

**DATA DRIVEN APPROACHES TO MONITORING OF POWER
SYSTEM DYNAMICS**

PRATYASA BHUI



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JULY, 2017

©Indian Institute of Technology Delhi (IITD), New Delhi, 2017

DATA DRIVEN APPROACHES TO MONITORING OF POWER SYSTEM DYNAMICS

by

PRATYASA BHUI
Department of Electrical Engineering

Submitted

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

to the



Indian Institute of Technology Delhi

February, 2017

Dedicated
to
My Parents

CERTIFICATE

This is to certify that the thesis entitled “**Data Driven Approaches to Monitoring of Power System Dynamics**” submitted by **Mr. Pratyasa Bhui**, to Indian Institute of Technology Delhi for the award of degree of **Doctor of Philosophy (PhD)** is a bona fide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted to any other institute or university for the award of any degree or diploma.

Date:

Dr. Nilanjan Senroy

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi-110016, India.

Acknowledgements

It is great pleasure and proud privilege to express my sincere gratitude to my research supervisor Dr. Nilanjan Senroy whose encouragement, supervision, guidance and personal support from the preliminary to the concluding level enabled me to develop an understanding of the subject. It is an honor for me to have been working under his supervision and being part of his working group. I also acknowledge my gratitude to Prof. Ashok Kumar Pradhan, my M.Tech supervisor, for his encouragement in research and personal support. I am greatly influenced by his practical solution oriented research which shaped my way of thinking while approaching any research problem.

I am grateful to Prof. B. C. Pal, Prof J. V. Milanovic, Dr. A. K. Singh, Dr. Panagiotis Papadopolus for their useful suggestion and guidance during my research visit to UK.

I acknowledge my deep sense of gratitude to the members of doctoral reserach committee Prof. Sukumar Mishra, Prof. Indra Narayan Kar and Dr. Ashu Verma for their valuable suggestions and scrutiny of this work. I am also grateful to Prof P. R. Bijwe, Dr. B. K. Panigrahi and Dr. A. R. Abhyankar for their co-operation and help in my research.

I am indebted to all my seniors, especially Mr. Niladri Shekhar Tripathy, Mr. Deep Kiran and Mrs. Snigdha Rani Behera, for providing a warm research atmosphere, sharing knowledge and personal support. I am also thankful to my friends and juniors, specially Dr. Rahul Dubey, Mr. Rajeev Ranjan, Mr. Deepak Pullagurram, Mr. Sathiyarayanan, Mr. Ganesh P Prajapat, Mr. Rajeev Jha, Mr. Subham Sahoo, Mr. Surya Prakash, Mr. Manas Kumar Jena, Mr. Abdul Saleem, Mr. Abhishek Dey, Mr. Joyjit Mukherjee, Mr. Nalin Sharma, Mr. Priyadarshi Mukherjee who have helped me and made my life in IIT Delhi very exciting and a good memory. I am also thankful to the technical and laboratory staff of the department, Mr. Anand Sansanwal and Mr. Gaurav Kumar for their support and constant encouragement.

I acknowledge Ministry of Human Resource and Development, India for the grant of scholarship for the last four years for the research program.

I owe my deepest gratitude to my parents and relatives for their love, affection, care and constant encouragement throughout the research work. Finally, I wish to mention a very special acknowledgement to Tithi, my best friend, for her continuous support and co-operation.

Dated:

Pratyasa Bhui

Abstract

Signal processing and data mining is a growing area of multidisciplinary research in power system monitoring and control. Copious amounts of data are being generated by measurement sensors installed at different power and voltage levels, as part of various worldwide smart-grid initiatives. This thesis intends to extract information from the synchronized phasor measurements and assess system dynamics as quickly as possible. Different data driven approaches have been used for this purpose, as follows:

- 1) Very often the power system measurements are corrupted with different types of noises- electromagnetic transients, measurement noises, noises introduced in communication channel etc. An innovative index was proposed in this thesis which can identify the best denoising technique and its parameters so that multiple techniques can be used simultaneously and the best one may be chosen online. The denoised signal can be used for different applications like event detection, modal analysis, control etc.
- 2) As the signal is denoised, it can be analyzed to detect and locate power system events. Recurrence Quantification Analysis (RQA), a nonlinear data analysis technique was used to locate any dynamic event. Recurrence Rate (RR) index of the rate of change of voltage was used to locate different dynamic events.
- 3) Apart from approximate location, information regarding post fault topology is important from the static and dynamic security point of view. PMU data of the generator buses were used along with the SCADA data to identify the tripped line just after the fault clearing. A data analysis technique called k^{th} nearest neighbor technique (k-NN search method) was used to rank the probable rank lines quickly using measured and simulated data so that computation burden in the online is minimum. As the method is very quick, it may be used for predicting transient stability and other dynamic analysis.
- 4) The information regarding the post fault topology may be used to assess transient stability after a fault. The group of generators that tend to separate out from the rest of the system (but may not separate from the system in reality), is called Mode of Disturbance (MOD). If the MOD information is known, total system energy margin may be computed quickly. K^{th} nearest neighbor method (k-NN search) was used to rank the probable MODs using a look up

table and PMU measurements and the correct MOD was identified from the ranked ones. Using the MOD, system energy margin can be calculated and control action may be decided.

- 5) Accurate information about governor dead-band, droop are required to simulate different frequency events offline and offline simulations required for other purposes. As these parameters are very often unknown, Unscented Kalman Filter was used to estimate these parameters using PMU measurements of the generator buses.

Key words: Wide Area Measurement Systems, Topology Identification, Tripped Line, Transient Stability, Event Location, Parameter Estimation, Load Frequency Control.

सारांश

सिग्नल प्रोसेसिंग और डेटा खनन पावर सिस्टम मॉनिटरिंग और कंट्रोल में बहुआयामी शोध का एक बढ़ता हुआ क्षेत्र है। विभिन्न विश्वव्यापी स्मार्ट-ग्रिड पहल के हिस्से के रूप में विभिन्न बिजली और वोल्टेज स्तरों पर स्थापित माप सेंसर द्वारा प्रचुर मात्रा में डेटा उत्पन्न किया जा रहा है। यह थीसिस सिंक्रनाइज़ फेजर माप से जानकारी निकालने और जितनी जल्दी हो सके प्रणाली गतिशीलता का आकलन करने का इरादा है। इस उद्देश्य के लिए अलग-अलग डेटा चालित दृष्टिकोण का उपयोग किया गया है:

1) बहुत बार बिजली व्यवस्था के माप विभिन्न प्रकार के शोर से भ्रष्ट होते हैं - विद्युत चुम्बकीय यात्रियों, माप शोर, आवाज़ संचार चैनल आदि में पेश किया जाता है। इस थीसिस में एक अभिनव सूचकांक प्रस्तावित किया गया था जो कि सबसे अच्छा डिनोइजिंग तकनीक और उसके पैरामीटर की पहचान कर सकता है ताकि कई तकनीकों का एक साथ इस्तेमाल किया जा सकता है और सर्वश्रेष्ठ ऑनलाइन ऑनलाइन चुना जा सकता है डेनोइज्ड सिग्नल अलग-अलग अनुप्रयोगों जैसे इवेंट डिटेक्शन, मोडल विश्लेषण, कंट्रोल आदि के लिए इस्तेमाल किया जा सकता है।

2) संकेत के रूप में डेनोइज्ड है, यह पावर सिस्टम घटनाओं का पता लगाने और पता लगाने के लिए विश्लेषण किया जा सकता है। आवर्ती क्वांटिफिकेशन एनालिसिस (आरक्यूए), एक गैर-लाइनर डेटा विश्लेषण तकनीक का उपयोग किसी भी गतिशील घटना को खोजने के लिए किया गया था। वोल्टेज के परिवर्तन की दर की पुनरावृत्ति दर (आरआर) सूचक विभिन्न गतिशील घटनाओं को खोजने के लिए इस्तेमाल किया गया था।

3) अनुमानित स्थान के अलावा, पोस्ट गलती टोपोलॉजी के बारे में जानकारी स्थिर और गतिशील सुरक्षा बिंदु से महत्वपूर्ण है। जनरेटर बसों का पीएमयू डेटा स्काडा डेटा के साथ साथ फॉल्ट क्लीयरिंग के बाद ट्रिपेड लाइन की पहचान करने के लिए उपयोग किया गया था। एक डाटा विश्लेषण तकनीक जिसे सबसे निकटतम पड़ोसी तकनीक (के-एनएन खोज पद्धति) कहा जाता है, का प्रयोग संभवतः रैंक लाइनों को मापा और नकली डेटा का उपयोग करने के लिए किया जाता है ताकि ऑनलाइन में गणना का बोझ न्यूनतम हो। जैसा कि विधि बहुत जल्दी है, इसका उपयोग क्षणिक स्थिरता और अन्य गतिशील विश्लेषण के पूर्वानुमान के लिए किया जा सकता है।

4) पोस्ट दोष टोपोलॉजी के बारे में जानकारी का उपयोग गलती के बाद क्षणिक स्थिरता का मूल्यांकन करने के लिए किया जा सकता है। जनरेटरों के समूह जो शेष सिस्टम से बाहर अलग हैं (लेकिन वास्तविकता से सिस्टम से अलग नहीं हो सकते हैं) को गड़बड़ी का मोड कहा जाता है (एमओडी)। यदि एमओडी की जानकारी ज्ञात है, तो कुल सिस्टम ऊर्जा मार्जिन को तुरंत गणना किया जा सकता है सबसे नज़दीकी पड़ोसी विधि (के-एनएन खोज) का उपयोग रैंक वाले तालिका से पीएचडी माप और पीओएम

माप के साथ संभावित एमओडी को रैंक करने के लिए किया गया था। एमओडी का उपयोग करना, सिस्टम की ऊर्जा मार्जिन की गणना की जा सकती है और नियंत्रण क्रिया का निर्णय लिया जा सकता है।

5) गवर्नर के बारे में सटीक जानकारी मृत-बैंड के लिए, अन्य उद्देश्यों के लिए आवश्यक विभिन्न आवृत्ति घटनाओं ऑफ़लाइन और ऑफ़लाइन सिमुलेशन अनुकरण करने की आवश्यकता है। चूंकि ये पैरामीटर अज्ञात हैं, जनरेटर बसों के पीएमयू माप का उपयोग करते हुए इन पैरामीटरों का अनुमान लगाने के लिए, अनसेन्टेड कालमान फ़िल्टर का उपयोग किया गया था।

कुंजी शब्द: वाइड एरिया मापन सिस्टम, टोपोलॉजी आइडेंटिफिकेशन, ट्रिपेड लाइन, क्षणिक स्थिरता, इवेंट स्थान, पैरामीटर एसिमेंटेशन, लोड फ्रीक्वेंसी कंट्रोल।

Content

Title Page	i
Certificate	v
Acknowledgements	vii
Abstract	ix
Contents	xi
List of Abbreviations and Symbols	xv
List of Figures	xxi
List of Tables	xxiii
CHAPTER 1. INTRODUCTION	1
1.1 General	1
1.2 State-of-Art & Research Motivation	2
1.2.1 De-noising of PMU Data.....	2
1.2.2 Dynamic Event Localization	3
1.2.3 Identification of Tripped Line After a Fault.....	5
1.2.4 Real Time Prediction and Control of Transient Stability.....	6
1.2.5 Parameter Estimation in Load Frequency Control	9
1.3 Thesis Objective	10
1.4 Brief Overview of Work Done.....	11
1.5 Major Contributions From This Thesis Work.....	12
1.6 Thesis Organization.....	13
CHAPTER 2. DIFFERENT DATA DRIVEN APPROACHES	15
2.1 General	15
2.2 Recurrence Quantification Analysis.....	16
2.3 k-NN Search Method	22
2.4 Unscented Kalman Filter.....	22
2.5 Wavelet Shrinkage	25

2.6	Empirical Mode Decomposition	26
2.7	Conclusion.....	27
CHAPTER 3. DENOISING OF PMU DATA		29
3.1	General	29
3.2	Proposed Method.....	29
3.3	Result.....	32
3.4	Application to Actual Measured Data from PMU.....	35
3.5	Conclusion.....	36
CHAPTER 4. DYNAMIC EVENT LOCALIZATION USING RQA		37
4.1	General	37
4.2	Proposed Method.....	37
4.3	Results	40
4.3.1	Event 1: Fault at bus 15.....	40
4.3.2	Event 2: Line14-15 outage:	40
4.3.3	Event 3: Fault on line7-8 and outage	41
4.3.4	Event 4: Generator outage at bus 30	41
4.3.5	Impact of noise and cascaded events.....	42
4.3.6	Limited Measurements	44
4.4	Conclusion.....	48
CHAPTER 5. IDENTIFICATION OF TRIPPED LINE AFTER FAULT.....		49
5.1	General	49
5.2	Normalized Kinetic Energy.....	49
5.2.1	Computation of Normalized Kinetic Energy	50
5.2.2	Observation 1: KE remains same for different fault types.	51
5.2.3	<i>Observation 2: KE</i> remains almost same for change in fault duration	56
5.3	Proposed Technique for Identification of Tripped Line.....	57
5.4	Results	61

5.4.1	Kundur's 2 Area System	61
5.4.2	IEEE 39 Bus Test System:	63
5.4.3	NRPG Test System.....	63
5.4.4	Impact of Wrong Identification in Predicting Dynamic Behavior	64
5.4.5	Line Outage Causing Islanding in the Grid.....	67
5.5	Issues with Practical Implementation.....	68
5.6	Comparison	72
5.7	Conclusion.....	73

CHAPTER 6. REAL TIME PREDICTION AND CONTROL OF TRANSIENT

	STABILITY USING TRANSIENT ENERGY FUNCTION	75
6.1	General	75
6.2	Transient Energy Function (TEF)	76
6.2.1	Mode of Disturbance (MOD) Technique	77
6.2.2	BCU Technique.....	78
6.2.3	Identification MOD using BCU Method in Offline	79
6.3	Proposed Method.....	80
6.3.1	Offline Computation –building the look-up table	81
6.3.2	Online Computation – using PMU data	81
6.4	Results	86
6.4.1	Plant Model Instability-.....	88
6.4.2	Inter Area Mode Instability-.....	91
6.4.3	No instability-.....	92
6.4.4	Other Faults:	93
6.4.5	Demonstration using Time Domain Simulation.....	93
6.4.6	Performance on Northern Grid of India	94
6.5	Issues with Practical Implementation.....	96
6.5.1	Computation Time.....	96

6.5.2	Impact of Error in Generator Speed and Angle.....	98
6.5.3	Advantages of TEF.....	100
6.5.4	Inclusion of Detailed Model.....	101
6.6	Maximum Communication Latency in WAMS Based TSC.....	103
6.6.1	Proposed Method-	105
6.6.2	Results	106
6.6.3	Performance on Large Grid- NRPG Test System	111
6.7	Conclusion.....	113
CHAPTER 7. ESTIMATION OF PARAMETERS IN LOAD FREQUENCY		
	CONTROL.....	115
7.1	General	115
7.2	Mathematical Model of Load Frequency Control (LFC).....	115
7.3	Unscented Kalman Filter (UKF).....	120
7.4	Results	124
7.5	Comparison with Least Square	128
7.6	Application	129
7.7.	Impact of Noise on Estimation.....	131
7.8.	Impact of GRC on Estimation.....	133
7.9.	Bad Data Detection.....	136
7.10.	Conclusion.....	133
CHAPTER 8. CONCLUSIONS.....		
8.1	Summary of the Work	145
8.2	Scope of Future Work	146
References		149
Appendix		157
Publications from the Thesis.....		167

LIST OF FIGURES

Fig. 2.1 Recurrence plot of a sinusoid [0^0 to 1200^0] and a random noise	17
Fig. 3.1 Flow chart of the proposed method for de-noising	31
Fig. 3.2 Voltage waveform after adding 3% zero mean random noise	33
Fig. 3.3 Voltage waveform after adding 3% zero mean random noise	33
Fig. 3.4 Final de-noised waveform and original waveform	34
Fig. 3.5 Denoising of actual measurement data obtained from PMU	36
Fig. 4.1 Probability distribution curve of ΔV for few selected buses after outage of line 14-15	39
Fig. 4.2 Neighbourhood threshold for selected buses for outage of line 14-15	39
Fig. 4.3 RR of ΔV for each bus for fault at bus 15	40
Fig. 4.4 RR of ΔV for each for Line 14-15 outage	41
Fig. 4.5 RR of ΔV for each bus for fault at Line 7-8 and outage of that line	41
Fig. 4.6 RR of ΔV for each bus generator outage at bus 30	42
Fig. 4.7 cascaded event 1: RR of ΔV for each bus outage of Line 17-18	42
Fig. 4.8 Cascaded event 2: RR of ΔV for each bus for fault at bus 3 and outage of Gen10, Data window considered is 1s before the first event to 2.3s after the Gen outage	43
Fig. 4.9 Cascaded event 2: RR of ΔV for each bus for fault at bus 3 and outage of Gen 10 at bus 30, Data window considered is just after the first event to 3.3 s after the Gen outage	43
Fig. 4.10 Voltage waveform measured using PMU at different locations after a disturbance	45
Fig. 4.11 Disturbance arrival time based on the method proposed in [27]	46
Fig. 4.12 Disturbance arrival time based on the method proposed in [26]	47
Fig. 5.1. Thevenin's equivalent at point of fault in a two machine system.	52
Fig. 5.2. Equivalent Circuit for L-L-L fault and L-L fault.	53
Fig. 5.3 Accelerating Power of generators during L-L-L and L-L fault at different buses in Kundur's 2 Area System.	53
Fig. 5.4. Three machine system	55
Fig. 5.5. Swing curves for a 0.1 s fault near bus 8 and different line tripping at 1.1 s. <i>a)</i> Generator 1 angle, <i>b)</i> Generator 3 angle	66
Fig. 5.6. Error in predicting dynamic behaviour of post fault system and P_{errL} considering line "L" as tripped	67
Fig. 5.7. Multiple line outage due to relay/breaker failure.	71
Fig. 6.1. Flowchart for generation shedding	85

Fig. 6.2. Effectiveness of generation shedding in IEEE 39 Bus Test System to mitigate transient stability.	94
Fig. 6.3. Effectiveness of generation shedding in NRPG Test System to mitigate transient stability.	96
Fig. 6.4. Calculation of Allowable Maximum Time Delay	105
Fig. 6.5. Better estimate of maximum allowable communication latency using modified CUEP	109
Fig. 6.6. Calculation of generation shedding requirement using linear extrapolation for critical cases.	111
Fig. 6.7. Generation Shedding Required obtained from TEF and TDS for a fault at bus 157 of duration 0.39s. Generation was shedded from Generator 31.	112
Fig. 7.1. <i>a)</i> Transfer function model of a generator in load frequency control, <i>b)</i> Governor dead-band	117
Fig. 7.2. Daily load deviation curve. Base load is taken as the load at the starting point of the day.	124
Fig. 7.3. Estimation of parameters for old thermal generators with larger dead-band- dead-band and droop estimation, set frequency known	125
Fig. 7.4. Actual mechanical power and mechanical power calculated from electrical power and generator speed.	127
Fig. 7.5. Estimation of parameters for fully nonlinear thermal generator with zero dead-band (taken from matlab simulink model library).	127
Fig. 7.6. Performance of AGC for different setting of frequency bias.	130
Fig. 7.7. Estimation of parameters with noisy measurement of speed.	132
Fig.7.8. Inclusion of GRC in turbine model	135
Fig.9. <i>a)</i> Rate of change of mechanical power before the GRC block and after GRC limits it, <i>b)</i> Actual and estimated mechanical power, <i>c)</i> Actual and estimated droop and <i>d)</i> Actual and estimated deadband width	138
Fig. 10. Bad data tests on measurements without any bad data.	139
Fig. 11. Actual frequency and frequency measurement corrupted with noise. 10mHz temporary noise and steady state error added with actual frequency at 120s and 320s.	140
Fig. 12. Impact of bad data in frequency measurement on UKF performance and detection of bad data.	141
Fig.13. Actual ΔP_m and ΔP_m measurement corrupted with noise. 0.01 pu temporary noise and steady state error added with ΔP_m at 120s and 320s	142
Fig. 14. Impact and detection of bad data in ΔP_m measurement	143

LIST OF TABLES

Table 3.1 comparison of de-noising methods in terms of error	34
Table 3.2 error and SNR for different basis functions in NWS	35
Table 5.1. <i>KE</i> for different types of fault at bus 7	51
Table 5.2. Effective fault impedance for different type of fault	52
Table 5.3. Normalized <i>KE</i> i.e. <i>KE</i> for L-L-L and L-L faults at different buses in Kundur's 2 Area System	54
Table 5.4. <i>KE</i> for balanced fault at bus 7 of different durations	56
Table 5.5. <i>PerrL</i> computed for different line outages for fault on Line6-7 and subsequent outage	61
Table 5.6. <i>PerrL</i> computed for different line outages for fault on Line7-8 and subsequent outage	62
Table 5.7. Accuracy and average computational burden for identifying tripped line in Kundur's 2 Area System	62
Table 5.8. Accuracy and average computational burden for identifying the tripped line in IEEE 39 bus system	63
Table 5.9. Accuracy and average computational burden for identifying tripped line in North Indian Grid	64
Table 5.10. <i>PerrL</i> for all line outage calculations for fault on Line7-8	68
Table 5.11 Impact of error in calculating output power	69
Table 5.12 Identification multiple line outage	71
Table 5.13 Comparison between proposed method and LIS method	73
Table 6.1. Average Error in Predicted Generator Angles for Different Prediction Functions	83
Table 6.2. MODs and Corresponding Fault Locations	86
Table 6.3 <i>KE</i> and MOD for Different Fault Locations, Calculated Offline Using Simulation Data	87
Table 6.4. Gained by Generators in 0.1 s of Fault at Bus 29, Calculated Using Speeds Measured With PMU	88
Table 6.5. Ranking of the MODs in Ascending Order of Euclidean Distance "D"	89
Table 6.6. Identification of the Correct MOD from the Ranked MODs	89
Table 6.7. Error between Predicted and Actual Values	90
Table 6.8. Amount of Generation Shedding Required	90

Table 6.9. Identification of the Correct MOD from the Ranked MODs	91
Table 6.10. Identification of the Correct MOD	92
Table 6.11. Estimation of the Generation Shedding Required for Faults at Different Locations	93
Table 6.12. Identification of the Correct MOD from the Ranked MODs	95
Table 6.13. Computation time of each step of the method	97
Table 6.14 Error in KE_{corr} for different error in Generator Speed	99
Table 6.15. Error in δ for different error in Generator Angle	100
Table 6.16 Accuracy of the proposed method with exciter	102
Table 6.17. Maximum allowable communication latency obtained from Transient Energy Function and Time Domain Simulation	107
Table 6.18 Maximum Allowable Communication Latency obtained from TDS and TEF with actual and modified CUEP, for critical cases only	110
Table 6.19 Maximum Allowable Communication Latency obtained from TDS and TEF with actual and modified CUEP for different fault duration.	112
Table 7.1. Comparison with Least Square Error	128
Table 7.2. Noise Level in Speed Vs Estimation Error	133