Physical Resilience of the Electricity Transmission Grid against Earthquake: Analysis of a Prototype Model

Mahban Arghavani[1], Mohsen Ghafory-Ashtiany[2], Nadejda Komendantova[3], Stefan Hochrainer-Stigler[4]

1- Ph.D. Student, IIEES, Tehran, Iran, and a 2017 YSSPer at IIASA, Laxenburg, Austria

2- Professor, International Institute of Earthquake Engineering and Seismology (IIEES), and President of Iranian Earthquake Engineering Association (IEEA), Tehran, Iran

3- Research Scholar, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria and Senior Research Scholar, ETH, Zurich, Switzerland

4- Senior Research Scholar, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Corresponding Author's E-mail: ashtiany@iiees.ac.ir

Abstract

Increasing number of power supply interruptions due to earthquakes leads to heavy direct and indirect economic losses and indicates the importance of resilience of electric power networks. The present study, focusing on seismic resilience of the electricity transmission grid, is looking to develop a basic framework for calculating power grid performance and resilience. This research, based on the network performance analysis and the graph theory, is using a prototype model of the electricity transmission grid to calculate the average performance of the system over recovery time, as the system resilience. This research distinguishes between the damaged facilities in the network by classifying damage levels to different degrees between zero and one and assigning performance values to each level to go beyond the binary statement of connectivity analysis, while having fast and simple calculations.

Keywords: Power Transmission Grid, Earthquake, Resilience, Recovery

1. INTRODUCTION

Electric power is essential to the continued functionality of critical infrastructure, lifelines and economic vitality of every community. Several natural and man-made hazards affect electricity grids and might lead to power outages or even blackouts, which have serious effects beyond the direct losses. Indirect economic losses can be up to five times higher than the direct economic losses [1]. Cascading failure, as a sequence of dependent failures, can lead to the spread of damage and thus exacerbates both the direct and indirect economic losses. For reducing the losses and recovery of the stricken region, rapid restoration of electric power is critical.

Electric power system of Iran has high vulnerability to earthquakes. This vulnerability is defined by two reasons such as the fact that Iran is one of the most seismic countries in the world and its poor performance of electricity network against moderate earthquakes and not populated cities. On one hand, the Iranian's power grid resilience against earthquakes has not been investigated in detail and comprehensive until now. On the other hand, in Iran the majority of power outages happen because of problems with electricity transmission and distribution rather than problems with electricity generation. The main focus of this study is on transmission grid because of high economic value of its components, high potential of widespread cascading effects and complicated and longer recovery time. So, the objective of this research is to develop a comprehensive framework for resilience analysis of power transmission grids due to earthquakes. The study will focus on modeling the power grids, performance analysis and network restoration in earthquake-prone areas, with a prototype model.

2. THEORETICAL BACKGROUND: DEFINING AND MEASURING THE RESILIENCE

Resilience represents the ability of a system to return to an equilibrium state after a temporary disturbance; the more rapidly it returns to equilibrium and the less it loses its function, the more resilient it would be. In more general, resilience means ''the ability to recover from (or to resist being affected by) some shock, insult or disturbance'' [2]. Due to the widespread use of resilience and its related implications in various fields, the wide variety of definitions and methods for measuring resilience is widely used in many subjects and applications. The basic formula for measuring resilience, which represents the basis of this research, is shown in the Figure 1. Suppose that the area underneath the blue function of performance is equal to green shaded area or performance area, A_P and the area over the blue function of performance is equal to red shaded area or losses area, A_L. The total area, A_T is the sum of these two areas. According to the definition [3, 4, 5], resilience over time of T, is equal to performance area or A_P divided by time of T, that is a representation of resilience based on the level of performance. Performance area, A_P is equal to loss area, A_L subtracted from total area, A_T. Thus, resilience is equal to one minus loss area divided by time of T, that is a representation of resilience based on the level of losses.

$$R = \frac{A_P}{T} = \frac{A_P}{A_T} = \frac{A_T - A_L}{A_T} = 1 - \frac{A_L}{A_T} = 1 - \frac{A_L}{T} \qquad (1)$$

These representations of resilience are equivalent to each other, see Equation 1. But due to the challenges in calculating losses including indirect economic losses, calculation of resilience based on the performance level was selected for this research. Therefore, the average performance over defined duration of T can be defined as the resilience of the system over that period. So, in order to calculate the area under the performance curve, starting performance P_s, ending performance P_e, recovery time, and recovery function values over recovery time are needed to be calculated. Note that for the high-magnitude earthquakes, impact on structural systems are very fast. For example, the performance of power grid is severely affected and may be interrupted. Therefore, the performance curve drops rapidly. On the other hand, the time needed to retrieve the power grid should be as short as possible, usually within a few hours, a few days or eventually several weeks.

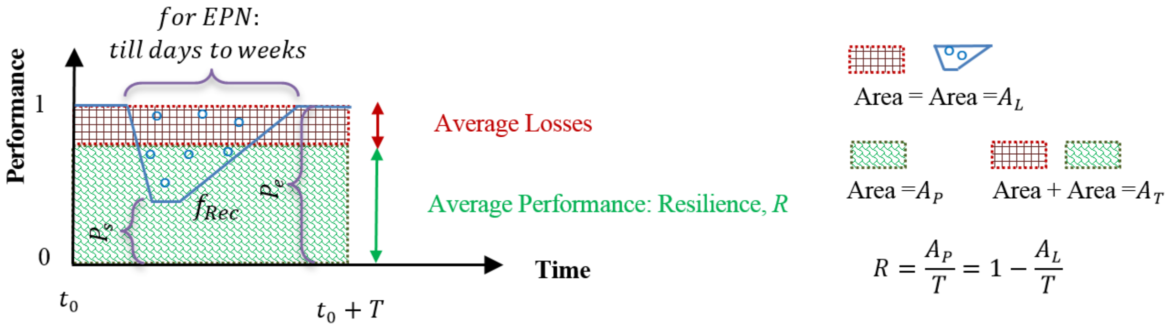
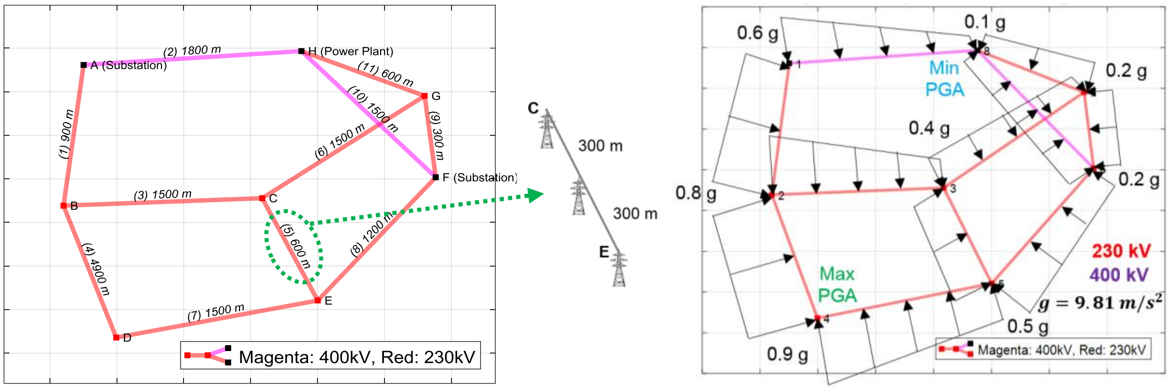


Figure 1. Calculation of resilience based on the level of performance or losses [6].

3. NETWORK MODELING

The main focus of this research is to develop a framework for seismic resilience assessment of the power transmissions grid based on the network performance analysis and the graph theory. For this purpose, assumed data is used for a pilot sample as a small scale preliminary study in order to evaluate feasibility of applying the suggested method and to improve it prior to a full-scale case study. It's notable that by considering a part of the Iran's electric power grid to reduce the volume of computations, one will get to neither significant changes of peak ground acceleration (PGA) values, nor closed loops, nor redundancies, nor a combination of series and parallel connections. Considering larger area with significant variation of PGA values, closed loops, redundancies and a combination of series and parallel connections, one will face with high volume data of power grid and consequently high volume of computations. Therefore, the possibility of focusing on the method will be lost. That's why a prototype model of the electricity transmission grid is used to calculate the average performance of the system over considered time. An appropriate method for modeling of this prototype and, in general, the electric power network (EPN) is graph theory. For more explanation, power plants and substations can be modeled as the graph vertices, while transmission lines, including towers and cables will be modeled as the graph edges. Figure 2a represents a prototype of the overhead power transmission grid, including 8 nodes (vertices) and 11 edges, that are two 400 kV transmission lines in magenta color and nine 230 kV transmission lines in red color. Span length between transmission towers is 300 m. Edges labels stand for lengths of transmission lines. Figure 2b shows the distribution of considered PGAs on the grid. The PGA values are assumed to be between 0.1g to 0.9g, (g=9.81 m/s^2).



a. A prototype network model for overhead power transmission grid

b. Example of PGA distribution on the Grid

Figure 2. A prototype network model and considered PGAs

4. Classification of Effective Parameters on the GRID Performance

In order to calculate the electric network resilience, the effect of the constituent components of EPN on the network resilience should be considered. In general, effective parameters on the performance of each component in a power grid are divided into two categories, see Table 1:

1- Parameters related to the function of each component alone, which are considered by the vulnerability curves, e.g. voltage levels, height of towers, and so on.

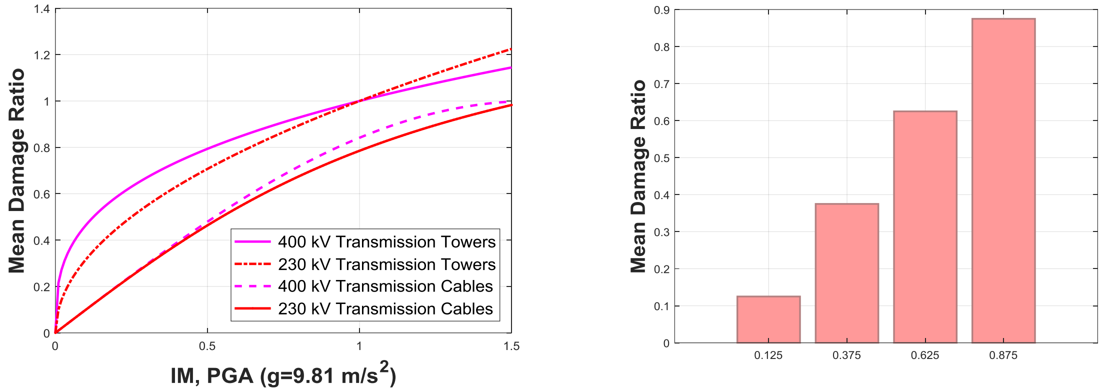
2- Parameters related to the performance of each component, considering its arrangement / positioning in the network, which are considered by the weight factors, e.g. number of lost loops after losing a line, distances between transmission lines and power plants and substations, changes on the shortest and longest paths between transmission lines and power plants and substations after losing a line, and so on.

Table 1- Classification of effective parameters on the performance of each component of power transmission grid for calculation of its resilience.

Effective parameters	Function of each component, alone: vulnerability and/or fragility functions	Element typology (macro-components, micro-components);
		Anchoring or unanchoring of the components;
		Voltage levels (low, medium, high);
		…
	Function of each component, considering its arrangement / positioning in the grid: weight factors	Changes in the power grid structural / operative parameters such as connectivity level, clustering coefficient, degree correlation, betweenness centrality (based on shortest paths), … after losing a part of the network;
		Number of lost loops after losing a line;
		Distances between transmission lines and power plants and substations;
		Changes on the shortest and longest paths between transmission lines and power plants and substations after losing a line;
		…

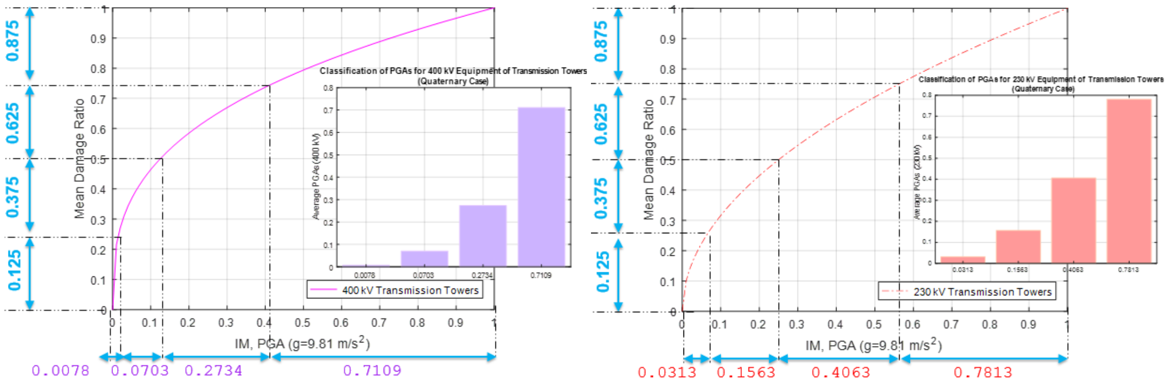
4.1. Vulnerability Curves

Considering the strong relationship between resilience and vulnerability, resilience can be calculated with help of the vulnerability functions, which are defined as the probability of losses or mean damage ratio (MDR) of the system (e.g. ratio of repair cost to replacement cost). Available studies in the field of vulnerability functions and also deriving vulnerability functions from fragility functions, make a potential support for resilience calculations using vulnerability functions. As shown in the Figure 3 by use of different vulnerability curves, which are different from each other for different EPN components, corresponding MDR for each component would be determined. In the absence of suitable curves for Iran, some synthetic curves, considering other available curves in the world such as UWG, HAZUS and FEMA were used, with agreeing that the vulnerabilities of the power transmission equipment are directly proportional to their working/ operating voltages. Also, the curves of the towers are considered to be higher than the curves of the cables because cable damage is usually the result of damage to the towers. So, by use of vulnerability curves, interaction of input, i.e. seismic hazard and system, i.e. EPN would be considered in the model. But there are a lot of different components on the network. Therefore, an appropriate engineering approach is needed to reduce the volume of computations and make simplification in the model. Dividing the vertical axis of damage and finding the corresponding intervals on the horizontal axis of intensity measure (IM) can be a good solution to assign a damage value to each category. These divisions are not necessarily equal or linear. By changing the number of intervals, the accuracy, speed and simplicity of the method will also change. Then, in each interval, the average amount of the start and the end points of that interval is allocated to it, i.e. the numbers displayed in each interval on the axes of the Figure 4. Therefore, by dividing the vertical axis of MDR on the vulnerability curves and finding the corresponding intervals on the horizontal axis of IM, different levels of excitation accelerations will be classified according to different levels of MDRs, see Figure 4. In the following, four assumed vulnerability curves for transmission towers and cables at two voltage levels of 400 and 230 kV were considered. The calculations were then carried out using the quaternary case, that is, the four divisions on the axes.

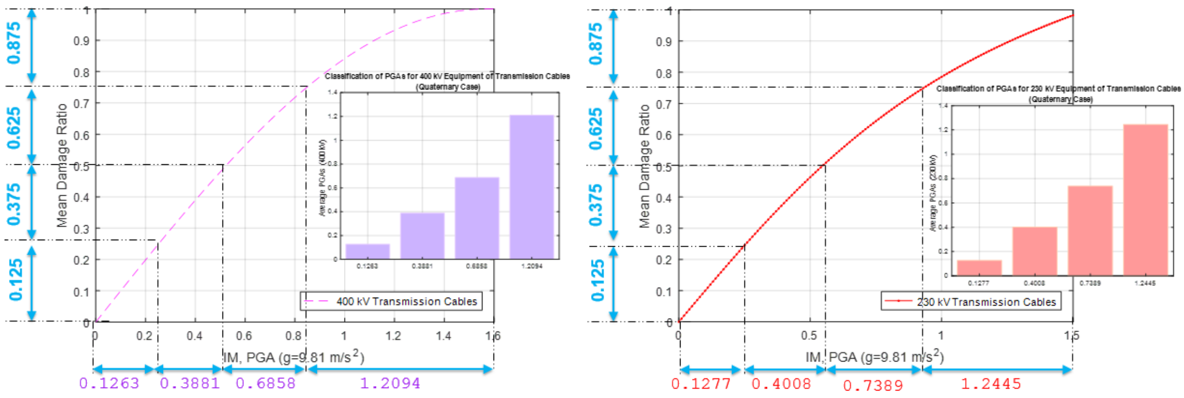


a. Vulnerability curves of transmission lines **b. Classification of MDR (quaternary case)**

Figure 3. Vulnerability curves of overhead transmission lines; dividing the vertical axis to allocate the average amount of each interval as the value of damage class.



a. 400 kV transmission towers **b. 230 kV transmission towers**



c. 400 kV transmission cables **d. 230 kV transmission cables**

Figure 4. Finding the corresponding intervals on the horizontal axis to classify the excitation acceleration into different levels (quaternary case).

4.2. WEIGHT FACTOR ASSIGNED TO EACH TRANSMISSION LINE

In order to consider the effect of grid structure, a weight factor (w_i) to each transmission line (i) is assigned based on the connectivity criterion. In other words, transmission lines with smaller degrees of vertices are usually more important in terms of connectivity. In order to consider this effect, a weight factor for each transmission line is applied, which is the sum of average degrees of vertices of the considered transmission line ($2\langle Deg\ v\rangle$) divided by the sum of degrees of vertices of that transmission line ($\sum Deg\ v_i$):

$$w_i = \frac{2\langle Deg\ v\rangle}{\sum Deg\ v_i},\ i = number of\ transmission\ line \quad (2)$$

where $\langle\ \rangle$ describes averaging over the degrees of vertices with considering the whole system and (v) stands for each vertex. Labeling the model edges, i.e. the transmission lines with their assigned weights and making the width of the edges proportional to their weights, leads to Figure 5.

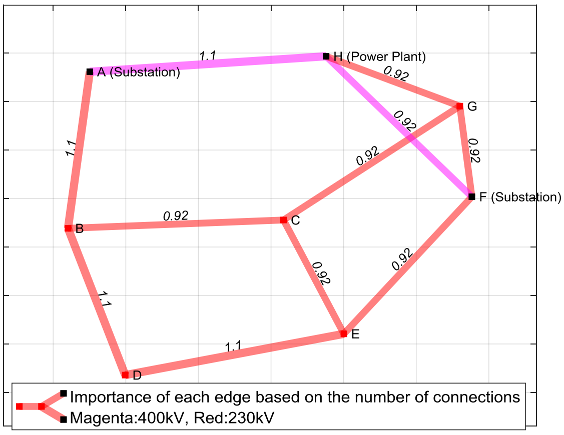


Figure 5. Weighted network model for overhead power transmission grid.

5. RECOVERY TIME CALCULATION USING GAMMA CUMULATIVE DISTRIBUTION FUNCTION

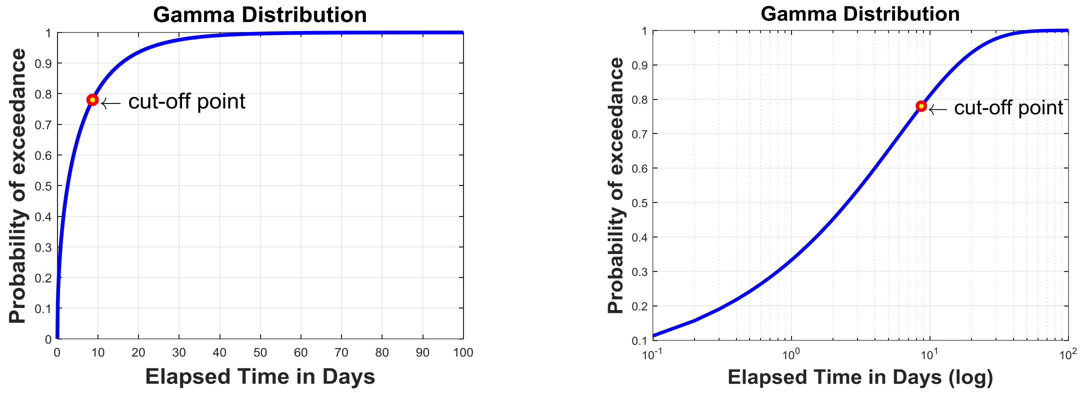
An empirical method for the estimation of recovery time is to use a global database of earthquake damage to the electric power grids, and their downtimes (the precise numbers of days without services of the power utility). Figure 6 shows the location of 31 damaging earthquakes (including the 2003 Bam earthquake in Iran) in an available database [7], which is used in this study in the absence of a suitable database for Iran.

Figure 6. Location of the different earthquakes of the considered database [7].

Considering a suitable distribution, e.g. Gamma because of having a rich variety of shapes, it is possible to calculate the values of mean ($\mu_D = 5.78$), standard deviation ($\sigma_D = 8.3$), scale parameter (β=12.05), and shape parameter (α=0.48) based on the downtime data of 31 last earthquakes. Afterwards, the cumulative distribution function (*CDF*) can be calculated by use of Equation 3 [7].

$$CDF: F(x \setminus \alpha, \beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^x t^{\alpha-1} e^{-t/\beta} dt \text{ , which } \Gamma(k) = \int_0^{\infty} x^{k-1} e^{-x} dx \quad (3)$$

where k is the shape parameter, which must be positive to ensure the convergence of the integral.



a. Horizontal axis in the linear / normal scale **. Horizontal axis in the nonlinear / logarithmic scale**

Figure 7. Cut-off approach to calculate the recovery time using Gamma CDF.

The *CDF* curves on the Figure 7 were developed based on the quantitative data on the previous earthquakes. The horizontal axis can be interpreted as the number of days required for grid to recover its performance at the corresponding level, that is the level of network recovery (by comparing baseline performance before and after the event) which its information used in plotting the curve, e.g. ultra full or getting a better situation than the pre-disaster situation, full or returning to the pre-disaster situation, just getting connectivity, and so on. The vertical axis (probability of exceedance) can be interpreted as the likelihood that the grid will be restored considering the corresponding level.

One may estimate the time for recovery by finding the cut-off point of chart with the number of one on the vertical axis, to find the corresponding point on the horizontal axis, which would be easier by use of logarithmic scale. But this method is not applicable because it leads to an infinite value on the horizontal axis. So, it's required to cut-off the chart below the number of one on the vertical axis to calculate the recovery time, T_R on the horizontal axis. Chart cut-off point on the vertical axis, P_c, can be selected using trial and error method, as the following equation:

$$P_c = 1 - \left(\frac{P_s}{P_e}\right)^2 \quad (4)$$

Considering Equation 4, calculation of recovery time in the two boundary states, will lead to the following expected equations:

1- Full failure of power transmission grid: $P_s = 0 \Rightarrow P_c = 1 \Rightarrow T_R \rightarrow \infty$ (5)

2- No significant damage on power transmission grid: $P_s = P_e \Rightarrow P_c = 0 \Rightarrow T_R \rightarrow 0$ (6)

6. Overall Performance and Resilience of Transmission Grid

For calculating the resilience by use of the area under the curve method, it is necessary to calculate the seismic performance of the power grid. The overall system performance can be defined as:

$$P = \langle P_i \rangle = \langle 1 - \langle weighted\ MDRs \rangle \rangle \quad (7)$$

where P_i is the performance for each part of grid such as cables, towers, etc. and i is the number of all considered parts of the grid. Consider the two following boundary / extreme modes in the Equation 7. Full failure of transmission grid leads to P =0 and no significant damage on transmission grid leads to P=1, as it is expected.

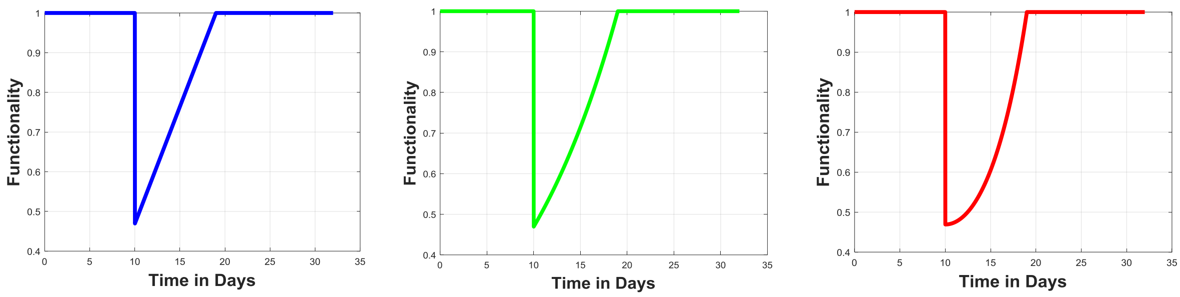
Therefore, by calculating the Equation 7 after an earthquake, minimum point on resilience curve immediately after earthquake i.e. P_s will be achievable. Then, expected performance at the end of recovery phase i.e. P_e can be considered, for example 1 in this study. In other words, recovery measures are supposed to be in such a way that the power grid has returned to its basic performance before occurring the earthquake. In order to find other points on the performance curve between P_s and P_e, it's necessary to calculate the system performance over the time difference between these two points, T_R by use of recovery functions, f_r. Depending on how recovery is performed, recovery functions can be in a great variety. In order to use the most common simplified recovery function models different recovery functions can be considered. For example linear recovery function for the case of average prepared system; which is useful when there is no information, exponential recovery function for the case of not well prepared system; which the rapidity of recovery increases as the process nears its end, and trigonometric recovery function for the case of unprepared system; which the rapidity of recovery increases as the process nears its end, see Equations 8 to 10 and Figure 8 (adapted from [2]).

$$Linear: f_r(t) = a\left(\frac{t-t_0}{T_R}\right) + b \tag{8}$$

$$Exponential: f_r(t) = a \exp\left[-\frac{b(t-t_0)}{T_R}\right] \tag{9}$$

$$Trigonometric: f_r(t) = \frac{a}{2}\left\{1+\cos\left[\frac{\pi b(t-t_0)}{T_R}\right]\right\} \tag{10}$$

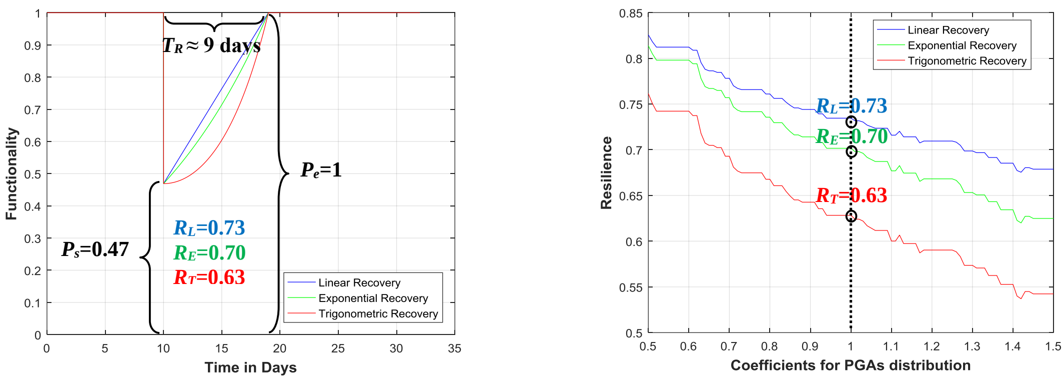
where a, b are constant values that are calculated using curve fitting to available data sources i.e. using the two points of (t_0, P_s) and (t_0+ T_R, P_e), while t_0 is the instant of time when the extreme event strikes and T_R is the recovery time necessary to go back to pre-disaster condition evaluated starting from t_0.



a. Linear recovery **b. Exponential recovery** **c. Trigonometric recovery**

Figure 8. Adopted recovery function models based on Cimellaro et al. [2].

By calculating the points of P_s, P_e, P_c, T_R, and f_r, required parameters to calculate resilience are obtained. Therefore grid resilience using linear, exponential, and trigonometric recovery functions - respectively R_L, R_E, and R_T - would be measured. Then, by repeating the calculations using different values as the input PGAs Figure 9 will be obtained, which indicates on reduction of resilience by increasing PGAs. Effective coefficients on the input PGAs are selected from 0.5 to 1.5, so that the effect of decreasing and increasing the input acceleration can be investigated. With regards to the Figure 9b, chart values at point 1 shows the results of this study, depicted in the Figure 9a.



a. Most common simplified recovery functions **b. Effect of PGAs changes on resilience**

Figure 9. Calculation of grid resilience using three recovery functions under different distributions of PGAs

7. CONCLUSIONS

The aim of the study, focousing on the electricity transmission grid, is to develop a basic framework for calculating power grid performance and resilience and to investigate how effective parameters act. In order to consider the effect of components arrangement / positioning on the grid resilience, a weighting coefficient has been used based on the concept of redundancy. The numerical problem in calculating recovery time has been overcome by use of a coefficient, obtaining from the trial and error method. The methodology of this study allowed the calculation of physical resilience based on the seismic performace of the transmission grid resulting from the seismic vulnerability curves of the power network components. Based on the level of damage to different components on the vulnerability curves, network components have been divided into different groups to classify the coresponding excitation PGAs. This classification reduces the volume of computation and makes the method more efficient. The number of divisions will be selectable based on the expected level of accuracy, speed, and simplicity. This research distinguishes between the damaged facilities in the network by classifying damage levels to different degrees between zero and one and assigning performance values to each category. Therefor, while having fast and simple calculations, it goes beyond the binary statement of connectivity analysis.

8. ACKNOWLEDGMENT

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