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A power-flow emulator approach for resilience assessment of repairable power grids subject to weather-induced failures and data deficiency

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HIGHLIGHTS

- Weather extreme conditions affect power grid failures/repairs and data is scarce.
- A stochastic resilience framework is proposed for assess the weather-grid interaction.
- A power-flow emulator is constructed to reduce the computational cost.
- Imprecise probabilistic methodology is used to tackle lack of data issues.
- Most relevant weather-grid factors are identified by the global sensitivity analysis.

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ABSTRACT

A generalised uncertainty quantification framework for resilience assessment of weather-coupled, repairable power grids is presented. The framework can be used to efficiently quantify both epistemic and aleatory uncertainty affecting grid-related and weather-related factors. The power grid simulator has been specifically designed to model interactions between severe weather conditions and grid dynamic states and behaviours, such as weather-induced failures or delays in components replacements. A resilience index is computed by adopting a novel algorithm which exploits a vectorised emulator of the power-flow solver to reduce the computational efforts. The resilience stochastic modelling framework is embedded into a non-intrusive generalised stochastic framework, which enables the analyst to quantify the effect of parameters imprecision. A modified version of the IEEE 24 nodes reliability test system has been used as representative case study. The surrogate-based model and the Power-Flow-based model are compared, and the results show similar accuracy but enhanced efficiency of the former. Global sensitivity of the resilience index to increasing imprecision in parameters of the probabilistic model has been analysed. The relevance of specific weather/grid uncertain factors is highlighted by global sensitivity analysis and the importance of dealing with imprecision in the information clearly emerges.

1. Introduction

The power grid is the largest man-made critical infrastructure and is extremely complex in both its operations and structure. The weather conditions drifting towards extremes and the increasing use of renewable energy sources are tightening the interactions between power network states and the external environment. Reliability/availability analysis frameworks have, then, to incorporate weather models and consider interactions between grid states and environmental states, accounting for relevant sources of randomness (i.e. aleatory uncertainty) but also for parameters values imprecision (i.e. epistemic uncertainty).

Power network reliability is a well-defined mathematical concept [1]. Many frameworks for reliability assessment have been proposed in the past, which generally focus on known threats such as $N-1$ or $N-2$ failures paradigms [2] or on a predefined contingency set [3,4]. System resilience broadens the reliability concept by accounting for low-probability-high-consequence events (such as severe weather conditions [5]) and recovery process of the system. A generally accepted definition of resilience still has to be formulated, an example being '*the network ability to withstand high impact low probability events, rapidly recovering and improving operations and structures to mitigate the impact of*

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similar events in the future' [6,7]. It can be argued that a main difference between a reliable power grid and a resilient power grid is that, in the latter, low-probability-high-consequence events (e.g. extreme weather events) are specifically considered and handled, with the ability to learn from past occurrences. To achieve this, a comprehensive analysis of the relevant sources of uncertainty should be performed. In particular, lack of data is generally affecting low probability events. To improve overall robustness of the analysis, it is uttermost important to develop and improve frameworks capable of tackling (effectively and efficiently) data deficiency issues. A rigorous quantification of the lack of data affecting extreme low-probability-high-consequence events is necessary.

In the last years, many studies have focused on analysing the effect of extreme weather events on the power grid risk and reliability. Some research was carried out with the support of international organizations [8]; other focused on different extreme events such as floods, ice storms, strong wind gusts and more [6,8–13]. More recently, Cadini, Zio and Agliardi [9] proposed a probabilistic reliability/availability assessment framework extended from Ref.[12]. The framework incorporates a sampler of severe weather conditions and models weather-induced effects on the grid's components failures and replacements. One of the challenges for the application of the framework is the high computational cost. This is mainly attributable to the number of calls to the cascading failure model (i.e. the power-flow solver): '*…analysis of a more realistic grid is probably still feasible, although more complex analyses, e.g. including uncertainty and sensitivity analyses or optimizations, would require either to resort to processor clusters, or to identify strategies for accelerating the computations, possibly based on the use of surrogate, approximating models*' [9].

In general, the time needed to compute the load curtailed can be quite small (e.g. that of a single optimal power flow evaluation); this is especially true if the power network size is modest. Unfortunately, optimisation problems cannot be vectorised and power flows have to be solved one-at-a-time. Consequently, any analysis for which a large number of power flow evaluations are needed may result computationally untreatable. Examples of such costly analysis are global sensitivity analysis [14], cascading failures analysis [9], or imprecise (generalised) uncertainty quantification analysis [15]. To perform such computationally demanding analysis, a significant reduction in the computational complexity (while reducing marginal accuracy) is needed and emulators can be adequate for this aim. A surrogate model, also known as emulator or meta-model, is a numerically cheap mathematical approximation of a computationally expensive realistic model [16]. Some examples of popular meta-models are Artificial Neural Networks [17,18], Poly-Harmonic Splines [19] and Kriging models [20]. Surrogates have been extensively applied to reduce time expenses of numerically burdensome models and few works have attempted to use meta-models to analyse power grids, see for instance [21–26]. Amjady et al. [23] proposed an emulator to assess the power system reliability providing as input forced outage rates. Silva et al. employed artificial neural networks to monitor voltage magnitudes [24]. Chen et al. [25] adopted a surrogate-based strategy for optimal power flow inequality constraints aggregation. To the Authors knowledge, none of the reviewed papers attempted to mimic the relationship between the grid components state vector, load profile and power load curtailed within a resiliency assessment framework.

Probabilistic reliability assessments of power grids are traditionally carried out with reference to a well-defined probabilistic characterisation of the uncertain output, whose calculation generally requires a large body of empirical information. A sufficient amount of samples are necessary to properly estimate the underlying probability distributions parameters and often, due to technological limits or time/cost constraints, the available data is not sufficient for accurately estimating all relevant parameters [27]. In those situations, expert assumptions are made on the probabilistic model, which can lead to erroneous conclusions, overestimation of the system performance and a false sense of confidence [28]. Data scarcity often affects the analysis of power grid resilience and safety [29]. In fact, consider the highly reliable components (e.g. transformers, underground cables, etc.) of which power grids are made. Those components will likely fail only a few times during their life span (or possibly even never). The lack of statistical failure data makes it difficult to characterise the failure behaviour of these components with confidence. In this situation, a common practice is to estimate the failure rates of the components by considering the few available failure occurrences in similar components. This procedure, so-called "data pooling" [27], assumes similar elements behave as described by the same probabilistic model. This is a rational assumption, but when (similar) components operate differently (e.g. close/far from their thermal limits or in harsh/mild environments) or undergo different maintenance/repairing policies, such assumption is rarely true. In practice, different factors influence the components, leading to different failure behaviours even for identical components. In those situations, it is advisable to relax the assumption of a precise probabilistic model, for instance, by accounting for imprecision in the distribution parameters (e.g. in the estimation of components failure rates and events occurrence rates) [28,31]. Generally speaking, a set of plausible distribution families can be considered for describing imprecision (for instance, an envelope of Weibull, Exponential, Normal, etc. CDFs modelled using a non-parametric P-box). However, dealing with several distribution families was not the aim of this work. In this research, the parameters of the probability distribution families (e.g. used to sample the high wind event duration and intensity) and of the components of the grid-weather model are assumed affected by an increasing level of imprecision.

In this paper, a generalised framework is proposed for (imprecise) probabilistic resilience assessment of power networks. The framework has been designed to capture complex coupling between weather conditions and power grid operations, by incorporating weather-influenced failures and repairs of the grid's components. An Artificial Neural Network (ANN) is trained to emulate the total load curtailed given specific lines failures and the load profile, and has been embedded within the framework to increase computational efficiency. Comparison between the novel surrogate-based framework and the original solver shows significant improvement in efficiency at the expense of a small reduction in accuracy. Aleatory uncertainty is accounted for and epistemic uncertainty is associated with imprecision and lack of knowledge. Both types of uncertainty are propagated by generalised probabilistic methods based on Credal sets and Fuzzy sets. The sensitivity of the resilience index to parameters imprecision is quantified. Aleatory uncertainty propagation and generalised uncertainty propagation (i.e. accounting also for imprecision) are performed and the ANN capabilities tested against the full power-flow. The results again show that the use of the ANN meta-model allows advanced sensitivity analysis to be performed on the parameters of the probabilistic model at the expense of a small reduction in accuracy but with a significant gain in computational time.

The rest of the paper is organised as follows. Section 2 introduces the probabilistic model for coupling weather conditions and grid states. The emulator is presented in Section 3. Section 4 presents the overall modelling and computational framework. In Section 5 the generalised probabilistic framework based on Credal sets is described. The case study and results are presented in Section 6. Section 7 presents a discussion of the findings from an applicative perspective and Section 8 closes the paper.

2. A probabilistic model for weather-grid coupling

A power grid topology can be represented by a graph $\mathscr{G}(\mathscr{N},\mathscr{E})$, where i denotes a node within the node set $\mathscr{N}$ and (i,j) the link between node i and j in the line set $\mathscr{E}$ [31–34]. Denote with N_L the number of loads, with N_l the number of lines and with N_g the number of generators in $\mathscr{G}$.

Optimal-Power-Flow (OPF) methods can used to solve the network