



# A modeling and simulation framework for the reliability/availability assessment of a power transmission grid subject to cascading failures under extreme weather conditions



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## HIGHLIGHTS

- We combine stochastic extreme weather model and realistic power grid fault dynamics.
- We introduce a novel restoration model accounting for the weather conditions.
- The complete model is quantified by means of a customized sequential Monte Carlo.
- Reliability/availability indicators show importance of rare extreme weather events.

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## ABSTRACT

Electrical power transmission networks of many developed countries are undergoing deep transformations aimed at (i) facing the challenge offered by the stochastically fluctuating power contributions due to the continuously growing connections of renewable power generating units and (ii) decreasing their vulnerability to failures or malicious attacks and improving their resilience, in order to provide more reliable services, thus increasing both safety and profits. In this complex context, one of the major concerns is that related to the potentially catastrophic consequences of cascading failures triggered by rare and difficult to predict extreme weather events. In this work, we originally propose to combine an extreme weather stochastic model of literature to a realistic cascading failure simulator based on a direct current (DC) power flow approximation and a proportional re-dispatch strategy. The description of the dynamics of the network is completed by the introduction of a novel restoration model accounting for the operating conditions that a repair crew may encounter during an extreme weather event. The resulting model is solved by a customized sequential Monte Carlo scheme in order to quantify the impact of extreme weather events on the reliability/availability performances of the power grid. The approach is demonstrated with reference to the test case of the IEEE14 power transmission network.

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## 1. Introduction

Electric energy has an impact on all modern life activities. Consequently, the public expectation for reliable electric energy delivery has significantly grown in the past decades. For this, the so-called power grids, i.e., the interconnected systems that transmit electric power from where it is generated to where it is consumed, play a fundamental role. Thus, it comes with no surprise that the assessment of the risk of failures of these infrastructures

and the study of strategies for the mitigation of the consequences have gained increased attention. However, these tasks are difficult because of the inherent complexities of the power transmission networks, the complex physical laws governing the power flow dynamics and the uncertainties affecting the boundary conditions (operational and environmental) in which they operate. Additional difficulties come from the evolution of society and energy markets, that demand changes and adaptations of the large-scale power transmission infrastructures for continuing to satisfy the requirements of reliability/availability under the continuous increase in electric power demand, avoiding congestions and overloads, so as to improve safety and increase economic margins. In addition,

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power transmission systems can no longer be considered solely as a means for energy delivery; rather, they are operated as an electricity market trading platform for shifting power volumes across different regions or even different countries, for economic reasons.

Furthermore, in recent years we have witnessed an exponential growth in the connection of renewable power generating units (photovoltaic power plants, wind farms, biomass plants, etc.) and poly-generation systems (electrical power, heat and cooling), which add even more complexity to the system. In fact, such connections were obviously not planned in the initial design of the power networks, which now need to adapt to accommodate their fluctuating power contributions, difficult to predict and geographically distributed [1].

In this new setting, concerns come for the protection from failures and attacks, and their possible cascading effects, i.e., the propagation of disconnections of components from the grid due to the power flows redistribution (manually or automatically) following the initial failure or attack. Cascading failures may lead to catastrophic disconnections of wide portions of the power transmission networks, as epitomized by several large-scale blackouts occurred in developed countries in the recent years, such as for example the blackout in Italy on September, 28 2003 [2], that in the United States and Canada on August 14, 2003 [3] or that in Europe on November, 6 2006 [4].

Normally, a power transmission network is designed and operated so that a single component disconnection does not give rise to any load shedding, so that cascading failures do not occur ( $N - 1$  criterion [2]); however, rare combinations of circumstances, uncommon events or inadequate countermeasures may result in further line disconnections, eventually leading to disruptive consequences. In fact, the operative conditions at a given time are determined by many, usually correlated factors, such as power demand, generating capacity, economic optimizations, technical limits and environmental conditions. Some of these factors are defined as operative limits or determined by technical-economical optimizations (e.g., the power generation) and, as such, they are more predictable. Others, such as the power demand and the environmental conditions, are uncertain by nature and many efforts are, thus, devoted to quantify the effects of these uncertainties on the power production and transportation capabilities, like, for example in [5] and [6], where the fluctuations of the power demand and of a specific environmental feature, i.e. the wind speed, are taken into account, respectively.

Furthermore, human errors, intentional attacks or extremely severe natural contingencies, such as earthquakes, volcanic eruptions and weather related events (floodings, wind storms, lightning, icing, heat and cold waves, etc.), may even directly fail the components of the network [7].

In this context, we address the problem of quantifying the reliability/availability of a transmission grid specifically with respect to the occurrence of extreme weather events, which have been identified as major threats to the operation of power networks [8]. Indeed, the decision making process of the grid designers and operators should be driven by the results of cost-benefit analyses, accounting for the reliability/availability of the system and the costs required to design, build and operate it. Proper assessment of the transmission grid reliability/availability allows informed decisions on grid design and operation by the players involved in the utility management upon. Also, reliability/availability analysis is a key factor for supporting the power quality regulation of transmission grids in many developed countries.

The problem addressed is twofold: first, a realistic, possibly stochastic, model of the extreme weather event occurrences must be developed and its parameters properly identified on the basis of available weather statistics; then, this model is coupled with realistic transmission grid dynamic models for the computation of the

network performances in presence of failures triggered by the extreme weather events.

With regards to extreme weather event modeling for power grids reliability/availability estimation, the common approach is that of resorting to the “two-state” model [9], or to its improved, “three-state” version [10], where the weather conditions are divided into two or three classes, normal, adverse and, in case of three state models, major disaster, and the stochastic transitions among the different classes are modeled as homogeneous Poisson processes with constant transition rates, to be estimated from weather data.

The major drawbacks of these approaches are that (i) they are not flexible enough to represent the wide range of possible weather events types and intensity levels and (ii) their rates of occurrence are, in general, dependent on time, due to their typically seasonal behaviors. Significant advances towards a more realistic modeling of the impact of weather events on power networks reliability/availability is proposed in [11] and further extended in [16]. In those works, non-homogeneous Poisson distributions of the occurrence times and suitable distributions of the events intensities are derived on the basis of available weather statistics; furthermore, the failure rates of the networks’ lines are mathematically related to the times of occurrence and the intensities of the weather events considered, following the approaches proposed in previous works of literature. In fact, it is recognized that the failure rates of the grid’s components, typically taken constant, are actually significantly increased by the occurrence of severe weather events. For example, quadratic and exponential models are introduced in [12] and [13], respectively, to describe the overhead line failure rates as functions of the wind speed; a linear model is presented in [14] to model the relationship between the number of line interruptions and that of lightning flashes; the combined effect of high winds and lightning, possibly occurring during severe storms, on the grid components failure rates are analyzed in [15]. The resulting model is then solved by means of a sequential Monte Carlo scheme simulating the annual “lives” of the power grid subject to the weather events.

The approaches illustrated above, however, have been only applied either to very simple, representative power grids with few components [10] or to power distribution grids (e.g., a the Swedish rural reliability test system in [16] or an actual distribution system in the Northeast US in [17]). Limited research efforts have been made in developing ways for performing weather-related reliability/availability analyses on power transmission network models including realistic representations of cascading failure phenomena. For example, in [18] simple stochastic models representing the occurrences of extreme weather events are coupled to grid cascading failure models, where the network reliability is abstractly quantified with respect to the existence of connecting paths between grid nodes; however, the realistic electrical behavior of the networks are not taken into account.

In this work, we originally propose to resort to the stochastic model for representing the uncertainties related to extreme weather events introduced in [16] and further developed in [11], and to combine it to a realistic cascading failure simulation model based on a MATLAB-based DC power flow approximation of a power transmission network [19] and a proportional re-dispatch strategy [20]. Furthermore, in order to offer an even more realistic description of the power grid dynamics in response to extreme weather events, we develop an original restoration model based on the definition of suitable repair “velocities” correlated to the occurrence of the different events.

The complexity of the resulting model is such that its resolution for the estimation of the system reliability/availability indices is not easy. We, then, develop a customized, sequential Monte Carlo simulation scheme, where several annual histories of power

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