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Assessing Power Grid Reliability Using Rare Event Simulation

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Renewable energy generators such as wind turbines and solar panels supply more and more power in modern electrical grids. Although the transition to a sustainable power supply is desirable, considerable implementation of distributed and intermittent generators may strain the power grid.

First, most renewable sources have an uncertain generation pattern: predicting the amount of generation of a wind turbine or solar panel can be very challenging. Therefore, implementation of many renewable energy generators in a power grid increases the risks of connection overloads and voltage deviations. Grid operators may have to curtail power to prevent violation of grid stability constraints. These events are obviously undesirable, especially as modern societies have grown accustomed to a very reliable power grid. econd, since many renewable generators are distributed over the power grid, the generation of power is decentralized instead of operating in a 'top-down' fashion. For this reason it is in general not clear what typical combinations of generation and consumption patterns - or stated more general, power injection patterns - will lead to a violation of stability constraints.

Since grid operators are responsible for a highly reliable power grid, they want to estimate to what extent these constraint violations occur. To assess grid reliability over a period of interest, various reliability indices exist. The main challenge of this research is to develop reliability assessment methods for a power grid given the uncertainty of power injections.

Deterministic methods for power flow analyses are well-established in the power system community. Many power flow analyses employ the steady state AC power flow equations. These equations form a nonlinear algebraic system relating the power injections at all nodes to the nodal voltages and other variables that determine if the grid is stable. We model the power injections as stochastic processes to account for their uncertainty. At each time step the mapping from the state of these processes to the occurrence of a constraint violation requires solving the nonlinear system. Since this solution is only defined implicitly, we can not derive the reliability indices directly and we estimate them by a Monte Carlo simulation.

We illustrate the feasibility of Monte Carlo reliability estimation of a stochastic power flow model with wind power modeled as an autoregressive-moving-average (ARMA) model. Instead of enforcing current constraints on connections, short-term current overloading is allowed by enforcing the more realistic temperature constraints. We show that - especially when intermittent power constitutes a significant part of the power supply - a model allowing for temporary current overloading may save costs by avoiding over-investments.

Power curtailments are typically rare in modern power grids. Using conventional Monte Carlo or Crude Monte Carlo (CMC) simulation for grid reliability estimation may therefore require a prohibitively large number of samples to achieve a sufficient level of accuracy. Over the last decades, rare event simulation techniques have been developed to reduce the variance of estimators for very small probabilities. This research area is an established methodology in molecular biology, telecommunications and finance, but in power systems applications have emerged only recently and in limited number. Splitting and importance sampling are the two main categories of rare event simulation. In this thesis we extend a Crude Monte Carlo (CMC) method with a splitting technique to efficiently compute unbiased estimators for several indices.

Splitting techniques replicate sample paths whenever the rare event is presumed considerably more likely given the current chain state. Crucial for a significant variance reduction of the estimator is choosing a suitable importance function. This function ideally maps each system state to the probability that a sample path starting from that state will hit the rare event set. In an example of a small power grid, splitting estimation with a heuristically chosen importance function already requires orders of magnitude less workload than CMC estimation to obtain a fixed accuracy.

However, a heuristically chosen importance function may replicate sample paths that are relatively unlikely to hit the rare event set, especially in case of many stochastic processes. In this case the variance of the estimator is hardly reduced - it may in fact have become larger than the variance of a CMC estimator. In power grid reliability analyses with many distributed uncertain power injections this is a substantial problem as it is not clear a priori what multidimensional sample path will typically lead to rare event occurrences. Specifically, we address this problem of heuristically choosing an importance function for a disconnected rare event set.

Asymptotic results from large deviations theory give an insight into the typical path to the rare event set. These results also yield an approximation of the rare event probability starting from a specified system state. We construct an importance function based on these results to compute splitting estimates for connection overload probabilities in a power grid. Experiments show that for a fixed accuracy the splitting technique based on large deviations computationally outperforms CMC estimators by orders of magnitude. The computational gain remains of similar size even for a larger number of stochastic processes.

In an example we compare the performance of this importance function to that of a heuristically chosen importance function based on the Euclidean distance to the rare event set. This example showed that heuristic splitting - unlike large deviations based splitting - requires even more workload than CMC simulation to obtain a fixed accuracy of probability estimates. This clearly illustrates that accelerating Monte Carlo simulation by using a splitting technique requires a carefully chosen importance function.