Electric Power Systems Research 90 (2012) 79–84

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

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

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ARTICLE INFO

Article history:
Received 28 November 2011
Received in revised form 6 March 2012
Accepted 12 April 2012
Available online 10 May 2012

Keywords:
Electricity transmission grid
Reliability
Network topology
Energy not supplied
Total loss of power
Restoration time

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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http://dx.doi.org/10.1016/j.epsr.2012.04.007

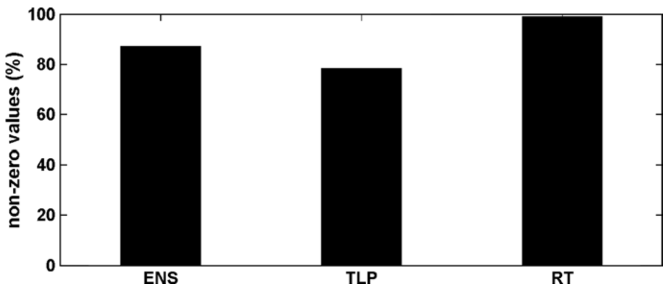

Fig. 1. Percentage of non-zero values for ENS, TLP and RT.

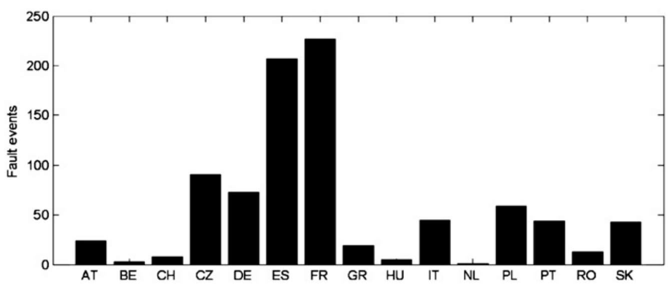

Fig. 2. Number of fault events per country (January 2002–March 2011).

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.

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 γ is the exponential degree distribution exponent. The larger γ is, the more interconnected a power grid is (inside its borders, not taking into account the interconnectivity with other networks). The values of γ 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

[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).

[2] A Lorentz 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).

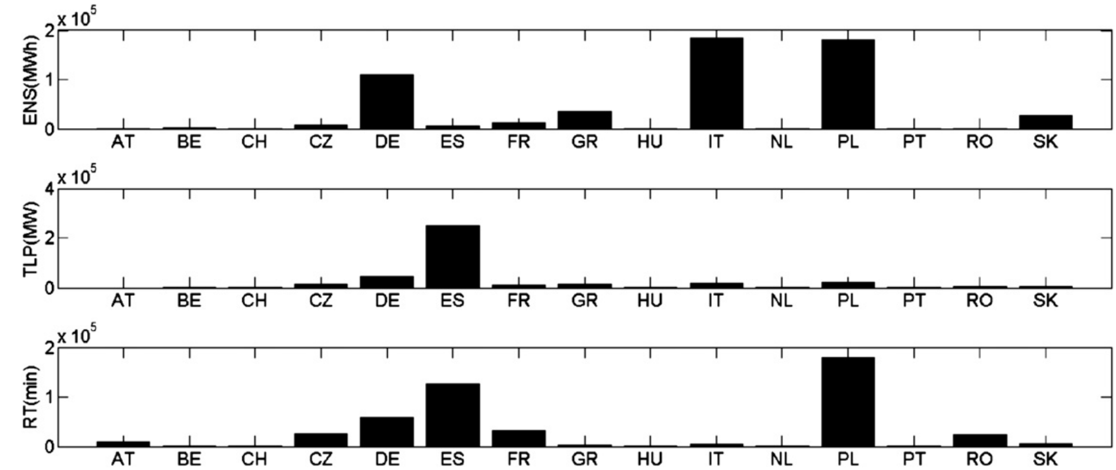

Fig. 3. Total ENS, TLP and RT per country (January 2002–March 2011).

group [4]). The robust group corresponds to the less interconnected grids and the fragile group to the more interconnected ones.

The 15 countries under analysis are therefore divided in two groups (less and more interconnected) depending on their topological nature. Fig. 5a shows the two groups' power grid characteristics and reliability indicators shares. The power grid characteristics are energy share (ES), power share (PS) and size share (SS). They are obtained by summing the energy consumed in a year, the peak power in the year and the number of nodes of each power grid in a group respectively. The sum is then divided by the total sum over all the countries in both groups. Using one-year hourly electricity consumption data [11] for each country, it is shown that the two groups have similar yearly energy consumption and maximum peak power. Therefore, even if the more interconnected group accounts for 60% of the total number of nodes, it is assumed that the two groups' reliability indicators can be compared.

Fig. 5b shows previously presented results [4] updated until March 2011. The more interconnected group experiences 80% (684) of the total number of fault events since 2002 and shows a very large share in two of the three indicators, TLP and RT (around 80%). However, ENS is higher for the less interconnected group. The latter statement shows an opposite outcome compared to the results presented in [4] where ENS is also larger for the more interconnected group (in the reference mentioned as the fragile group). Observing the reliability indicators data representing the fault events that have happened in the UCTE countries since 2002 and described in Section 2 of this paper, we conclude that, especially in the case of the ENS indicator, a single event can change the final result of the analysis. In order to better illustrate this, Fig. 6 applies the same technique for two different cases. They both represent fault events up to 2008, as in [4]. In the first case the Italian blackout from September 2003, which caused 180,000 MWh of energy not supplied [7], a total loss of power of 12,400 MW [12] and a restoration time of 1092 min [7], is not taken into account. In the second case, it is included. The results for the TLP and RT indicators are very similar, but the result for the ENS indicator is substantially different if the single event of the Italian 2003 blackout is taken into account or ignored. This example highlights the vulnerability of such an analysis to the data set characterised by extreme events. In addition, the relatively short temporal span for statistically sound results must be considered, as well as the probable network topology evolution over time.

Figs. 5 and 6 show that the ENS result is dependent on single events such as the Italian 2003 blackout which on its own accounts for more than 30% of the total ENS in the UCTE countries since 2002. Such dependence is also valid for TLP and RT to a lower extent. In fact, Fig. 4 shows how a small fraction of the three reliability indicators account for a very large fraction of their total sum.

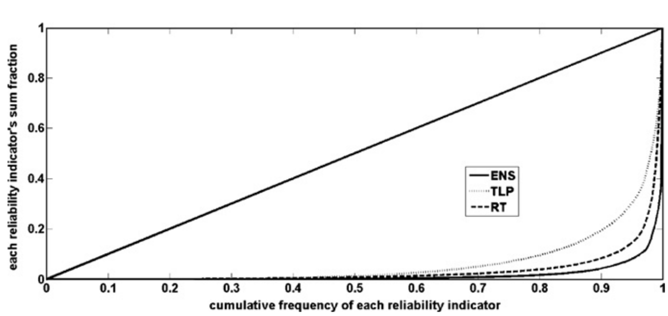

Fig. 4. Lorenz curve for the three reliability indicators.

4. Improving the methodology

The second goal of this paper is to propose a more robust statistical tool to analyse the relationship between network topology and its reliability. The methodology proposed in [4], which compares the relative shares of the indicator's sums for the two network groups, is not a robust statistical tool when the data is highly contingent on a few extreme events which account for a very large portion of the total ENS (mainly), TLP and RT since 2002. In addition, no test that determines if the differences found are statistically significant is known. We propose to observe single events rather than summing their reliability indicators in order to avoid results being outweighed by extreme values. Therefore, comparisons between the Empirical Cumulative Distribution Functions (ECDF) for each reliability indicator between the two groups are performed. In addition, these comparisons are supported by the Kolmogorov–Smirnov (KS) statistical test.

Fig. 7 compares the ECDF for the ENS indicator between the two network groups. For the more interconnected grids, ENS is systematically lower. However, if the largest event (the 2003 Italian blackout previously mentioned) is not taken into account, the plot would not show the last step of the grey line (less interconnected group) and the ENS share (shown in Fig. 5) would change drastically, which suggests that the less interconnected grids show lower ENS. Fig. 7, however, shows how along the whole plot, the line representing the more interconnected grids is always behind, giving a lower ENS. In addition, the KS test gives a p-value in the order of 10^{-15} proving that the difference represented in Fig. 7 is statistically significant.

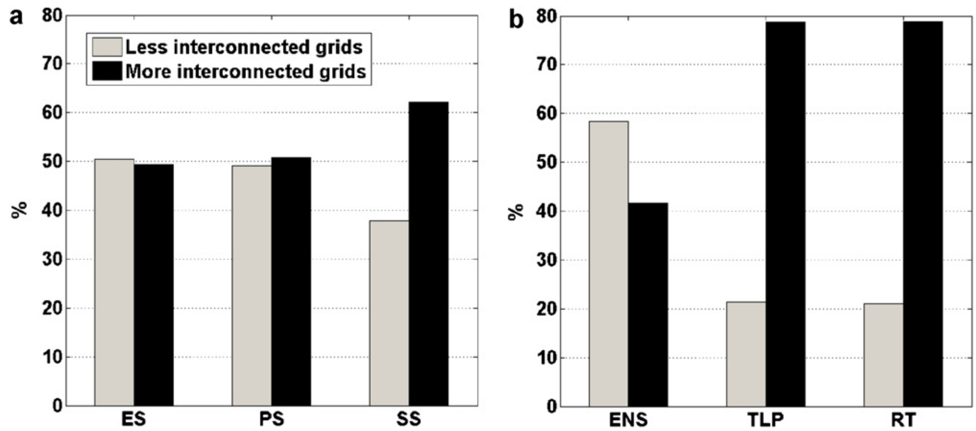

Fig. 5. (a) Topology vs. power grid characteristics. Energy share (ES), power share (PS) and size share (SS). (b) Topology vs. reliability indicators. Energy not supplied (ENS), total loss of power (TLP) and restoration time (RT). Less interconnected countries: AT, BE, NL, DE, IT, RO, GR. More interconnected countries: PT, PL, SK, CH, CZ, FR, HU, ES.

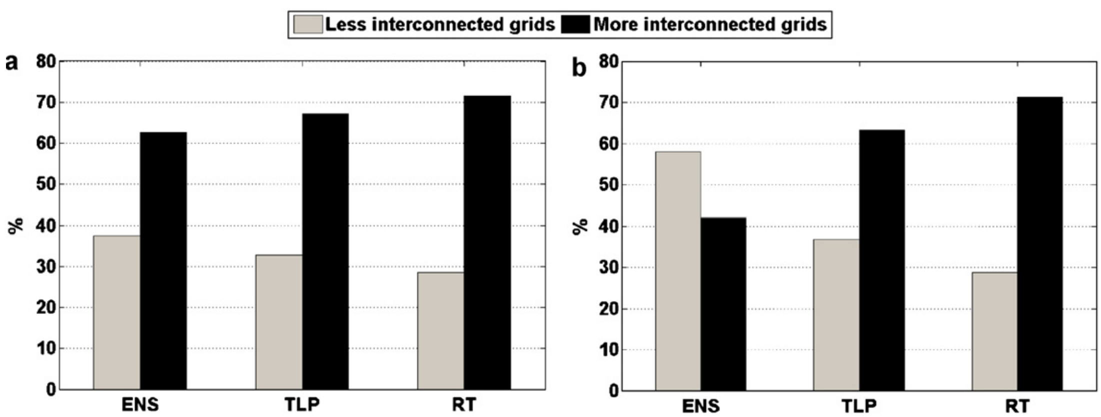

Fig. 6. The Italian 2003 blackout example. (a) Without Italian 2003 blackout. (b) With Italian 2003 blackout.

The same approach is used to compare the TLP and RT indicators between the two groups. Figs. 8 and 9 compare the ECDF for the TLP and RT respectively for the two network groups. The KS test gives statistically significant *p*-values, in the order of 10^{-11} and 10^{-7} respectively. The two plots show very similar results. The TLP and RT shares are much larger (80%) for the more interconnected group (Fig. 5), however the ECDF plots show how for the majority of the events the more interconnected group has lower TLP and RT values. At higher TLP and RT values, the two lines cross each other. The higher TLP and RT shares for the more interconnected group are mainly given by the fact that it experiences more fault events, especially in the range of larger TLP and RT values.

Due to the limited data availability on past fault events in European power grids and the complex and stochastic nature of such events, including very few extreme cases, it is difficult to identify a firm relationship between the interconnectivity of a power grid and its reliability, particularly if the shares of the reliability indicators' sums are used as means of comparison. Results show that the more interconnected grids experience 80% of the total number of events. In spite of this, the comparisons of the ECDF for the

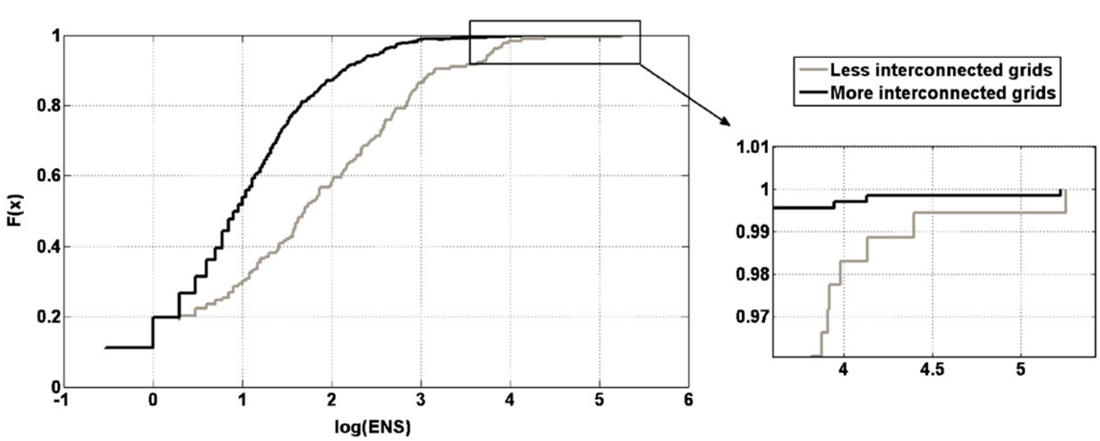

Fig. 7. ECDF of ENS indicator for less and more interconnected grids.

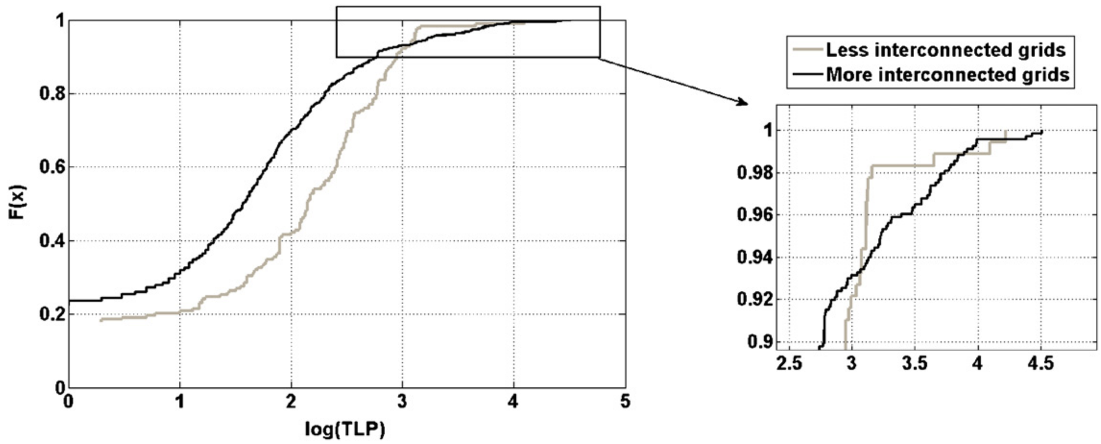

Fig. 8. ECDF of TLP indicator for less and more interconnected grids.

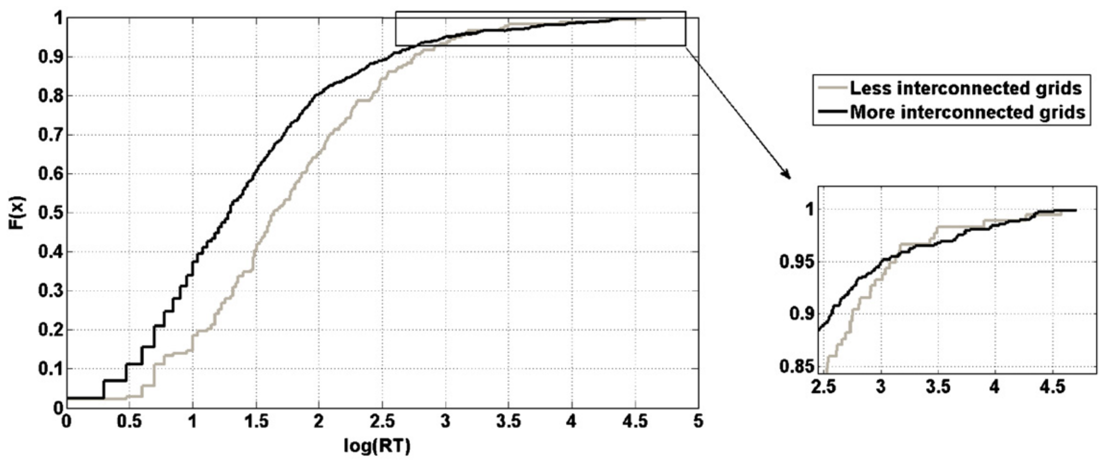

Fig. 9. ECDF of RT indicator for less and more interconnected grids.

three reliability indicators between less and more interconnected groups show that more interconnected European power grids have systematically lower ENS, TLP and RT. This outcome partly corresponds with the common security standard ($n - 1$) which is more easily met with higher interconnectivity.

It is important to mention that, as already shown in the literature [6,13], the distribution functions of the three reliability indicators are fat-tailed. In addition, the tails of the network groups' distributions for the three indicators cross each other. The two latter statements support the sensitivity of the analysis to rare extreme events, mainly when comparing the relative share of the indicators' sums.

The results presented throughout the paper are based on the topological grid data for a single time point. The fact that the grid has evolved over time should have some influence on our analysis. However, this influence of the topological evolution on the results has been neglected because data about topological evolution was not available.

5. Conclusions and future work

ENTSOE and the former UCTE provide reliability indicators (energy not supplied, total loss of power and restoration time) for each major fault events in the European electricity transmission network from January 2002 through March 2011. The two goals of this paper were to assess the usefulness of these indicators and to gain a better understanding of the impact of network topology upon transmission network reliability.

We have shown that comparing the sums of the indicators for groups of countries with less and more interconnection is not a robust statistical tool. Instead, we propose to compare the Empirical Cumulative Distribution Functions for each indicator with the support of the Kolmogorov–Smirnov test. The fat tails of the distributions of the reliability indicators indicate the sensitivity of the analysis to rare extreme events. We conclude that transmission grid reliability indicators must be used carefully. Rare, extreme events can account for a very large portion of the total energy not supplied, total loss of power or restoration time.

We observe that more interconnected European power grids have experienced four times as many fault events as the less interconnected ones. On the other hand, they show significantly better values for all of the three reliability indicators for the largest portion of their distributions. This means that the majority of these fault events in more interconnected networks have a smaller impact on reliability than the fault events in less interconnected networks.

These results confirm the conventional wisdom that more interconnected networks are more reliable. However, it is interesting that the higher reliability is not a consequence of fewer faults, but of the smaller consequences of most faults. From the available data, it cannot be concluded why the number of faults is not lower in more interconnected networks, as it only contains key performance indicators and a basic description of the causes. Future work is needed to study the temporal evolution of power grid topology and its relationship with network reliability.

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