

ADVANCED STATISTICAL TECHNIQUES FOR ROBUST POWER SYSTEM ANALYTICS

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ADVANCED STATISTICAL TECHNIQUES FOR ROBUST POWER SYSTEM ANALYTICS

by

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Submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



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I dedicate this thesis to my loving family . . .

Certificate

This is to certify that the thesis titled, "**Advanced Statistical Techniques for Robust Power System Analytics**", submitted by **Tabia Ahmad**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by her under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Tabia Ahmad
August 2021

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Abstract

The electric power system is witnessing significant transformations towards an integrated, active, and ubiquitously-sensed cyber-physical system. An abundance of multi-scaled data from phasor measurement units (PMUs), point on wave (POW) measurement devices, and digital disturbance recorders (DDRs) offers tremendous opportunities as well as scientific challenges to infer the state of the grid. Building on mathematical foundations and statistical analysis, this thesis aims to provide an overview of data analytic tools in the modeling and operation of modern power systems. The key findings of this work are as follows:

1. The assumption of non-Gaussian statistical nature of noise encountered in power system is revisited. The imperfect components of the measurement and instrumentation chain are supposed to contribute to the measurement noise present in PMU data. A generic Gaussian Mixture Model (GMM) based modelling of measurement noise is proposed in this work.
2. Data-driven techniques for monitoring the health of critical power system substation components are presented. Based on the non-Gaussian nature of noise, the work develops (a) a GMM based Bayesian framework and (b) a spectral kurtosis-based index to detect equipment malfunction.
3. Traditional indices of power system situational awareness under increasing system complexity are reviewed, and robust schemes that consider the effect of realistic noise present in power systems are proposed. Towards this end, the work proposes a robust formulation of Dynamic State Estimator (DSE), taking into account the non-Gaussian nature of measurement noise.
4. Due to the modeling uncertainty of practical power systems, measurement-based power system electromechanical mode estimation is desirable in practice. The work addresses the issue of imperfect mode estimation due to low-quality measurements acquired in the field. A robust mode-metering scheme that performs fairly even in the presence of non-Gaussian measurement noise is proposed in this work.

5. Complementary to the dynamic frequency indices used for planning against transient frequency excursions, the study of steady-state frequency deviation encountered due to continuous and random power system perturbations like load and renewable power injections is also essential. The present work reports the effect of these stochastic input perturbations on power system frequency fluctuations under ambient conditions using a physics-informed data-driven method of frequency dynamics.

The analytics mentioned above are supported with rigorous mathematical treatment and simulation studies on benchmark test systems, field data, and data acquired from laboratory-scale PMU.

Keywords: Power system measurements, statistical power system modelling, Gaussian Mixture Model, frequency fluctuations, stochastic power systems, power system data analytics.

सार

विद्युत शक्ति प्रणाली एक एकीकृत, सक्रिय और सर्वव्यापी रूप से संवेदनशील साइबर-भौतिक प्रणाली की दिशा में महत्वपूर्ण परिवर्तन देख रही है। फेजर मेजरमेंट यूनिट्स (पी एम यू), पॉइंट ऑन वेव (पीओडब्ल्यू) माप उपकरणों, और डिजिटल डिस्ट्रिब्यूट रिकॉर्डर (डी डी आर) से बहु-स्तरीय डेटा की बहुतायत ग्रिड की स्थिति का अनुमान लगाने के लिए जबरदस्त अवसर के साथ-साथ वैज्ञानिक चुनौतियां भी प्रदान करती है। गणितीय नींव और सांख्यिकीय विश्लेषण पर निर्माण, इस थीसिस का उद्देश्य आधुनिक बिजली प्रणालियों के मॉडलिंग और संचालन में डेटा विश्लेषणात्मक उपकरणों का एक सिंहावलोकन प्रदान करना है। इस कार्य के प्रमुख निष्कर्ष इस प्रकार हैं:

1. बिजली व्यवस्था में आने वाले शोर की गैर-गॉसियन सांख्यिकीय प्रकृति की धारणा पर दोबारा गौर किया गया है। माप और उपकरण श्रृंखला के अपूर्ण घटकों को पीएमयू डेटा में मौजूद माप शोर में योगदान देना चाहिए। इस काम में एजेनेरिक गॉसियन मिक्सचर मॉडल (जीएमएम) आधारित मापन शोर का मॉडलिंग प्रस्तावित है।
2. महत्वपूर्ण पावर सिस्टम सबस्टेशन घटकों के स्वास्थ्य की निगरानी के लिए डेटा-संचालित तकनीकें प्रस्तुत की जाती हैं। शोर की गैर-गॉसियन प्रकृति के आधार पर, कार्य विकसित होता है (ए) एक जीएमएम आधारित बायेसियन फ्रेमवर्क और (बी) उपकरण की खराबी का पता लगाने के लिए एक स्पेक्ट्रलकुटोसिस-आधारित इंडेक्स।
3. बढ़ती प्रणाली जटिलता के तहत बिजली व्यवस्था स्थितिजन्य जागरूकता के पारंपरिक सूचकांकों की समीक्षा की जाती है, और मजबूत योजनाएं जो बिजली प्रणालियों में मौजूद यथार्थवादी शोर के प्रभाव पर विचार करती हैं, प्रस्तावित हैं। इस दिशा में, मापन शोर की गैर-गॉसियन प्रकृति को ध्यान में रखते हुए, कार्य गतिशील राज्य अनुमानक (डीएसई) के एक मजबूत फॉर्मूलेशन का प्रस्ताव करता है।
4. व्यावहारिक शक्ति प्रणालियों की मॉडलिंग अनिश्चितता के कारण, माप-आधारित विद्युत प्रणाली इलेक्ट्रोमैकेनिकल मोड अनुमान व्यवहार में वांछनीय है। कार्य क्षेत्र में प्राप्त निम्न-गुणवत्ता माप के कारण अपूर्ण मोड अनुमान के मुद्दे को संबोधित करता है। एक मजबूत मोड-मीटरिंग योजना जो गैर-गॉसियन माप शोर की उपस्थिति में भी उचित प्रदर्शन करती है, इस कार्य में प्रस्तावित है।
5. क्षणिक आवृत्ति भ्रमण के खिलाफ योजना बनाने के लिए उपयोग किए जाने वाले गतिशील आवृत्ति सूचकांकों के पूरक, निरंतर और यादृच्छिक बिजली प्रणाली गड़बड़ी जैसे लोड और नवीकरणीय बिजली इंजेक्शन के कारण स्थिर-राज्य आवृत्ति विचलन का अध्ययन भी आवश्यक है। वर्तमान कार्य फ्रीक्वेंसी डायनेमिक्स की भौतिकी-सूचित डेटा-चालित पद्धति का उपयोग करके परिवेशी परिस्थितियों में पावर सिस्टम फ्रीक्वेंसी में उतार-चढ़ाव पर इन स्टोकेस्टिक इनपुट गड़बड़ी के प्रभाव की रिपोर्ट करता है। ऊपर उल्लिखित एनालिटिक्स बेंचमार्क टेस्ट सिस्टम पर कठोर गणितीय उपचार और सिमुलेशन अध्ययन के साथ समर्थित हैं, फील्ड डेटा, और प्रयोगशाला-पैमाने पर पीएमयू से प्राप्त डेटा।

सूचक शब्द : पावर सिस्टम मापन, सांख्यिकीय पावर सिस्टम मॉडलिंग, गाऊसी मिक्सचर मॉडल, आवृत्ति उतार-चढ़ाव, स्टोकेस्टिक पावर सिस्टम, पावर सिस्टम डेटा एनालिटिक्स।

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Nomenclature

Acronyms / Abbreviations

ACF Auto-correlation Function

CBR Converter Based Resources

CCVT Coupling Capacitor Voltage Transformer

CT Current Transformer

DAE Differential Algebraic Equations

DFR Digital Fault Recorder

DSE Dynamic State Estimation

EKF Extended Kalman Filter

EM Expectation Maximization

EnKF Ensemble Kalman Filter

GMM Gaussian Mixture Model

GPS Global Positioning Unit

ICT Information and Communications Technology

MLE Maximum Likelihood Estimation

PDF Probability Density Function

PF Particle Filter

PMU Phasor Measurement Unit

POW Point On Wave

RLS Recursive Least Squares

SA Situational Awareness

SCADA Supervisory Control and Data Acquisition

SK Spectral Kurtosis

TVE Total Vector Error

UKF Unscented Kalman Filter

WAMS Wide Area Measurement System