

Data-Driven Estimation of Failure Probabilities in Correlated Structure-Preserving Stochastic Power System Models

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Abstract—We propose a data-driven approach for propagating uncertainty in stochastic power grid simulations and apply it to the estimation of transmission line failure probabilities. A reduced-order equation governing the evolution of the observed line energy probability density function is derived from the Fokker-Planck equation of the full-order continuous Markov process. Our method consists of estimates produced by numerically integrating this reduced-order equation. Numerical experiments for scalar- and vector-valued energy functions are conducted using the classical multimachine model under spatiotemporally correlated noise perturbation. The method demonstrates a more sample-efficient approach for computing probabilities of tail events when compared with kernel density estimation. Moreover, it produces vastly more accurate estimates of joint event occurrence when compared with independent models.

Index Terms—uncertainty quantification, stochastic differential equations, power system dynamics, reduced-order models

I. INTRODUCTION

Recent blackout events and fires caused by power lines have continued to raise awareness of the need for designing robust circuit systems and devising mitigation strategies when catastrophic events occur [11]. Uncertainties in peak power demands, operative states of components, load, and seasonal factors contribute to considerable difficulties in modeling line failures [4], [18].

Failure events are typically studied through traversal/clustering of time-dependent graphs [27] or by solving differential systems that incorporate transient/line-removal dynamics [5]. Particularly for large cases, the first class of approaches is restricted to predicting local behavior that may not yield accurate results corresponding to real-world observations [8]. On the other hand, extensive simulations are needed in order to obtain statistical information of failure distributions as tail events, making the dynamical systems approach computationally intensive. In this work, we build upon the systematic approach of [17] to incorporate uncertainty in a structure-preserving dynamics model by including the Ornstein-Uhlenbeck (OU) process as load stochastic fluctuations. In the absence of

approximations, resolving the full probability profile of all random states suffers from the curse of dimensionality. Although reduction methods such as the method of moments (MoM) [13] and Karhunen-Loève (KL) expansions [20] exist, they are known to underperform standard Monte Carlo simulations and kernel density estimation (KDE) for realistic power system models. In particular, the MoM requires state data to be nearly Gaussian, while KL expansions degrade when the noise input exhibits a short correlation time scale [14].

To address this need, instead of approximating the full joint probability density, we exploit the fact that in the model of [17] the probability of failure of a transmission line depends on a scalar function that can be efficiently evaluated. Subsequently, we directly propagate its probability density function (PDF) by expressing it as a solution of a low-dimensional partial differential equation (PDE) that we solve numerically. This reduced-order formulation allows us to simultaneously consider the joint density of multiple transmission lines, whose conditional probabilistic structure is typically difficult to simulate using kinetic Monte Carlo methods [22]. Furthermore, the method is data-driven, where measurements from system states can be incorporated into estimating unknown terms in the PDE using regression methods. The resulting PDE is a linear equation that is readily solved with standard finite volume schemes, with comparable accuracy to plug-in Gaussian KDE, while using significantly fewer samples from the law of the underlying stochastic process. We also note that the previous approach in [22], while being more sample-efficient, computed only the large deviation (low-temperature limit) approximation of the failure probability whereas this approach with enough samples will converge to the true probability of failure.

The paper is organized as follows. Section II introduces the general power system model along with the correlated noise process, which is jointly considered as a diffusion process admitting a Fokker-Planck equation (FPE). In Section III we discuss the derivation of the reduced-order equation by integrating over extraneous variables in the FPE, allowing one to formulate the density of arbitrary quantities of interest. In addition, we discuss estimation of unknown terms in the PDE as a regression problem. Effectiveness of the method is tested in Section IV on the classical multimachine model with an emphasis on use cases of computing tail event probabilities

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Managing Dynamic Contexts Using Failure Driven Stochastic

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