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Bayesian assessment of electrical power transmission grid outage risk

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ABSTRACT

Lack of unified risk assessment approach to electrical power transmission grid outages when taking into account uncertain data is addressed in this paper. Authors take on Bayesian approach to analyse statistical data of electric grid outages – this enables to achieve a more coherent way to express uncertainty in data and to obtain reliability related measures of the grid. The considered methodology of how to properly manage the statistical inference process is demonstrated through real outage data collected from North American transmission grid. The different cases of electrical power lines unreliability as well as cascading outages are addressed on various levels of complexity – starting from simple Bayesian assessment and then building a more general hierarchical Bayesian model. As a result, geography and environment related variability level is found to be of significant influence suggesting that unreliability of grid lines should in general be analysed having in mind specificity of each line. In addition, such variability highly influences the reliability of the whole grid or any network, as demonstrated in the paper as well. Considering the case of cascading outages, we obtained a hierarchical model, built under the basis of Borel–Tanner distribution, and demonstrated the capability to simulate large blackouts, which has a non-negligible probability of occurrence, as the history of blackouts in the last decades has already demonstrated.

1. Introduction

Although the risk or unreliability assessment of grid or network is not something very recent, it still lacks a coherent probabilistic treatment of uncertain data and parameter estimates. Failure data of separate nodes or connecting lines typically are pooled in one sample neglecting all the variability due to difference in sources, and to worsen – raw estimates are plugged into obtain the overall assessment of network. Lynn et al. started to discuss it awhile ago [20], however, little efforts have been made to advance this matter.

Lynn et al. divided the state-of-the-art research of network reliability into those who compute reliability by combinatorial-like algorithms – assuming known failure probabilities but dealing with complex topologies, and those who apply statistical inference techniques to incorporate uncertainties of data sample but work with simple parallel and series configurations or some "easy" mixture of both. Extending the last case we would like to add another, more recent, trend – Complex Network Analysis (CNA), when the reliability of the grid is evaluated taking into account the topological relations between nodes and connecting lines. Nice survey of the look at power grid as a complex network can be found in a survey of Pagani and Aiello [25].

The result of such scientific community division is that complex networks typically are left without any proper treatment of uncertainty. Having this in mind, Lynn et al. developed a methodology of any network reliability assessment by joining pivotal decomposition [3] together with Bayesian inference.

Following this work, reliability assessment of networks functioning in random environments started to appear, mostly due to Özekici [24,23]. The main idea is that system functions within fluctuating weather conditions and the failure probability is conditioned on the state of the environment. Developed assessment methods allowed incorporating uncertainty due to different states of environment. However, the application areas were never extended to the power grids where various stochastic phenomena cause, e.g. random outages and cascades of outages.

Dobson did more fruitful work regarding power grid reliability, although just on the cascading outages matter [14,11]. He suggested to model cascades in transmission grid as a Galton–Watson branching processes [19]. Subsequent theoretical and practical works expanded this idea and analysed the behaviour of the branching propagation estimators [12,26,15]. Dobsons' and colleagues' work on transmission grid outages enriched the available literature of probabilistic risk assessment of power networks. Although there are some recent works that deal with uncertainty in power system data (see [16,9] where authors employ Bayesian approach to propagate uncertain states of systems to obtain importance ranking of individual system components), the uncertainty

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part in observed statistical reliability data somewhat was left out of the main framework, i.e. the uncertainty of cascade propagation rate estimates or uncertainty introduced by the variability between different cascades were not addressed.

The purpose and contribution of this paper is the advancement of aspects stated above. We seek a coherent probabilistic treatment of grid reliability parameters by "immersing" grid failure data into Bayesian framework – its ability to naturally handle uncertainty of data, to provide in form of probabilistic distributions all information about parameter estimates and possibility to deal with more complex models led to this choice. By analysing real data of North Americas electrical power transmission grid (Section 2.1) we go from simple analysis of lines outage rates to rates affected by heterogeneity of grid and the affecting environment (Section 2.2) and apply results to estimate reliability of arbitrary sub-configuration of the network (Section 2.3); and finally we go from cascading outages analysis to more complex case where cascading initiation and propagation intensities are assumed to vary across the cascades (Section 2.4). One of important results of the cascading outages analysis through the framework of hierarchical Bayesian models is the obtained evidences of non-negligible probability of large outages. The significant likelihood of sever outages have been already voiced in other works (see, e.g. [27,6]) and new improved deterministic techniques for rare large-scale outage probability estimations are starting to show up [28].

We refrain ourselves from describing the Markov Chain Monte Carlo methods which were used to implement Bayesian and hierarchical Bayesian methods applied in the analysis. Although it is interesting and at the same time not an easy task (especially in the last part of the paper were almost 1802 parameters were estimated), it is out of the scope of this paper and interested reader can found necessary information in our other papers [1] or textbooks of Gilks et al. [18] and Ntzoufras [22]. Also, we do not consider here power system reliability from point of view of power flow calculations, as this is already covered using non-Bayesian methods in other research papers. However, this area of research recently also faces with issue of uncertainty incorporation in the main picture as well; see for example work by Gallego and Padilha-Feltrin [17], where they incorporated uncertainty in electricity demand considering user connection and investigated how this is reflected in power flow calculations.

2. Bayesian analysis of transmission grid failure data

As already mentioned in the introduction, we will analyse the transmission grid in two aspects. The first one is the estimation of the unreliability of transmission grid lines. We will talk about how uncertain data and estimates of reliability of separate transmission lines can be propagated through the Bayesian inference framework to obtain reliability of arbitrarily chosen subset of North American electric transmission grid. The second aspect that we will consider is Bayesian analysis of cascading outages and what are possible ways to account for differences and uncertainty present in cascading phenomena.

2.1. Transmission grid outage data description

The data, that is analysed in subsequent sections, where obtained from Bonneville Power Administration (BPA) public database [5] that contains information about the outages, timings and causes of them. The considered transmission grid spans over the areas of California, Oregon, Idaho, Montana and Washington.

Since our research does not seek of full investigation of this particular power grid, we have confined ourselves with electrical power transmission grid of 500 kV lines. Time span of outage events is 11 years and involves 3179 events (non-planed outages) produced by 97 transmission lines (distribution of frequencies of outages for each line is presented in Fig. 1). At this stage of research we have discarded the consideration of causes of the outages in order to lay grounds for more robust Bayesian treatment of the outage phenomena. We will model these events as coming from Poisson distribution.

In order to investigate the cascades of the outages we have grouped the data into different cascades and into different stages of each cascade according to the rules used for cascading events in electric power transmission systems [10] – successive outages separated by more than an hour belong to different cascade and outages in a given cascade separated by time more than a minute belongs to different stages. There were 1799 cascades, of which 327 had more than one stage (Table 1).

2.2. Bayesian analysis of separate line outage

The number of outages can be modelled by the Poisson distribution. In this section we will perform analysis and calibration of the various modifications of simple Poissonian model.

Suppose that the data is described by the triplet $(X_i, L_i, t_i)_{i=\overline{1,N}}$, where X_i is the number of outages collected over the period t_i for the ith line with length L_i when the number of lines is N. According to these notations, the model can be expressed as follows:

$$X_i|\lambda \sim \text{Poisson}(\Delta t_i L_i \lambda), \quad i = \overline{1,N};$$

where λ denotes the intensity of outage events of transmission grid.

In order to have a full Bayesian model, initially we may chose improper prior distribution for intensity:

$$\pi(\lambda) \propto 1_{(0,+\infty)}.$$

Resulting posterior distribution is a gamma distribution:

$$\lambda|X \sim \text{Gamma}\left(\sum X_i + 1, \sum L_i \Delta t_i\right).$$

This distribution summarizes all the information about parameter λ necessary to make inference. Expected value and standard deviation are 0.00215 and 4.73e−05 accordingly. No normality assumptions are required (as in maximum likelihood estimation) in order to obtain confidence interval, which in this case is

$$Pr[0.00205 \leqslant \lambda \leqslant 0.00224] = 0.95.$$

This model, although is very simple and straightforward to analyse, as assumes that all lines produces outages with the same intensity. But this assumption could be misleading, since the

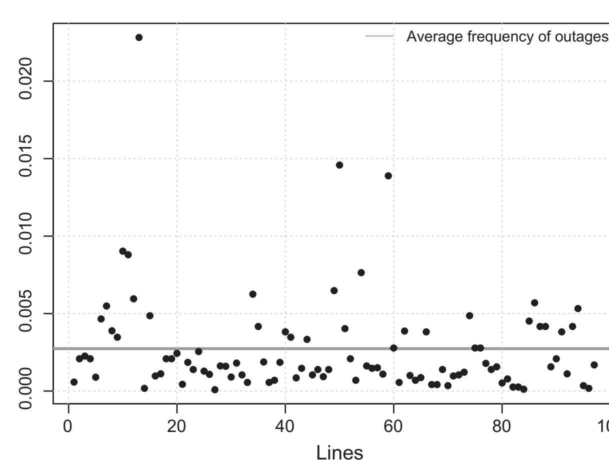

Fig. 1. Outage frequencies for each transmission line compared to overall average frequency.