity parameter</td><td colspan="3">PGA (g)</td></tr>
<tr><td>Background</td><td colspan="3">Data-set on the performance of electrical substation equipment in past earthquakes, compiled by Anagnos; Bayesian analysis</td></tr>
<tr><td colspan="4">Figures


</td></tr>
<tr><td>Parameters (graphically retrieved from the curves)</td><td colspan="3">
<table>
<tr><th>Typology of model</th><th>25th percentile (g)</th><th>Median (g)</th><th>λ (g)</th><th>β</th></tr>
<tr><td>Traditional model</td><td>0.35</td><td>0.62</td><td>-0.48</td><td>0.85</td></tr>
<tr><td>Improved model</td><td>0.36</td><td>0.93</td><td>-0.07</td><td>1.41</td></tr>
<tr><td>Predictive model</td><td>0.35</td><td>0.78</td><td>-0.25</td><td>1.19</td></tr>
</table>
</td></tr>
<tr><td>Comments</td><td colspan="3">a) statistical dependence and statistical uncertainty are both neglected;
b) only statistical dependence is considered;
c) both effects are included (predictive model);
β = 1.4826 * [ln(median) - ln(25th percentile)]</td></tr>
</table>

Table 3.42 Detailed table on EPN10

Element at risk	230 kV live tank circuit breaker	**Element Code**	EPN10
Reference	Straub, D., and A. Der Kiureghian. 2008		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Damage states	Failure (Collapse)		
Seismic intensity parameter	PGA (g)		
Background	Data-set on the performance of electrical substation equipment in past earthquakes, compiled by Anagnos; Bayesian analysis		

Figures



Parameters (graphically retrieved from the curves)

Typology of model	**25th perc. (g)**	**Median (g)**	**75th perc. (g)**	**λ (g)**	**β**
Traditional model	0.14	0.2	0.27	-1.61	0.49
Improved model	0.007	0.2	-	-1.61	4.97
Predictive model	0.025	0.2	-	-1.61	3.08

Comments

a) statistical dependence and statistical uncertainty are both neglected;

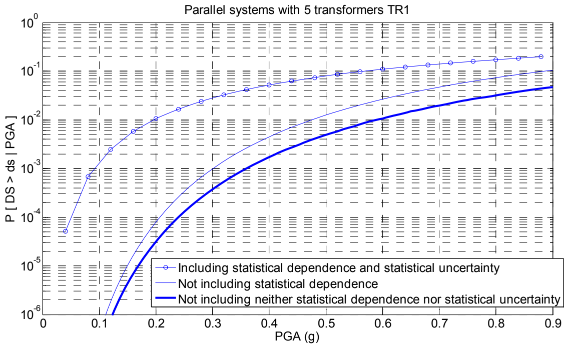
b) only statistical dependence is considered;

c) both effects are included (predictive model);

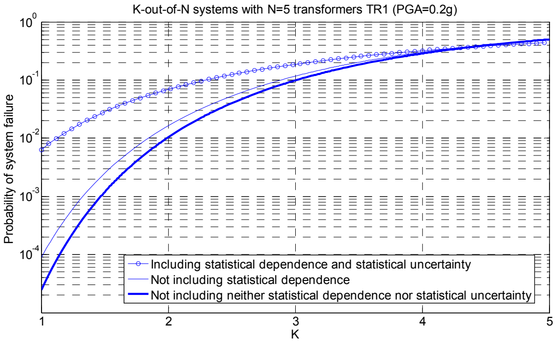
For the 2nd and 3rd typologies, β = 1.4826 * [ln(median) - ln(25th percentile)]

Table 3.43 Detailed table on EPN14

<table>
<tr><td>Element at risk</td><td>1-phase 230 kV transformer – system of various components</td><td>Element Code</td><td>EPN14</td></tr>
<tr><td>Reference</td><td colspan="3">Straub, D., and A. Der Kiureghian. 2008</td></tr>
<tr><td>Method</td><td>Empirical</td><td>Function</td><td>Lognormal, LN(λ, β)</td></tr>
<tr><td>Typology</td><td colspan="3">Two typologies:
1) parallel systems with five components
2) <i>K</i>-out-of-<i>N</i> systems, with <i>N</i> = 5 (PGA = 0.2 g)</td></tr>
<tr><td>Damage states</td><td>Failure (Collapse)</td><td>Seismic int. parameter</td><td>PGA (g)</td></tr>
<tr><td>Background</td><td colspan="3">Data-set on the performance of electrical substation equipment in past earthquakes, compiled by Anagnos; Bayesian analysis</td></tr>
<tr><td colspan="4">Figures



1)

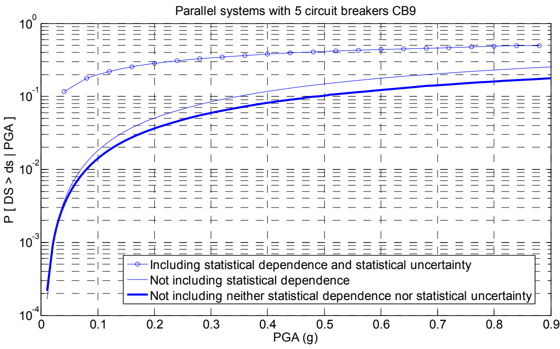


2)</td></tr>
<tr><td>Parameters (graphically retrieved from the curves)</td><td colspan="3">
<table>
<tr><th>Typology</th><th>1st perc. (g)</th><th>Median (g)</th><th>5th perc. (g)</th><th>λ (g)</th><th>β</th></tr>
<tr><td>1a)</td><td>0.23</td><td>2.1</td><td>0.46</td><td>0.74</td><td>1.02</td></tr>
<tr><td>1b)</td><td>0.48</td><td>1.9</td><td>0.72</td><td>0.64</td><td>0.6</td></tr>
<tr><td>1c)</td><td>0.58</td><td>2.65</td><td>0.9</td><td>0.97</td><td>0.65</td></tr>
<tr><th>Typology</th><th>5th perc. (g)</th><th>Median (g)</th><th>10th perc. (g)</th><th>λ (g)</th><th>β</th></tr>
<tr><td>2a)</td><td>2.73</td><td>5.5</td><td>3.5</td><td>1.7</td><td>0.68</td></tr>
<tr><td>2b)</td><td>-</td><td>5</td><td>3.8</td><td>1.61</td><td>0.43</td></tr>
<tr><td>2c)</td><td>-</td><td>5</td><td>3.95</td><td>1.61</td><td>0.4</td></tr>
</table>
</td></tr>
<tr><td>Comments</td><td colspan="3">a) Including statistical dependence and statistical uncertainty;
b) Not including statistical dependence;
c) Not including neither statistical dependence nor statistical uncertainty;
For 1a), 1b), 1c), β = 1.47 * [ln(5th percentile) - ln(1st percentile)]
For 2a), β = 2.75 * [ln(10th percentile) - ln(5th percentile)]
For 2b), 0.1st percentile = 1.75 g
For 2c), 0.1st percentile = 1.93 g β = 0.55 * [ln(10th perc.) - ln(0.1st perc.)]</td></tr>
</table>

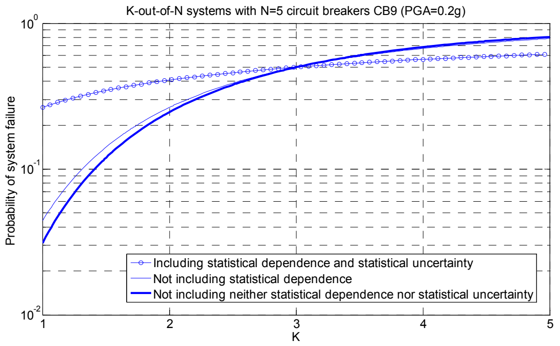
Table 3.44 Detailed table on EPN10

Element at risk	230 kV live tank circuit breaker – system of various components	**Element Code**	EPN10
Reference	Straub, D., and A. Der Kiureghian. 2008		
Method	Empirical		
Function	Lognormal, LN(λ, β)		
Typology	Two typologies: 1) parallel systems with five components 2) *K*-out-of-*N* systems, with *N* = 5 (PGA = 0.2 g)		
Damage states	Failure (Collapse)	**Seismic int. parameter**	PGA (g)
Background	Data-set on the performance of electrical substation equipment in past earthquakes, compiled by Anagnos; Bayesian analysis		

Figures



1)



2)

Parameters (graphically retrieved from the curves)

Typology	5th perc. (g)	Median (g)	10th perc. (g)	λ (g)	β
1a)	-	0.9	-	-0.1	2.61
1b)	0.2	2.5	0.35	0.92	1.54
1c)	0.25	4.5	0.47	1.5	1.74

Typology	6th perc. (g)	Median (g)	λ (g)	β
2a)	-	3	1.1	1.75
2b)	1.1	3	1.1	0.65
2c)	1.2	3	1.1	0.59

Comments

a) Including statistical dependence and statistical uncertainty;

b) Not including statistical dependence;

c) Not including neither statistical dependence nor statistical uncertainty;

For 1a), 20th percentile = 0.1 g, β = 1.19 * [ln(median) - ln(20th percentile)]

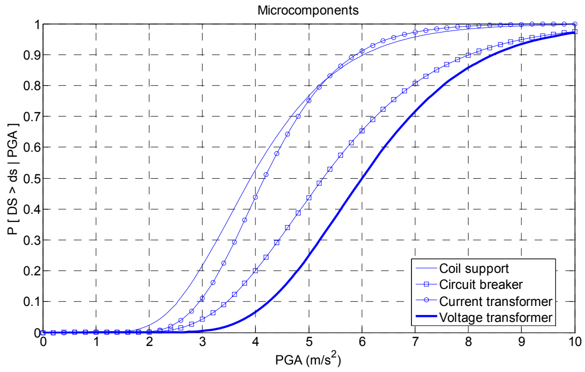
For 1b), 1c), β = 2.75 * [ln(10th percentile) - ln(5th percentile)]

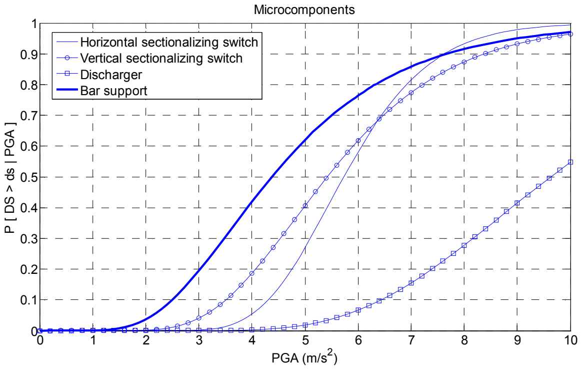
For 2a), 30th percentile = 1.2 g, β = 1.91 * [ln(median) - ln(30th percentile)]

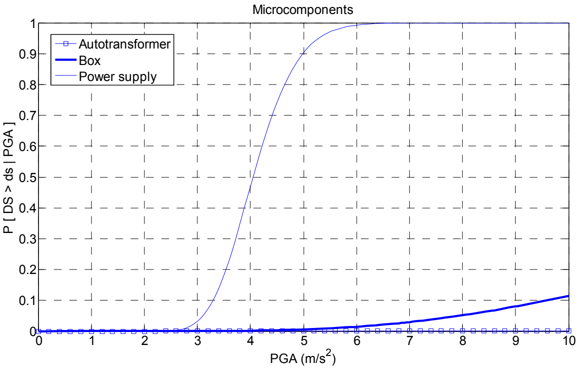
For 2b), 2c), β = 0.643 * [ln(median) - ln(6th percentile)]

Table 3.45 Detailed table on EPN10 to EPN20

<table>
<tr><td>Element at risk</td><td>11 electric microcomponents</td><td>Element Code</td><td>EPN10 to EPN20</td></tr>
<tr><td>Reference</td><td colspan="3">Vanzi, I. 1996</td></tr>
<tr><td>Method</td><td colspan="3">Numerical, FORM/SORM methods</td></tr>
<tr><td>Function</td><td colspan="3">Lognormal, LN(λ, β)</td></tr>
<tr><td>Damage states</td><td colspan="3">Failure (Collapse)</td></tr>
<tr><td>Seismic intensity parameter</td><td colspan="3">PGA (m/s^2)</td></tr>
<tr><td>Background</td><td colspan="3">Data from shaking table tests on microcomponents</td></tr>
<tr><td colspan="4">Figures

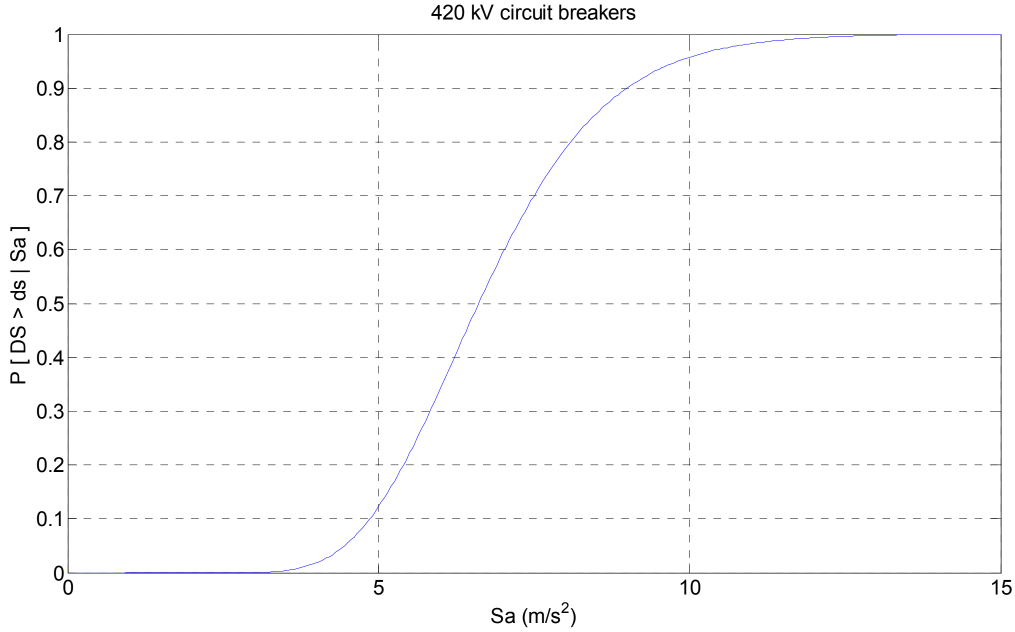






The considered microcomponents are: (1) Coil support, (2) Circuit breaker, (3) Current transformer, (4) Voltage transformer, (5) Horizontal sectionalizing switch, (6) Vertical sectionalizing switch, (7) Discharger, (8) Bar support, (9) Autotransformer, (10) Box, (11) Power supply to protection system.</td></tr>
<tr><td>Parameters</td><td colspan="3">Listed in Table 3.26</td></tr>
<tr><td>Comments</td><td colspan="3">Components like line boxes, power supply to protection system and transformers are not standardized, hence they require <i>ad hoc</i> analyses. A standard reliability analysis has been carried out for these components, considering randomness in both the mechanical properties of concrete and steel and in the dynamic action. The probability of failure has then been computed via numerical integration from the probability distributions of the available and required ductilities</td></tr>
</table>

Table 3.46 Detailed table on EPN10

<table>
<tr><td>Element at risk</td><td>420 kV circuit breaker</td><td>Element Code</td><td>EPN10</td></tr>
<tr><td>Reference</td><td colspan="3">Vanzi, I., A. Rasulo, and S. Sigismondo. 2004</td></tr>
<tr><td>Method</td><td colspan="3">Numerical</td></tr>
<tr><td>Function</td><td colspan="3">Lognormal, LN(λ, β)</td></tr>
<tr><td>Damage states</td><td colspan="3">Failure (Collapse)</td></tr>
<tr><td>Seismic intensity parameter</td><td colspan="3">Spectral acceleration (m/s^2)</td></tr>
<tr><td>Background</td><td colspan="3">Cornell method</td></tr>
<tr><td colspan="4">Figures
 </td></tr>
<tr><td>Parameters</td><td colspan="3">λ = 1.89 g
β = 0.24</td></tr>
<tr><td>Comments</td><td colspan="3">The retrieved fragility curve matches the curve based on a lognormal distribution with parameters λ = 1.89 g and β = 0.24</td></tr>
</table>

4 Proposal of standard damage scales for electric power system components

This section proposes standard damage scales for EPN components. For each of the main typologies, the different damage states are related to the serviceability of the whole network or the single station, depending on the considered analysis level. In particular, for the *network* and *distribution-system* levels, the tables refer to the serviceability of the single station.

The damage scales below do not quantify the reduction of power flow corresponding to each damage state. Actually, however, the performance of the network and even of a single station can not be predicted without a power flow analysis, continued serviceability resulting from the interaction between various components, both inside the individual station and within the neighbouring ones, as well as from the spread of short circuits to other parts of the station and to the remaining parts of the network.

4.1 DAMAGE SCALES FOR ELECTRIC POWER GRIDS

The paper by Dueñas-Osorio presents fragility curves related to the whole electric power grid, composed of the different types of stations, transmission and distribution lines. Two damage scales are proposed for electric power grids and reported in Table 4.1 and Table 4.2, differing for the damage state definition, which are those for which fragility curves are reported in Table 3.2 and Table 3.3, respectively. It should be noted how the definition of nominal and reduced power flow is not quantitative and, hence, not operational.

Table 4.1 Damage scale for electric power grids: first proposal

Serviceability		**Damage State description**	
No power available	Operational after long term repairs	**Extensive**	This limit state implies damage beyond short-term repair, leaving the network systems under consideration as completely non-functional.
Nominal power flow	Operational without repair	**None**	None

Table 4.2 Damage scale for electric power grids: second proposal

Serviceability		**Damage State description**	
No power available	Operational after repairs	***CL* = 80%**	Connectivity loss levels of *CL* = 20, 50 and 80% represent three limiting states to measure the ability of the network to function properly. More precisely, they quantify the likelihood of the distribution nodes to decrease their capacity to be connected to generation nodes as function of seismic intensity.
Reduced power flow	Operational without repair	***CL* = 50%**	
		***CL* = 20%**	
Nominal power flow		**None**	None

4.2 DAMAGE SCALE FOR GENERATION PLANTS

The FEMA – HAZUS^{MH} Technical Manual presents fragility curves related to generation plants. The proposed damage scale for this type of station is displayed in Table 4.3, while the corresponding fragility curves are reported for reference in Table 3.4 and Table 3.5.

Table 4.3 Damage scale for generation plants

Serviceability		**Damage State description**	
No power available	Not repairable	**Complete**	Extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or the building being in complete damage state.
	Operational after repairs	**Extensive**	Considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or the building being in extensive damage state.
Reduced power flow	Operational without repair	**Moderate**	Chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or the building being in moderate damage state.
		Slight/Minor	Turbine tripping, or light damage to diesel generator, or the building being in minor damage state
Nominal power flow		**None**	None

4.3 DAMAGE SCALE FOR SUBSTATIONS

In Table 4.4 is reported the proposed damage scale for substations. It is based on the classification and definition of damage states given by the FEMA – HAZUS^{MH} Technical Manual. The four damage states are linked to the percentage of components which fail under the seismic action or to the building damage.

Table 4.4 Damage scale for substations

Serviceability		**Damage State description**	
No power available	Not repairable	**Complete**	Failure of all disconnect switches, all circuit breakers, all transformers, or all current transformers, or the building being in complete damage state.
	Operational after repairs	**Extensive**	Failure of 70% of disconnect switches (e.g., misalignment), 70% of circuit breakers, 70% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or failure of 70% of transformers (e.g., leakage of transformer radiators), or the building being in extensive damage state.
Reduced power flow	Operational without repair	**Moderate**	Failure of 40% of disconnect switches (e.g., misalignment), or 40% of circuit breakers (e.g., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), or failure of 40% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or the building being in moderate damage state.
		Slight/Minor	Failure of 5% of the disconnect switches (i.e., misalignment), or failure of 5% of the circuit breakers (i.e., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), or the building being in minor damage state.
Nominal power flow		**None**	None

4.4 DAMAGE SCALE FOR DISTRIBUTION CIRCUITS

Table 4.5 reports the proposed damage scale for distribution circuits. It is based on the classification and definition of damage states given by the FEMA – HAZUS^{MH} Technical Manual. The four damage states are linked to the percentage of circuits which fail under the seismic action.

Table 4.5 Damage scale for distribution circuits

Serviceability		Damage State description	
No power available	Not repairable	**Complete**	Failure of 80% of all circuits.
	Operational after repairs	**Extensive**	Failure of 50% of all circuits.
Reduced power flow	Operational without repair	**Moderate**	Failure of 12% of all circuits.
		Slight/Minor	Failure of 4% of all circuits.
Nominal power flow		**None**	None

4.5 DAMAGE SCALE FOR MACROCOMPONENTS

Table 4.6, Table 4.7 and Table 4.8 present the proposed damage scales for electric macrocomponents, according to their definitions given in the works by Vanzi, 1996, and Hwang and Chou, 1998, and reported below for reference. All macrocomponents are considered as series systems of several microcomponents. The failure of some macrocomponents involves the failure of the entire substation, since they constitute the minimal cut sets of the system. The failure of some other macrocomponents only involves a reduction of the power flow outgoing from the substation.

1. Autotransformer line (autotransformer + dischargers + current transformers + circuit breakers + bearings)
2. Line without transformer (voltage transformer + coil support + sectionalizing switch + current transformer + circuit breaker + bearings)

Table 4.6 Damage scale for macrocomponents 1. and 2.

Serviceability		Damage State description	
Reduced power flow	Operational without repair	**Failure**	Failure of any of the microcomponents (in one of their failure modes) composing the macrocomponent (series system).
Nominal power flow		**None**	None

3. Bars-connecting line (sectionalizing switch + current transformer + circuit breaker + bearings)
4. Bars (voltage transformer + bearings)

Table 4.7 Damage scale for macrocomponents 3. and 4.

Serviceability		Damage State description	
No power available	Operational after repairs	**Failure**	Failure of any of the microcomponents (in one of their failure modes) composing the macrocomponent (series system).
Nominal power flow	Operational	**None**	None

5. Cluster (pothead, 6 lightning arresters, 115 kV switch structure [bus])

Table 4.8 Damage scale for macrocomponent 5.

Serviceability		Damage State description	
No power available	Operational after repairs	**Failure**	Failure of the pothead, or any of the six lightning arresters, or the 115 kV switch structure (bus).
Nominal power flow	Operational	**None**	None

4.6 DAMAGE SCALE FOR MICROCOMPONENTS

Table 4.9 and Table 4.10 present the proposed damage scales for electric microcomponents, listed and numbered below. Some of them stand alone inside the substation, being physically and logically separated from the rest of the components, while some others are assembled in series in macrocomponents.

Table 4.9 deals with the microcomponents whose failure involves a reduction of the power flow outgoing from the substation.

Table 4.10 refers to those microcomponents whose failure involves the failure of the entire substation, since either they though standing alone are vital for the performing of the substation or they are parts of the macrocomponents that are considered minimal cut sets of the system. In order to make this distinction, the substation’s logic scheme proposed by Vanzi is adopted, since it appears to be the most appropriate in the European context.

1. Circuit breaker
2. Lightning arrester or Discharger
3. Horizontal Disconnect switch or Sectionalizing switch
4. Vertical Disconnect switch or Sectionalizing switch
5. Transformer or Autotransformer
6. Current transformer
7. Voltage transformer
8. Box or Control house
9. Power supply to protection system
10. Coil support
11. Bar support or Pothead
12. Regulator
13. Bus
14. Capacitor bank

Table 4.9 Damage scale for microcomponents 2.,5.,8.,12. and 14.

Serviceability		**Damage State description**	
Reduced power flow	Operational without repair	**Failure**	Failure of the microcomponent in one of its failure modes.
Nominal power flow		**None**	None

Table 4.10 Damage scale for microcomponents 1.,3.,4.,6.,7.,9.,10.,11. and 13.

Serviceability		Damage State description	
No power available	Operational after repairs	**Failure**	Failure of the microcomponent in one of its failure modes.
Nominal power flow	Operational	**None**	None

5 Proposed fragility functions of electric power system components for use in SYNER-G systemic vulnerability analysis

In this section an appropriate fragility function is chosen, among the available ones, for the EPN macro- and microcomponents that are of interest within SYNER-G (i.e. are employed within the systemic vulnerability analysis).

The considered macrocomponents are those defined by Vanzi, for which only the curves retrieved by Vanzi exist.

Concerning the microcomponents, the curves proposed by Vanzi have been obtained using data from shaking table tests on components installed in Italian substations. For this reason, compared with the other available curves, they appear to be the most appropriate in the European context and, hence, have been chosen by the reviewers. The curves refer to components produced during the 80's and 90's, installed in substation of the Italian high voltage EPN (voltages ranging from 220 kV to 380 kV).

For some microcomponents are also reported for reference the fragility functions proposed by FEMA – HAZUS^{MH} and UWG, considering different voltage ranges and distinguishing between anchored and unanchored components.

Macrocomponent 5. and microcomponents 12.,13. and 14. have not been considered, since are installed only in US substations.

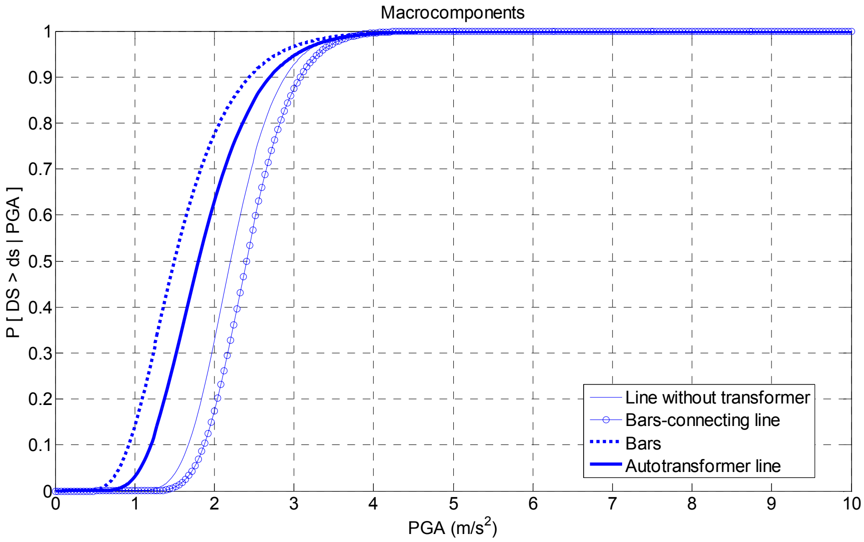
For all curves, the corresponding parameters are listed in Section 3.1.

5.1 FRAGILITY FUNCTIONS OF MACROCOMPONENTS

Table 5.1 presents the fragility functions of the electric macrocomponents defined by Vanzi, listed here for reference.

1. Autotransformer line (autotransformer + dischargers + current transformers + circuit breakers + bearings)
2. Line without transformer (voltage transformer + coil support + sectionalizing switch + current transformer + circuit breaker + bearings)
3. Bars-connecting line (sectionalizing switch + current transformer + circuit breaker + bearings)
4. Bars (voltage transformer + bearings)

Table 5.1 Proposed fragility functions of macrocomponents 1.,2.,3. and 4.

<table>
<tr><td>Element at risk</td><td>4 electric macrocomponents</td><td>Element Code</td><td>EPN05 to 08</td></tr>
<tr><td>Reference</td><td colspan="3">Vanzi, I. 1996</td></tr>
<tr><td colspan="4">Figures

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5.2 FRAGILITY FUNCTIONS OF MICROCOMPONENTS

Tables from Table 5.2 to Table 5.18 present the chosen fragility functions of electric microcomponents.

1. Circuit breaker

Table 5.2 Proposed fragility function of circuit breaker

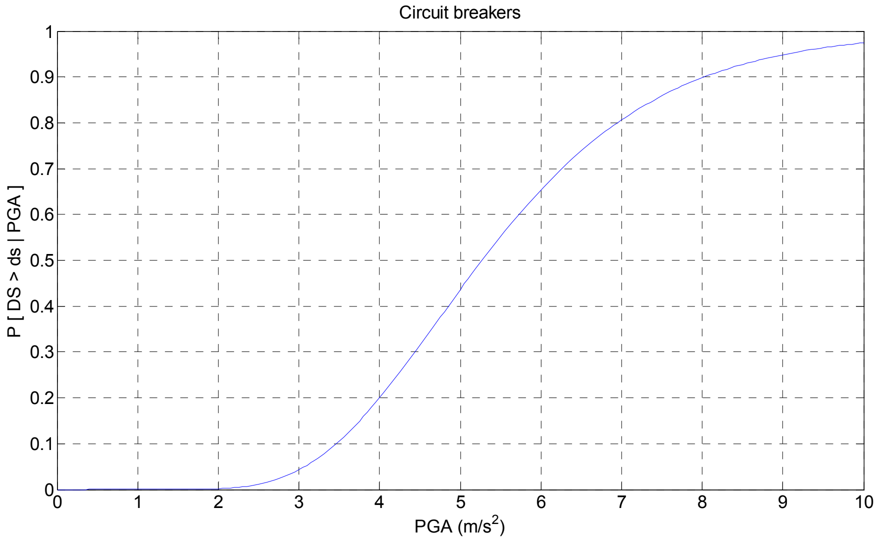
Element at risk	Circuit breaker	**Element Code**	EPN10
Reference	Vanzi, I. 1996		
Figures 			

Table 5.3 Alternative fragility functions of circuit breaker

<table>
<tr><td>Element at risk</td><td>Circuit breaker</td><td>Element Code</td><td>EPN10</td></tr>
<tr><td>Reference</td><td colspan="3">FEMA – HAZUS^{MH} Technical Manual. 2003</td></tr>
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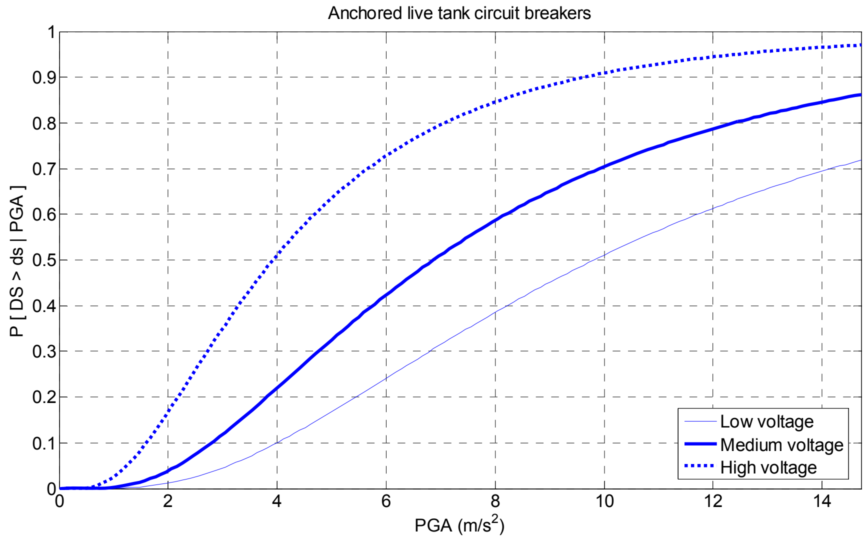

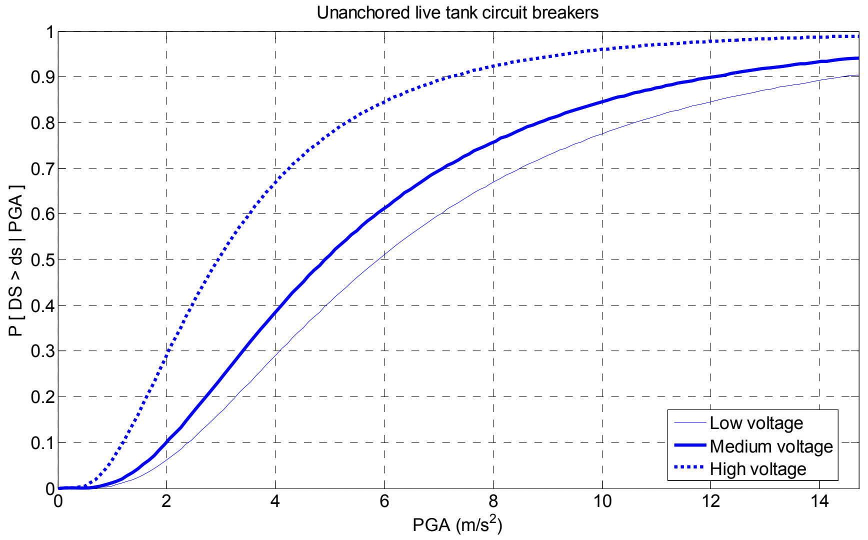

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</table>

2. Lightning arrester or Discharger

Table 5.4 Proposed fragility function of discharger

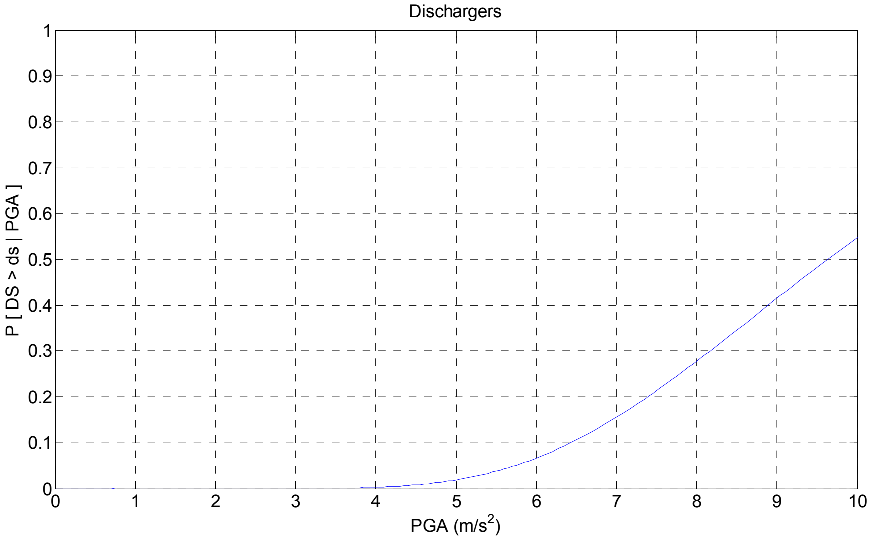
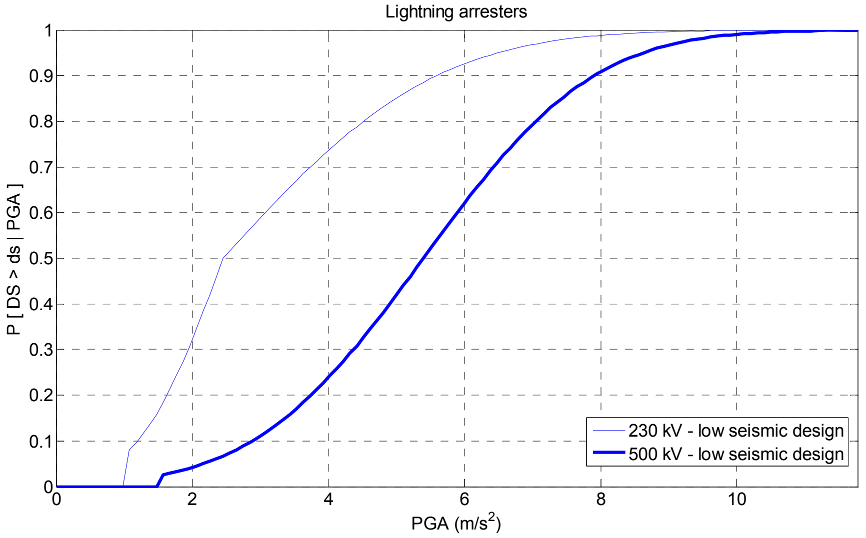
Element at risk	Discharger	**Element Code**	EPN11
Reference	Vanzi, I. 1996		
Figures			

Table 5.5 Alternative fragility functions of lightning arrester

Element at risk	Lightning arrester	**Element Code**	EPN11
Reference	Anagnos, T. 1999		
Figures			

3. Horizontal Disconnect switch or Sectionalizing switch

Table 5.6 Proposed fragility function of horizontal sectionalizing switch

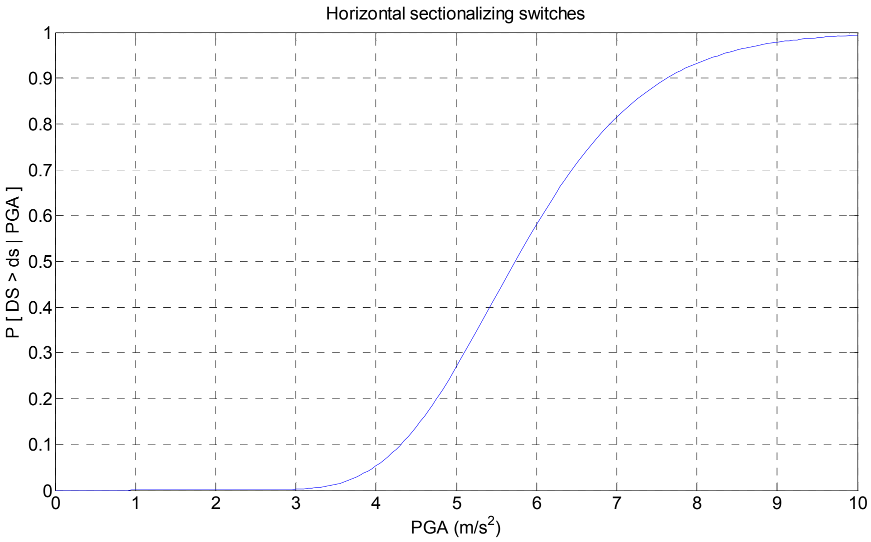
Element at risk	Horizontal sectionalizing switch	**Element Code**	EPN12
Reference	Vanzi, I. 1996		
Figures 			

Table 5.7 Alternative fragility functions of horizontal disconnect switch

<table>
<tr><td>Element at risk</td><td>Horizontal disconnect switch</td><td>Element Code</td><td>EPN12</td></tr>
<tr><td>Reference</td><td colspan="3">FEMA – HAZUS^{MH} Technical Manual. 2003</td></tr>
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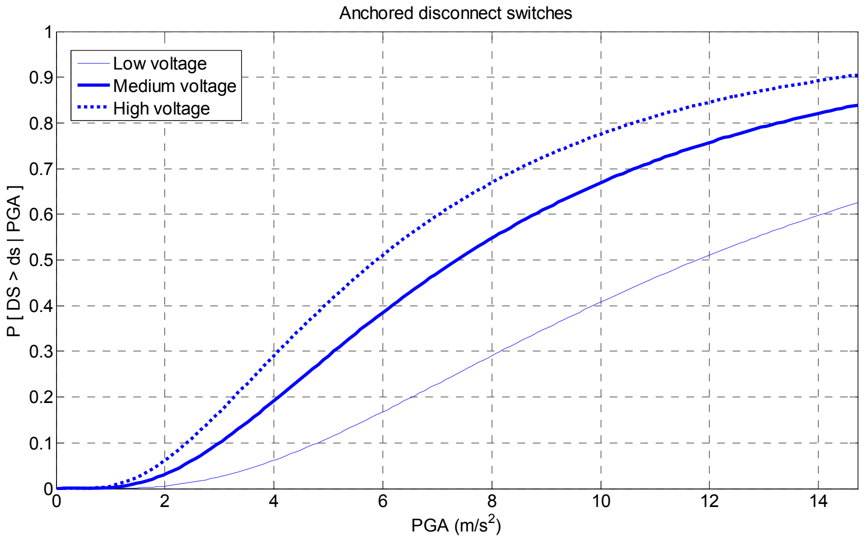
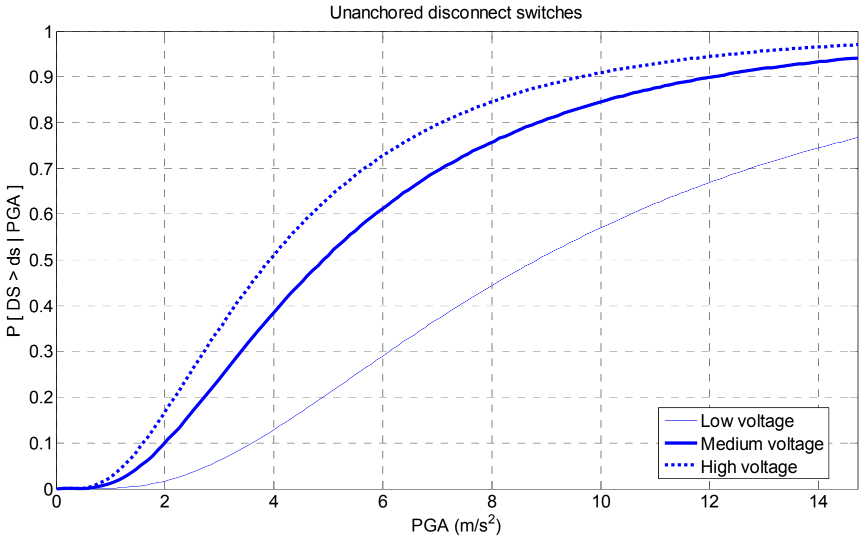


Anchored disconnect switches



Unanchored disconnect switches

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</table>

4. Vertical Disconnect switch or Sectionalizing switch

Table 5.8 Proposed fragility function of vertical sectionalizing switch

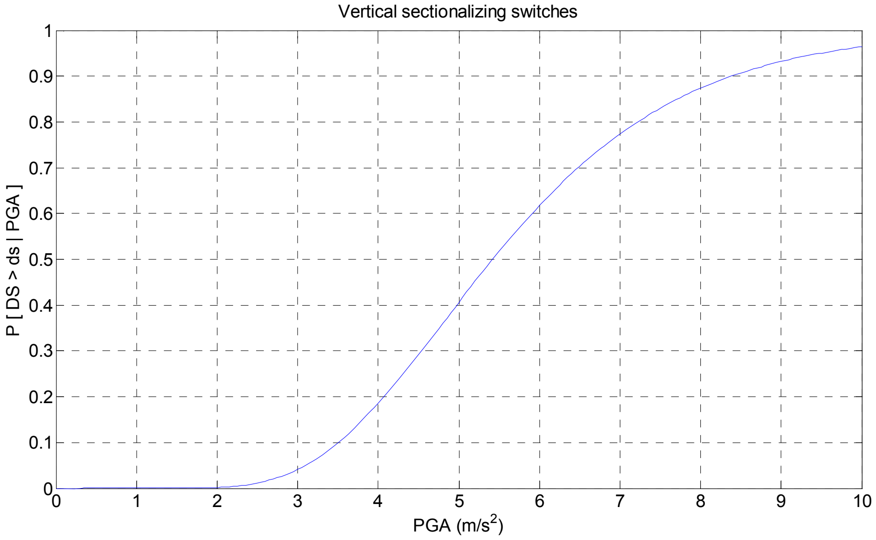
Element at risk	Vertical sectionalizing switch	**Element Code**	EPN13
Reference	Vanzi, I. 1996		
Figures 			

Table 5.9 Alternative fragility functions of vertical disconnect switch

<table>
<tr><td>Element at risk</td><td>Vertical disconnect switch</td><td>Element Code</td><td>EPN13</td></tr>
<tr><td>Reference</td><td colspan="3">FEMA – HAZUS^{MH} Technical Manual. 2003</td></tr>
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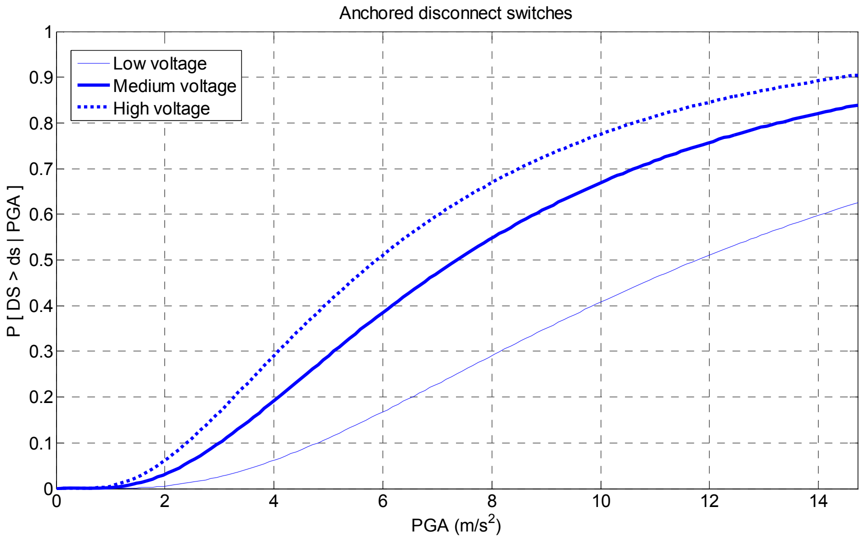

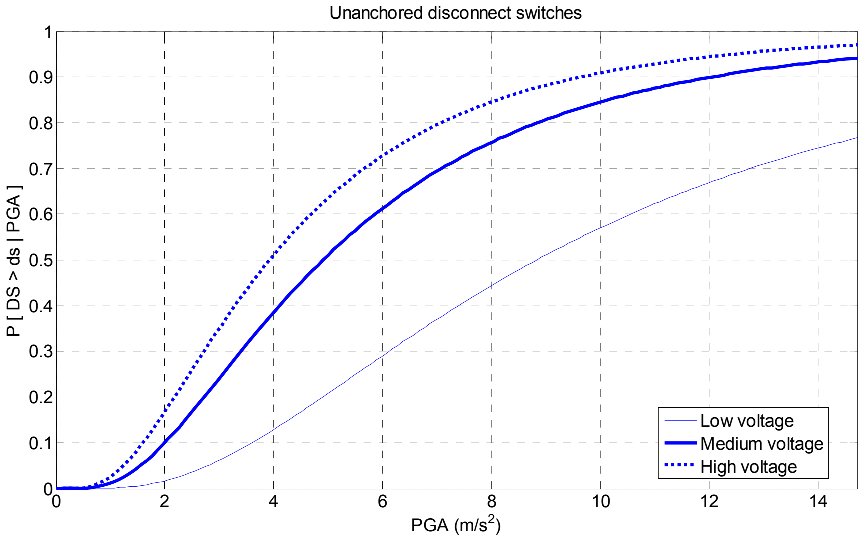

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</table>

5. Transformer or Autotransformer

Table 5.10 Proposed fragility function of autotransformer

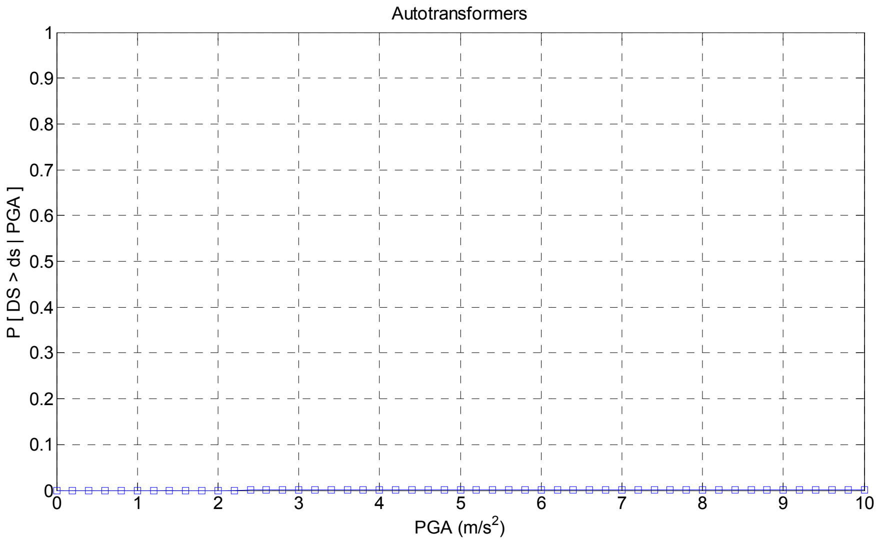
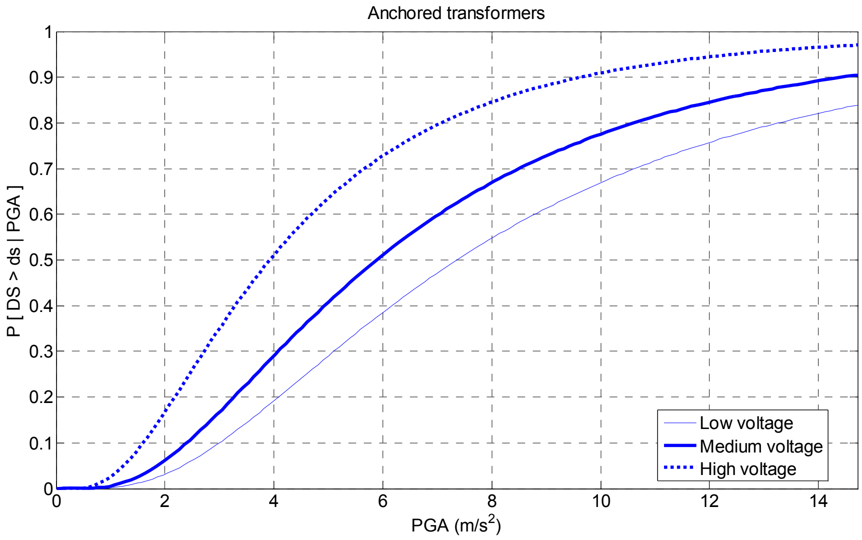
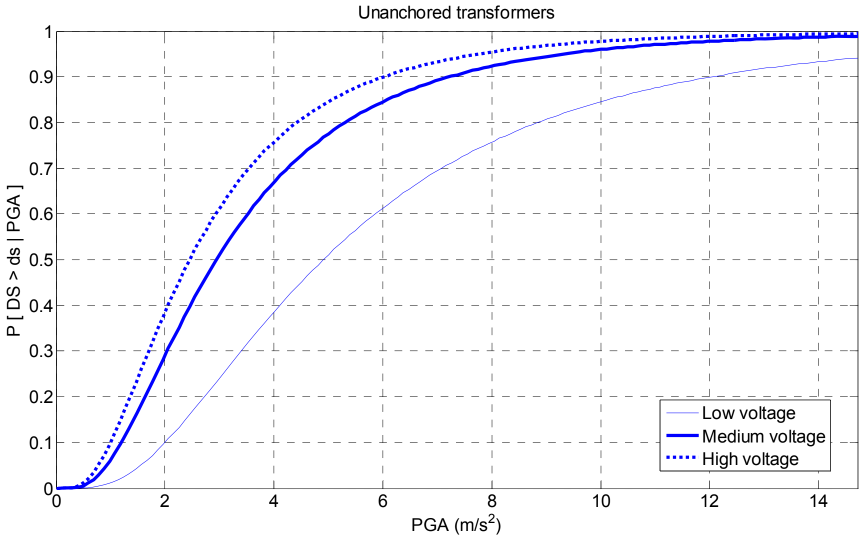
Element at risk	Autotransformer	**Element Code**	EPN14
Reference	Vanzi, I. 1996		
Figures  			

Table 5.11 Alternative fragility functions of transformer

<table>
<tr><td>Element at risk</td><td>Transformer</td><td>Element Code</td><td>EPN14</td></tr>
<tr><td>Reference</td><td colspan="3">FEMA – HAZUS^{MH} Technical Manual. 2003</td></tr>
<tr><td colspan="4">Figures

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</table>

6. Current transformer

Table 5.12 Proposed fragility function of current transformer

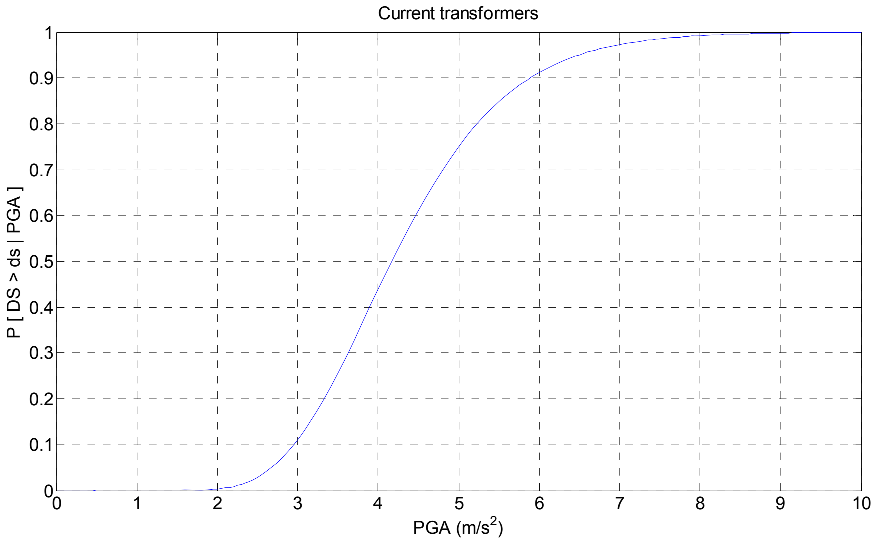
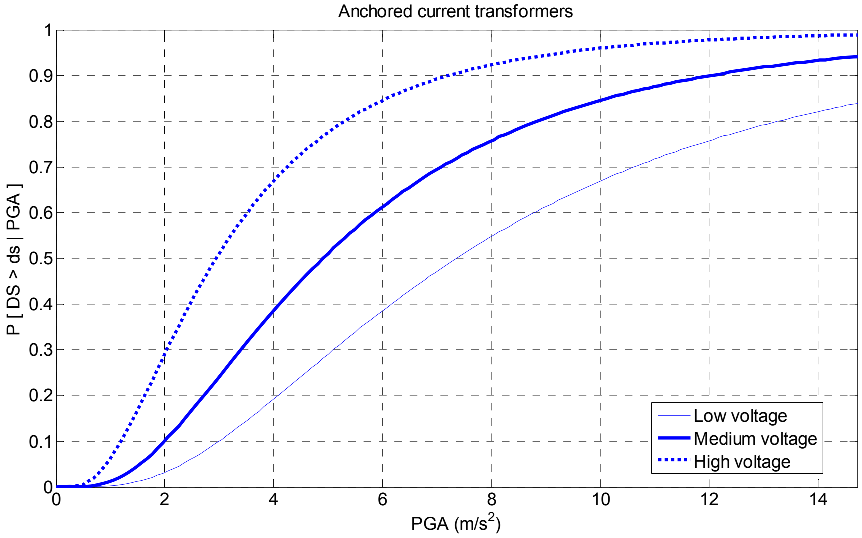
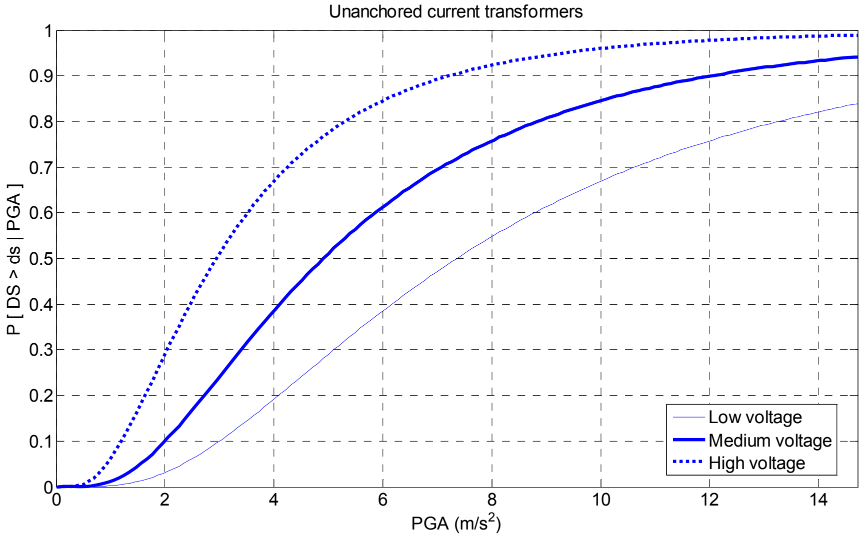
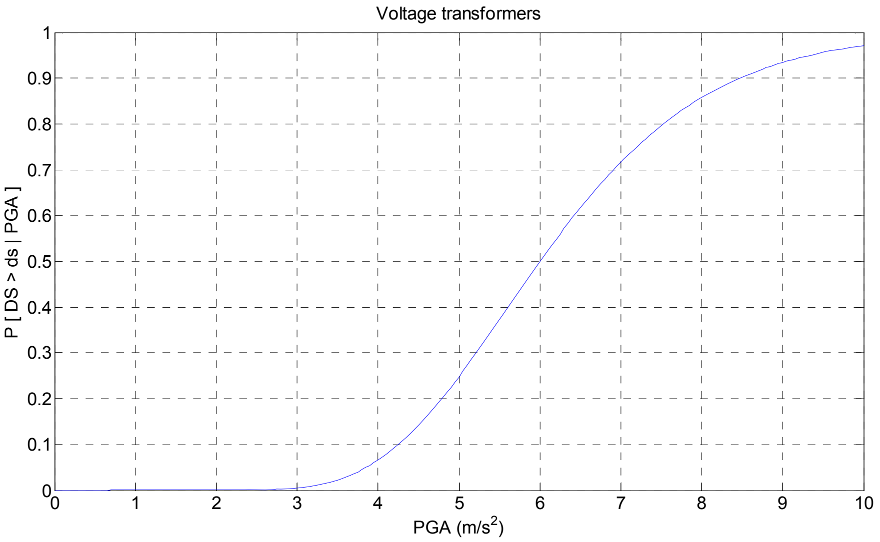
Element at risk	Current transformer	**Element Code**	EPN15
Reference	Vanzi, I. 1996		
Figures 			

Table 5.13 Alternative fragility functions of current transformer

Element at risk	Current transformer	**Element Code**	EPN15
Reference	FEMA – HAZUS^{MH} Technical Manual. 2003		
Figures   			

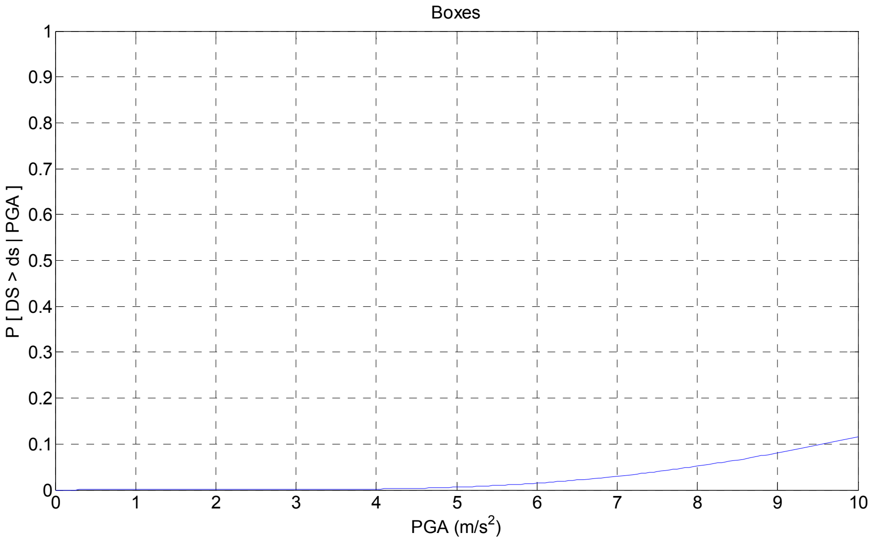
7. Voltage transformer

Table 5.14 Proposed fragility function of voltage transformer

Element at risk	Voltage transformer	**Element Code**	EPN16
Reference	Vanzi, I. 1996		
Figures 			

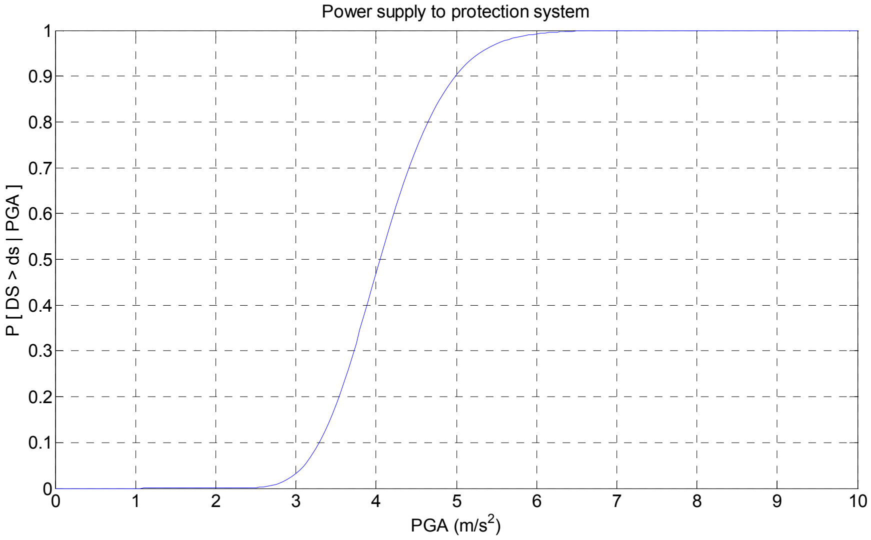
8. Box or Control house

Table 5.15 Proposed fragility function of box

Element at risk	Box	**Element Code**	EPN17
Reference	Vanzi, I. 1996		
Figures 			

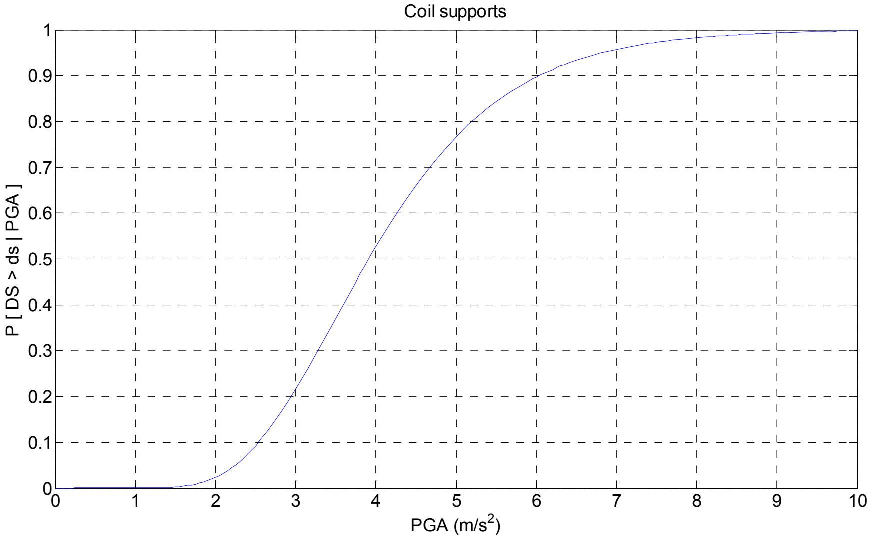
9. Power supply to protection system

Table 5.16 Proposed fragility function of power supply to protection system

Element at risk	Power supply to protection system	**Element Code**	EPN18
Reference	Vanzi, I. 1996		
Figures 			

10. Coil support

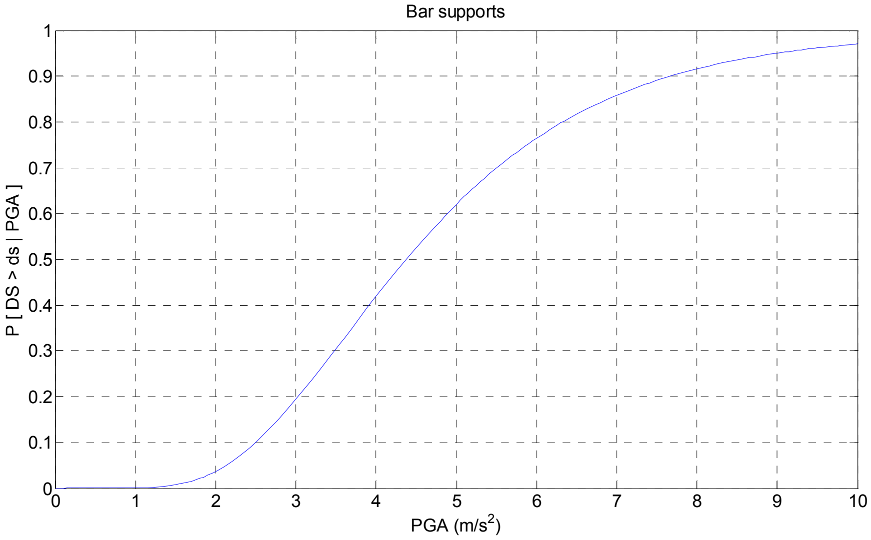
Table 5.17 Proposed fragility function of coil support

Element at risk	Coil support	**Element Code**	EPN19
Reference	Vanzi, I. 1996		
Figures 			

11. Bar support or Pothead

Table 5.18 Proposed fragility function of bar support

Element at risk	Bar support	**Element Code**	EPN20
Reference	Vanzi, I. 1996		
Figures			



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