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# European power grid reliability indicators, what do they really tell?

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ABSTRACT

The European Network of Transmission System Operators for Electricity has been publishing network reliability data for major fault events in the European electricity transmission network since 2002. The work presented focuses on three reliability indicators provided for each major fault event: energy not supplied, total loss of power and restoration time. The purpose of this paper is to assess the usefulness of these indicators and to gain a better understanding of the impact of network topology on transmission network reliability. The topology is assessed in terms of network interconnectivity. For each indicator, the sum of the observed values and the Empirical Cumulative Distribution Functions (ECDF) are used to compare networks with different topologies. More interconnected grids have experienced a larger number of fault events. However, their impacts in terms of reliability indicators are significantly lower. In spite of the observed differences between network groups, results show significant sensitivity to reliability indicators' data sets. The usefulness and significance of transmission network reliability indicators are discussed.



## 1. Introduction

The European power grid is the largest and most complex physical network ever made by human kind. Electricity demand in Europe has been and will keep increasing [1]. In this context one essential challenge of the European Network of Transmission System Operators for Electricity (ENTSOE) is to ensure a coordinated, reliable and secure operation of the electricity transmission network [2]. ENTSOE measures network reliability as the system's ability to deliver electricity to all points of utilisation within acceptable standards and in the amounts desired [3]. The assessment of the power grid's reliability has been an ambitious and attractive as well as necessary research field over the past decades. Failures in the electricity transmission grid have various causes and most of the times are extremely difficult to analyse due to their complex nature and cascading effects that lead to large disruptions.

This paper intends to expand previous work on the impact of topology upon the reliability of the European power grid [4–6] by extending the time frame of fault events. In addition, a different statistical method from one previously used in literature [4] is applied to gain a better understanding of the relationship between network topology and its reliability. The sensitivity of the analysis to the data set is discussed, mainly with reference to extreme events. The usefulness of reliability indicators is questioned in the context of analysing the impact of network topology upon transmission network reliability.

The paper is structured as follows. Section 2 describes the network reliability indicators used throughout the analysis. Section 3 defines and analyses the relationship between reliability indicators and network topology. The sensitivity of the results is explained and discussed throughout the analysis. Section 4 provides a new methodology for analysing the reliability indicators. Finally, Section 5 presents the conclusions and discusses future work.

## 2. Reliability characteristics

For the analysis of the reliability of the European transmission network in this paper, we use the reliability indicators by ENTSOE [7]. The data is available for each major fault event of the former UCTE between January 2002 and March 2011.

Three reliability indicators by ENTSOE are considered. The first is an estimation of energy not supplied (ENS) to the final customers due to incidents in the transmission network and given in MWh [3]. The second is the total loss of power (TLP), which is given in MW and is a measure of generation shortfall. Finally, the restoration time (RT), measured in minutes, corresponds to the time from the outage/disturbance until the system frequency returns to its nominal value [8]. A total of 862 fault events are taken into account from

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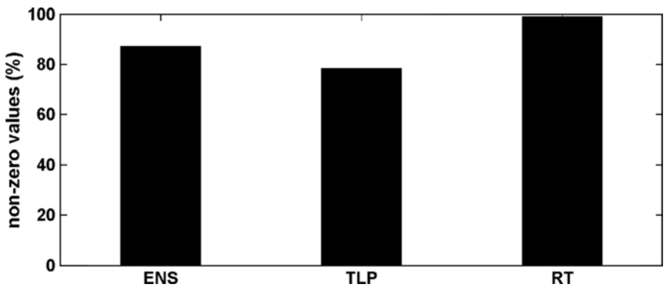


**Fig. 1.** Percentage of non-zero values for ENS, TLP and RT.

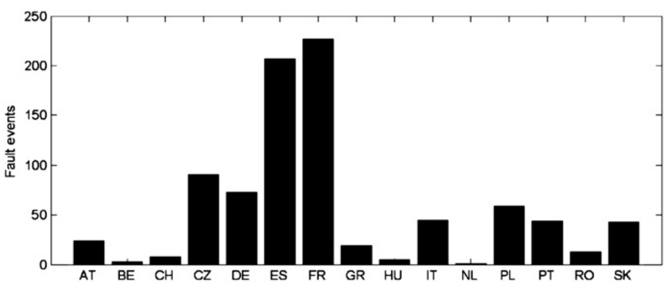


**Fig. 2.** Number of fault events per country (January 2002–March 2011).

the 15 countries under analysis.[1] A fault event in the transmission network is defined as an incident which causes loss of generation or transmission power capacity or the inability to serve the expected load. In other words, a fault event occurs when at least one of the three reliability indicators (ENS, TLP and RT) is larger than zero.

Fig. 1 shows the percentages of non-zero values for the three indicators. Some events show a zero in one or two of the three indicators, pointing out the different nature and condition of the events. In addition, due to the definitions of the three indicators, the values for each of them are not strongly correlated; in fact the correlation coefficients are 0.16 (ENS – TLP), 0.38 (ENS – RT) and 0.14 (TLP – RT). For each fault event ENTSOE provides the cause from one of four categories, namely overload, transmission network failure (operation failure, protection device failure, etc.), external reasons (weather conditions, force majeure, etc.) and other or unknown reasons. ENTSOE (UCTE in the past) receives information regarding major fault events from each different transmission system operators (TSOs) across Europe. It must be noted that it is the TSO's responsibility to collect and provide correct data to ENTSOE. This responsibility should be required of all administrative bodies in the electricity supply chain.

The events are not evenly distributed throughout the countries under analysis. Fig. 2 shows the number of events per country. A large discrepancy between countries can be noticed. The largest countries in terms of nodes and interconnectors (France, Spain and Germany) account for 58% of the total number of events in the 15 countries under observation. Fig. 3 shows the sum of each reliability indicator per country for the nine years under analysis. In the three plots it can be observed how a few countries account for a large portion of the total sum of one indicator. For instance, Spain experienced 64% of the total loss of power since 2002, while Italy and Poland accounted respectively for 32.2% and 31.8% of the total energy not supplied, and Poland added up 38% of the total restoration time.

[1] Austria (AT), Belgium (BE), Czech Republic (CZ), France (FR), Germany (DE), Greece (GR), Hungary (HU), Italy (IT), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Spain (ES), Switzerland (CH) and The Netherlands (NL).

**Table 1**
Highest values of the reliability indicators.

| | ENS (MWh) | TLP (MW) | RT (min) |
|---|---|---|---|
| Total | 571,025 | 393,505 | 470,204 |
| Highest | 180,000 – 32% (IT) | 31,990 – 8% (ES) | 50,432 – 11% (PL) |
| 2nd highest | 168,000 – 29% (PL) | 26,746 – 7% (ES) | 37,486 – 8% (DE) |
| 3rd highest | 24,824 – 4% (DE) | 24,120 – 6% (DE) | 32,126 – 7% (PL) |

For each of the three reliability indicators, 862 values are given (one per fault event). The sums for each indicator accounting for all the events are given in Table 1. This shows the three largest values for each indicator, as well as the portion of the total indicator's sum that they represent and the country in which the fault event occurred. It can be observed how a few events have a large impact on each indicator. This is especially apparent for ENS. Fig. 4 shows the Lorenz curve[2] for the three reliability indicators and, as in Table 1, it can be observed that a small fraction of events accounts for a large fraction of the sum of each reliability indicator. In other words, for the case of ENS, one event accounts for 32% of the total ENS in the UCTE region since 2002. TLP shows a less uneven distribution but there still is a great difference between the contribution of the many low values and a few high values to the total TLP sum. This feature is of particular relevance for the analyses described in the next section of the paper. Rare extreme events must be considered with caution.

## 3. Relations with topological characteristics

The first goal of this paper is to expand the time frame of similar analyses previously developed by other authors [4–6], aiming at deriving a relation between the topology of a power grid and its reliability indicators. The topology is analysed in terms of the interconnectivity of the 15 power grids under analysis (in other words, how interconnected grid nodes are to other nodes of the same grid). The previous research [4] analysed events up to 2008 (latest data available at that time). In this paper the same approach will be applied with a time frame covering the period up to March 2011. In addition, a different statistical methodology is proposed to gain a better understanding of the relationship between network topology and its reliability.

The topology of a power grid can be described using graph theory [9] as a set of nodes connected by a set of links. Each link connects a pair of nodes. An important characteristic of a node is the degree $k$, equal to the number of edges connecting it to other nodes. In order to characterise the topological robustness of a power grid the cumulated degree distribution is used. It corresponds to the probability that a node chosen at random has a degree $k$ or larger [10]. UCTE power grids have exponential cumulated degree distributions [10], $P(K \geq k) = C \cdot \exp(-k/\gamma)$. $C$ is a normalisation constant and $\gamma$ is the exponential degree distribution exponent. The larger $\gamma$ is, the more interconnected a power grid is (inside its borders, not taking into account the interconnectivity with other networks). The values of $\gamma$ for each country under analysis are taken from [5], in which a mean field theory approach is used to analytically predict the fragility of the power grids, where the results suggest an increased robustness against intentional attacks for power grids with $\gamma < 1.5$. The power grids are divided in two groups, one with $\gamma < 1.5$ (robust group [4]) and the other one with $\gamma > 1.5$ (fragile

[2] A Lorenz curve provides, for each value of the variable, the addition of the values smaller or equal than that one. In economics this curve is typically used to show unevenness or evenness of richness share in a society or a country (e.g. the 1% of the richest population has 80% of richness of the country).