

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

Luca Podofillini, Bruno Sudret, Bozidar Stojadinovic, Enrico Zio, Wolfgang Kröger

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Polystochastic Models for Complexity Octavian Iordache, 2010-03-20 Complexity understanding and management will be a main source of efficiency and prosperity for the next decades and thus is of highest industrial and scientific interest This book on the latest in polystochastic models for complexity includes case studies

Data-Driven Energy Management and Tariff Optimization in Power Systems Hamidreza Arasteh, Pierluigi Siano, Niki Moslemi, Josep M. Guerrero, 2025-10-27 Presents a comprehensive guide to transforming power systems through data Data Driven Energy Management and Tariff Optimization in Power Systems offers an authoritative examination of how data science is reshaping the energy landscape As the electricity sector grapples with increasing complexity this timely volume responds to a growing demand for adaptive strategies that enable accurate forecasting intelligent tariff design and optimized resource allocation underpinned by advanced analytics and machine learning Drawing on global expertise and real world case studies the book bridges the theoretical and practical dimensions of energy systems management providing deep insight into how data collected from smart meters SCADA systems and IoT devices can be mined for predictive modeling demand response and peak load management The book's accessible structure and didactic approach make it suitable for a wide readership while its breadth of topics ensures relevance across the spectrum of energy challenges Integrating rigorous analysis with application oriented strategies this book Presents advanced techniques in machine learning predictive modeling and pattern recognition tailored to energy management and tariff design Provides accessible explanations of complex algorithms through a didactic and visual teaching style including informative tables and illustrations Highlights tools for grid stability demand forecasting and peak load management using high resolution energy data Addresses the integration of renewable energy sources into existing infrastructures through data driven optimization Designed for a broad audience Data Driven Energy Management and Tariff Optimization in Power Systems is ideal for upper level undergraduate and graduate courses in energy management power systems analytics and smart grids as part of electrical engineering or energy policy programs It is also an essential reference for power system engineers energy analysts researchers and policymakers involved in grid planning and optimization

Advances in Safety, Reliability and Risk Management Christophe Berenguer, Antoine Grall, Carlos Guedes Soares, 2011-08-31 Advances in Safety Reliability and Risk Management contains the papers presented at the 20th European Safety and Reliability ESREL 2011 annual conference in Troyes France in September 2011 The book covers a wide range of topics including Accident and Incident Investigation Bayesian methods Crisis and Emergency Management Decision Making under Risk Dynamic Reliability Fault Diagnosis Prognosis and System Health Management Fault Tolerant Control and Systems Human Factors and Human Reliability Maintenance Modelling and Optimisation Mathematical Methods in Reliability and Safety Occupational Safety Quantitative Risk Assessment Reliability and Safety Data Collection and Analysis Risk and Hazard Analysis Risk Governance Risk Management Safety Culture and Risk Perception Structural Reliability and

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Modeling and Management of Resources under Uncertainty Thomas L. Vincent, Yosef Cohen, Walter J. Grantham, Geoffrey P. Kirkwood, Jan M. Skowronski, 2013-03-08 This volume contains the proceedings of the second U S Australia workshop on Renewable Resource Management held at the East West Center Honolulu Hawaii December 9-12 1985 The workshop was jointly sponsored by the National Science Foundation USA and the Department of Science and Technology Australia under the U S Australia Cooperative Science Program The objective of the workshop was to focus on problems associated with the management of renewable resource systems A particular emphasis was given to methods for handling uncertain elements which are present in any real system Toward this end the participants were chosen so that the collective expertise included mathematical modeling dynamical control game theory ecology and practical management of real systems Each participant was invited to give an informal presentation in his field of expertise as related to the overall theme The formal papers contained in this volume were written after the workshop so that the authors could utilize the workshop experience in relating their own work to others To further encourage this exchange each paper contained in this volume was reviewed by two other participants who then wrote formal comments These comments with author's reply in some cases are attached to the end of each paper

Dynamic Programming and Bayesian Inference Mohammad Saber Fallah Nezhad, 2014-04-29 Dynamic programming and Bayesian inference have been both intensively and extensively developed during recent years Because of these developments interest in dynamic programming and Bayesian inference and their applications has greatly increased at all mathematical levels The purpose of this book is to provide some applications of Bayesian optimization and dynamic programming

Managing Trade-offs in Adaptable Software Architectures Ivan Mistrik, Nour Ali, Rick Kazman, John Grundy, Bradley Schmerl, 2016-08-12 Managing Trade Offs in Adaptable Software Architectures explores the latest research on adapting large complex systems to changing requirements To be able to adapt a system engineers must evaluate different quality attributes including trade offs to balance functional and quality requirements to maintain a well functioning system throughout the lifetime of the system This comprehensive resource brings together research focusing on how to manage trade offs and architect adaptive systems in different business contexts It presents state of the art techniques methodologies tools best practices and guidelines for developing adaptive systems and offers guidance for future software engineering research and practice Each contributed chapter considers the practical application of the topic through case studies experiments empirical validation or systematic comparisons with other

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Steffen,2025-08-27 This book constitutes the proceedings of the 30th International Conference on Formal Methods for Industrial Critical Systems FMICS 2025 held in Aarhus Denmark during August 27 28 2025 The 13 full papers included in this book together with 2 invited papers were carefully reviewed and selected from 25 submissions The papers have been organized in the following topical sections verification automotive and railway cyber physical systems and embedded systems

Manufacturing 2030 - A Perspective to Future Challenges in Industrial Production Dominik T. Matt,Erwin Rauch,Patrick Dallasega,Luca Gualtieri,Matteo De Marchi,2025-10-29 This book offers practical insights into implementing Industry 4 0 technologies and exploring the evolving paradigm of Industry 5 0 It presents real world applications innovative engineering solutions and strategies for integrating digital tools into production and management practices Based on contributions from ISIEA 2025 and EPIEM 2025 the book spans topics from supply chain optimization to advanced human centric manufacturing and engineering design It introduces novel perspectives on merging technical and managerial approaches and highlights the educational challenges of aligning curricula with industrial innovation Intended for researchers professionals and academics it serves as both a reference for ongoing developments and a guide for incorporating cutting edge technologies and concepts into teaching and practice

Group Decision and Negotiation. A Process-Oriented View Pascale Zaraté,Gregory E. Kersten,Jorge E. Hernández,2014-06-05 This book constitutes the proceedings of the Joint INFORMS GDN and EWG DSS International Conference on Group Decision and Negotiation GDN held in Toulouse France during June 10 13 2014 The GDN meetings aim to bring together researchers and practitioners from a wide spectrum of fields including economics management computer science engineering and decision science The contributions report on research on individual and group decision support negotiation and auction support and the design of systems and agents supporting such processes From a total of 88 submissions 31 papers were accepted for publication in this volume The papers are organized into topical sections on collaborative decision making auctions knowledge decision support systems multi criteria decision making multi agent systems negotiation analysis preference analysis data analysis DSS GDSS use network analysis and semantic tools for group decision making

Outsourcing Management for Supply Chain Operations and Logistics Service Folinas, Dimitris,2012-08-31 Logistics and Supply Chain Management has been a vital part of every economy and every business entity Both sciences have become prestigious research fields focusing on best practices concepts and methods Outsourcing Management for Supply Chain Operations and Logistics Services is concentrated on the key players of the outsourcing paradigm the organizations that provide logistics services the Third Party Logistics 3PL s as well as their clients presenting and promoting the lessons learned by their cooperation Specifically this publication presents studies which are relevant to practitioners researchers students and clients of the application of the Outsourcing practice on the Logistics and Supply Chain Management services giving emphasis to 3PL s

Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future Theodor Borangiu,Damien Trentesaux,Paulo Leitão,2023-02-01 The scientific theme of

the book is Virtualisation a multifaceted key enabler of Industry 4.0 from holonic to cloud manufacturing which is addressed in the framework of cyber physical system development The book approaches cyber physical systems for manufacturing with emergent digital technologies Internet of Things digital twins based on the virtualization of production models embedded in the design virtual commissioning optimization and resilience of processes and fault tolerance of resources big data cloud control and computing machine learning and cobots that are applied in the book's chapters to industry and service sectors such as manufacturing energy logistics construction and health care The novelty of this approach consists in interpreting and applying the characteristics of RAMI4.0 the reference architecture model of the Industry 4.0 framework as combinations of virtualized cyber physical system elements and IT components in life cycle value stream models The general scope of the book is to foster innovation in smart and sustainable manufacturing and logistics systems and in this context to promote concepts methods and solutions for the digital transformation of manufacturing through service orientation in holonic and agent based control with distributed intelligence The book's readership is comprised by researchers and engineers working in the manufacturing value chain area who develop and use digital control solutions in the Industry of the Future vision The book also addresses to master's and Ph.D. students enrolled in Engineering Sciences programs

Data Analytics Applications in Latin America and Emerging Economies Eduardo Rodriguez, 2017-07-28 This book focuses on understanding the analytics knowledge management process and its comprehensive application to various socioeconomic sectors Using cases from Latin America and other emerging economies it examines analytics knowledge applications where a solution has been achieved Written for business students and professionals as well as researchers the book is filled with practical insight into applying concepts and implementing processes and solutions The eleven case studies presented in the book incorporate the whole analytics process and are useful reference examples for applying the analytics process for SME organizations in both developing and developed economies The cases also identify multiple tacit factors to deal with during the implementation of analytics knowledge management processes These factors which include data cleaning data gathering and interpretation of results are not always easily identified by analytics practitioners This book promotes the understanding of analytics methods and techniques It guides readers through numerous techniques and methods available to analytics practitioners by explaining the strengths and weaknesses of these methods and techniques

Cybersecurity Challenges in the Age of AI, Space Communications and Cyborgs Hamid Jahankhani, 2024-02-19 This book provides an opportunity for researchers scientists government officials strategist and operators and maintainers of large complex and advanced systems and infrastructure to update their knowledge with the state of best practice in the challenging domains while networking with the leading representatives researchers and solution providers The advancement of Artificial Intelligence AI coupled with the prolificacy of the Internet of Things IoT devices are creating smart societies that are interconnected Space exploration and satellite drone and UAV technology have travelled a long way in recent years and some may debate that we

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Oxford Handbook of Applied Bayesian Analysis Anthony O' Hagan, Mike West, 2010-03-18 Bayesian analysis has developed rapidly in applications in the last two decades and research in Bayesian methods remains dynamic and fast growing Dramatic advances in modelling concepts and computational technologies now enable routine application of Bayesian analysis using increasingly realistic stochastic models and this drives the adoption of Bayesian approaches in many areas of science technology commerce and industry This Handbook explores contemporary Bayesian analysis across a variety of application areas Chapters written by leading exponents of applied Bayesian analysis showcase the scientific ease and natural application of Bayesian modelling and present solutions to real engaging societally important and demanding problems The chapters are grouped into five general areas Biomedical Industry Economics Environment Policy Political and Natural Engineering Sciences and Appendix material in each touches on key concepts models and techniques of the chapter that are also of broader pedagogic and applied interest Adaptive Backstepping Control of Uncertain Systems with

Actuator Failures, Subsystem Interactions, and Nonsmooth Nonlinearities Wei Wang, Changyun Wen, Jing Zhou, 2017-09-18 In practice actuators often undergo failures and various factors influence its effectiveness Also due to the increasing complexity of large scale systems subsystems are often interconnected whereas the interactions between any two subsystems are difficult to deal with This book details a series of new methodologies of designing and analyzing adaptive backstepping control systems involving treatment on actuator failures subsystem interactions and nonsmooth nonlinearities Moreover it discusses some interesting open issues in adaptive failure accommodation decentralized adaptive control and distributed

adaptive coordinated control **Safety and Reliability of Complex Engineered Systems** Luca Podofillini, Bruno Sudret, Bozidar Stojadinovic, Enrico Zio, Wolfgang Kröger, 2015-09-03 Safety and Reliability of Complex Engineered Systems contains the Proceedings of the 25th European Safety and Reliability Conference ESREL 2015 held 7-10 September 2015 in Zurich Switzerland Including 570 papers on theories and methods in the area of risk safety and reliability and their applications to a wide range of industrial civil and social sectors this book will be of interest to academics and professionals involved or interested in aspect of risk safety and reliability in various engineering areas

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