

ELECTROMECHANICAL OSCILLATIONS IN POWER SYSTEM: DETECTION, CHARACTERIZATION AND UTILIZATION

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Electromechanical Oscillations in Power System: Detection, Characterization and Utilization

by

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Dedicated

to

My Family

whose constant love, support and encouragement drove me to complete this work

CERTIFICATE

This is to certify that the thesis entitled “**Electromechanical Oscillations in Power System: Detection, Characterization and Utilization**” submitted by **Mr. Rajiv Jha**, to Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide 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.

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Abstract

This thesis mainly concentrates on exploring the detection and analysis of the onset of lightly damped electromechanical oscillation as soon as they appear in the system response, and tools were developed to characterize the signal. Electromechanical oscillations of sustained nature were further investigated, and the source-effect relationship behind the event was established. Data-driven techniques to utilize electromechanical oscillation of the power system and ascertain the power system conditions were further discussed. Different mathematical formulations were used to support the theories and tools proposed in the thesis and validated by several measurement data obtained from the time-domain simulation as well as field phasor measurement units (PMUs) as discussed in detail as follows:

- 1) A novel signal processing technique, wavelet ridge technique (WRT), was introduced in this thesis to extract the slow varying feature of the power system response. The idea behind this WRT is that for electromechanical oscillation, there exists a unique time/curve called ‘ridge’ along which the dominant oscillating trend can be appropriately extracted. It was seen that the WRT showed superior performance when compared to empirical mode decomposition (EMD) to extract the low-frequency oscillation in the noisy signal. One can estimate the impact of the disturbance on a system by obtaining the dynamic trend from the noisy signal and determining its characteristics. The generalized wavelet used in this thesis was an analytic wavelet, and the extracted signal was in the analytic format. This feature was further used to characterize the oscillatory signal i.e., estimating amplitude, frequency, mode shape, damping parameter of the oscillation.
- 2) A well-damped electromechanical oscillations do not pose a threat to system security, whereas sustained oscillation has a detrimental effect on the power system. Sustained oscillation can persist in the system due to (i) small-signal disturbance to weakly damped power system or (ii) periodic forced disturbance to weakly/ well-damped power system. A new data-driven technique was proposed in this thesis to distinguish the sustained oscillation between the natural and forced oscillation. It uses the characteristics of the ambient noise, which gets affected differently in both types of disturbance to determine the nature of sustained oscillation.
- 3) A measurement-based technique has been suggested in this thesis to locate the source of

the disturbance. The methodology calculates the dissipating energy contribution of a generator into the system, and depending on the nature of it, the source of forced oscillation has been localized. Dissipating energy calculation uses the measurement data from the generator as well as the load buses. The discussed method was tested and verified for various scenarios such as single and multiple sources of disturbance present at single and multiple time instants.

- 4) A multidimensional approach, which utilizes the measurement data as well as system information to locate the source, was discussed in this thesis. In this approach, frequency response function (FRF) for a pair of input/ output has been utilized to define an index to quantify the contribution of a generator in the disturbance, and based on that generator numbers were ranked. Another index using the time measurement data was proposed to sort the generators depending on its participation in the forced disturbance. Then, both sequences were compared using a multidimensional search algorithm, and then, the source was revealed.
- 5) Electromechanical oscillation recorded in the power system may be used for various applications. Three different applications of utilizing power system scenarios were discussed in this thesis. In one application, the oscillating trend of the signals was utilized to determine the most potential candidate of controller location by processing multivariate signal. Therefore, a multidimensional signal processing technique was discussed to process multidimensional data and evaluate power system conditions following a disturbance. A data-driven technique to form a reduced area network for a large system utilizing electromechanical oscillatory signal was proposed in this thesis. Furthermore, in this thesis, measurement data recorded at the generator terminals were utilized to estimate key states and parameters of the synchronous generator represented in the classical form. Various time-domain simulations and field measurement data were used to verify the proposed methods.

Keywords: Electromechanical oscillation, Signal processing technique, wavelet ridge technique, transient stability, small-signal stability, forced disturbance, Dissipating energy, frequency response function, multivariate signal processing technique, State and Parameter Estimation, unscented Kalman filter.

सार

यह थीसिस मुख्य रूप से सिस्टम प्रतिक्रिया में प्रकट होने के साथ ही हल्के से विद्युत चुम्बकीय दोलन की शुरुआत का पता लगाने और विश्लेषण की खोज पर केंद्रित है, और सिग्नल को चिह्नित करने के लिए उपकरण विकसित किए गए हैं। निरंतर प्रकृति के विद्युत दोलनों की आगे जांच की गई, और घटना के पीछे स्रोत-प्रभाव संबंध स्थापित किया गया। विद्युत प्रणाली के विद्युत-दोलन का उपयोग करने और बिजली व्यवस्था की स्थिति का पता लगाने के लिए डेटा-चालित तकनीकों पर आगे चर्चा की गई। निरंतर प्रकृति के विद्युत दोलनों की आगे जांच की गई, और घटना के पीछे स्रोत-प्रभाव संबंध स्थापित किया गया। विद्युत प्रणाली के विद्युत-दोलन का उपयोग करने और बिजली व्यवस्था की स्थिति का पता लगाने के लिए डेटा-चालित तकनीकों पर आगे चर्चा की गई। थीसिस में प्रस्तावित सिद्धांतों और उपकरणों का समर्थन करने के लिए विभिन्न गणितीय योगों का उपयोग किया गया है और समय-डोमेन सिमुलेशन से प्राप्त फ़्रील्ड माप माप इकाइयों (PMUs) से प्राप्त कई माप डेटा द्वारा मान्य किया गया है, जैसा कि विस्तार से चर्चा की गई है:

- 1) एक नया सिग्नल प्रोसेसिंग तकनीक, तरंगिका रिज तकनीक (WRT), इस थीसिस में पेश की गई थी ताकि बिजली प्रणाली की प्रतिक्रिया की धीमी बदलती विशेषता को निकाला जा सके। इस WRT के पीछे का विचार यह है कि इलेक्ट्रोमैकेनिकल दोलन के लिए, एक अद्वितीय समय / वक्र होता है जिसे 'रिज' कहा जाता है, जिसके साथ प्रमुख दोलन प्रवृत्ति को उचित रूप से निकाला जा सकता है। यह देखा गया कि शोर संकेत में कम आवृत्ति दोलन निकालने के लिए अनुभवजन्य विघटन अपघटन (EMD) की तुलना में WRT ने बेहतर प्रदर्शन किया। एक शोर सिग्नल से गतिशील प्रवृत्ति प्राप्त करके और इसकी विशेषताओं का निर्धारण करके किसी सिस्टम पर गड़बड़ी के प्रभाव का अनुमान लगा सकता है। इस थीसिस में प्रयुक्त सामान्यीकृत तरंगिका एक विश्लेषणात्मक तरंगिका थी, और निकाले गए संकेत विश्लेषणात्मक प्रारूप में थे। इस विशेषता का उपयोग आगे थरथरानवाला संकेत को चिह्नित करने के लिए किया गया था, अर्थात्, आयाम, आवृत्ति, मोड आकार, दोलन के भिगोना पैरामीटर का आकलन।
- 2) एक अच्छी तरह से नम इलेक्ट्रोमैकेनिकल दोलन सिस्टम सुरक्षा के लिए खतरा पैदा नहीं करते हैं, जबकि निरंतर दोलन का बिजली व्यवस्था पर हानिकारक प्रभाव पड़ता है। (i) कमजोर सिग्नल प्रणाली को कमजोर करने के लिए या (ii) आवधिक रूप से कमजोर / अच्छी तरह से बिजली प्रणाली को परेशान करने के लिए आवधिक मजबूर गड़बड़ी के कारण निरंतर दोलन प्रणाली में बनी रह सकती है। इस थीसिस में एक नई डेटा-चालित तकनीक प्रस्तावित की गई थी जो प्राकृतिक और मजबूर दोलन के बीच निरंतर दोलन को अलग करती है। यह परिवेशीय शोर की विशेषताओं का उपयोग करता है, जो निरंतर दोलन की प्रकृति को निर्धारित करने के लिए दोनों प्रकार की गड़बड़ी में अलग-अलग प्रभावित होता है।
- 3) गड़बड़ी के स्रोत का पता लगाने के लिए इस थीसिस में माप-आधारित तकनीक का सुझाव दिया गया है। कार्यप्रणाली प्रणाली में एक जनरेटर के फैलने वाले ऊर्जा योगदान की गणना करती है, और इसकी प्रकृति के आधार पर, जबरन दोलन का स्रोत स्थानीयकृत किया गया है। ऊर्जा गणना को अलग करने के लिए जनरेटर के साथ-साथ लोड बसों के माप डेटा का उपयोग किया जाता है। चर्चा की गई विधि को विभिन्न परिदृश्यों जैसे एकल और एकाधिक समय में मौजूद अशांति के कई स्रोतों के लिए परीक्षण और सत्यापित किया गया है।
- 4) एक बहुआयामी दृष्टिकोण, जो माप डेटा के साथ-साथ स्रोत को खोजने के लिए सिस्टम जानकारी का उपयोग करता है, इस थीसिस में चर्चा की गई है। इस दृष्टिकोण में, इनपुट / आउटपुट की एक जोड़ी के लिए आवृत्ति प्रतिक्रिया फ़ंक्शन (FRF) का उपयोग गड़बड़ी में एक जनरेटर के योगदान को निर्धारित करने के लिए एक सूचकांक को परिभाषित करने के लिए किया गया है, और इसके आधार पर जनरेटर संख्याओं

को रैंक किया गया था। समय मापन डेटा का उपयोग करते हुए एक और सूचकांक को मजबूर गड़बड़ी में इसकी भागीदारी के आधार पर जनरेटर को सॉर्ट करने का प्रस्ताव दिया गया है। फिर, दोनों अनुक्रमों की तुलना एक बहुआयामी खोज एल्गोरिथ्म का उपयोग करके की गई, और फिर, स्रोत का पता चला।

- 5) विद्युत प्रणाली में दर्ज इलेक्ट्रोमैकेनिकल दोलन का उपयोग विभिन्न अनुप्रयोगों के लिए किया जा सकता है। इस थीसिस में पावर सिस्टम परिदृश्यों के उपयोग के तीन अलग-अलग अनुप्रयोगों पर चर्चा की गई है। एक आवेदन में, मल्टीवेरेट सिग्नल को संसाधित करके नियंत्रक स्थान के सबसे संभावित उम्मीदवार को निर्धारित करने के लिए संकेतों के दोलन प्रवृत्ति का उपयोग किया गया है। इसलिए, बहुआयामी डेटा को संसाधित करने और एक गड़बड़ी के बाद बिजली प्रणाली की स्थिति का मूल्यांकन करने के लिए एक बहुआयामी सिग्नल प्रसंस्करण तकनीक पर चर्चा की गई है। इस थीसिस में इलेक्ट्रोमैकेनिकल ऑसिलेटरी सिग्नल का उपयोग करने वाले एक बड़े सिस्टम के लिए एक कम एरिया नेटवर्क बनाने के लिए डेटा-चालित तकनीक का प्रस्ताव किया गया है। इसके अलावा, इस थीसिस में, जनरेटर टर्मिनलों पर रिकॉर्ड किए गए माप डेटा का उपयोग प्रमुख राज्यों और शास्त्रीय रूप में प्रतिनिधित्व किए गए सिंक्रोनस जनरेटर के मापदंडों का अनुमान लगाने के लिए किया गया है। प्रस्तावित विधियों को सत्यापित करने के लिए विभिन्न समय-डोमेन सिमुलेशन और फ्रील्ड माप डेटा का उपयोग किया गया है।

कीवर्ड: इलेक्ट्रोमैकेनिकल दोलन, सिग्नल प्रोसेसिंग तकनीक, तरंगिका रिज तकनीक, क्षणिक स्थिरता, छोटे-सिग्नल स्थिरता, मजबूर गड़बड़ी, डिसिपेटिंग एनर्जी, फ्रिक्वेंसी रिस्पांस फंक्शन, मल्टीवेरेट सिग्नल प्रोसेसिंग तकनीक, स्टेट एंड पैरामेट एस्टिमेशन, अनसंटेड कलमन फिल्टर।

Table of Contents

Certificate	i
Acknowledgments	iii
Abstract	v
Table of Contents	vii
List of Figures	xi
List of Tables	xv
List of Abbreviations and Symbols	xvii
CHAPTER 1 Introduction	1
1.1 General	1
1.2 State-of-Art & Research Motivation	3
1.2.1 Power System Electromechanical Oscillation: Detection and characterization	3
1.2.2 Classification of Power System Sustained Oscillations Between Natural and Forced Oscillations	4
1.2.3 Dissipating Energy-based Technique to Locate the Source of Forced Oscillation	5
1.2.4 A Multidimensional Approach to Locate the Source of Forced Oscillation	6
1.2.5 Data-driven Techniques to Utilize Electromechanical Oscillations of Power System for Various Applications	7
1.3 Thesis Objective	9
1.4 Brief Overview of Work Done	9
1.5 Major Contributions from this Thesis	12
1.6 Thesis Organization	13
CHAPTER 2 Detection and Characterization of The Power System Electromechanical Oscillations	15
2.1 General	15
2.2 A Mathematical Representation of the Power System Electromechanical Oscillations	

.....	16
2.2.1 Wavelet Function	17
2.2.2 Wavelet Ridge Transform (WRT).....	18
2.2.3 Mode of Oscillation	19
2.2.4 Mode Damping Ratio	19
2.2.5 Mode Shape.....	20
2.3 Results and Discussions	22
2.3.1 Synthetic Signal.....	22
2.3.2 Measurement Data from a Simulated Test System	24
2.3.3 Field Measurement Data	26
2.3.4 Verification of the Proposed Coherency Index.....	28
2.3.5 Field Measurement Data	32
2.4 Conclusion	33
CHAPTER 3 Power System Sustained Oscillations: Classification Between Natural and Forced Oscillations	35
3.1 General	35
3.2 Power System Sustained Oscillations: Preliminary Concept	35
3.3 Oscillation Model of the Measured Signal.....	37
3.4 Proposed Methodology	38
3.5 Result and Discussion	41
3.5.1 Synthetic Test System.....	41
3.5.2 IEEE New England Test System.....	42
3.5.3 Field Measurement Data	43
3.6 Conclusion	44
CHAPTER 4 Dissipating Energy Based Technique to Locate The Source of Power System Forced Oscillation	46
4.1 General	46
4.2 Forced Oscillation Source Location in Power Systems– Preliminary Concepts	46

4.3	Forced Oscillation Source Location in Power Systems– Algorithm Development	48
4.3.1	Algorithm Development	48
4.4	Forced Oscillation Source Location in Power Systems– Benchmarking.....	51
4.5	Impact of System Damping on its Response to the Forced Oscillation.....	52
4.6	Results and Discussion.....	53
4.6.1	Single Source of Disturbance.....	53
4.6.2	Multiple and Simultaneous Sources of Disturbance	55
4.6.3	Multiple Sources – Different Time of Application	57
4.6.4	Test Case Reported by IEEE PES Task Force on Oscillation Source Location	58
4.7	Conclusion	60
CHAPTER 5 A Multidimensional Approach to Locate the Source of Forced Oscillation		62
5.1	General	62
5.2	The Theoretical Foundation for Forced Oscillation Source Location: A Multidimensional Approach.....	63
5.3	Results and Discussion.....	69
5.3.1	Kundur Test System: <i>Problem 1</i>	70
5.3.2	IEEE 68 bus Test System: <i>Problem 2</i>	71
5.4	Conclusion	75
CHAPTER 6 Data-Driven Techniques to Analyze Electromechanical Oscillations of Power System		76
6.1	General	76
6.2	Accessing Power System Scenarios Using Multidimensional Signal Processing Technique	77
6.3	Results and Discussion: Multivariate Signal Processing	78
6.3.1	IEEE 16 machine 68 Bus Test System	78
6.3.2	Control Application of the Proposed DCI	83
6.3.3	Field measurement data	84

6.4	Measurement Data-based Network Reduction of a Large Power System	86
6.5	Results and Discussion: Measurement Data-based Network Reduction of a Large Power System	90
6.5.1	Estimating Reduced Dynamic System of Kundur Test System.....	90
6.5.2	Estimating Reduced Dynamic System of IEEE 39 Bus Test System ..	93
6.5.3	Estimating Reduced Dynamic System of IEEE 16 Machine 68 Bus Test System	96
6.6	Decentralized Dynamic State and Parameter Estimation in Multimachine Power Systems	99
6.6.1	Unscented Kalman Filter (UKF)	99
6.6.2	Implementation of UKF for dynamic states and parameters estimation	101
6.7	Results and Discussion: Decentralized Dynamic State Estimation Using UKF	103
6.8	Conclusion	106
CHAPTER 7 Conclusions and Scope of the Future Work		108
7.1	Summary of The Work.....	108
7.2	Scope of The Future Work	110
References.....		113
Appendix A.....		120
Appendix B.....		121
Publications from the Thesis.....		130
Bio-Data.....		131

List of Figures

Figure 2.1 Varying phase difference between two synthetic signals of same magnitude and frequency	21
Figure 2.2 Flow chart of the detection and characterization of the Oscillatory trend in the noisy measurement data.....	22
Figure 2.3 Comparison between noisy, actual and extracted signal	23
Figure 2.4 Graph between $\log_e(IA)$ vs time for the test signal.....	23
Figure 2.5 Kundur test system	24
Figure 2.6 Speed of the 2 nd Generator of the Kundur test system	24
Figure 2.7 Power spectral density of the actual and recovered signal shown in Fig. 2.5	25
Figure 2.8 Comparison of the gradient of the corrupted, recovered and original signal	25
Figure 2.9 Frequency Recorded at Mumbai, Kanpur, Kharagpur and Delhi on 4 th Feb 2013	26
Figure 2.10 Oscillating trend of the signal shown in Fig. 2.9	27
Figure 2.11 Generators' speed of the IEEE 16 machine test system for a contingency	28
Figure 2.12 WPD of machines speed of IEEE 16 machines test system for (a) generators 4 and 5 (b) generators 4 and 16.....	31
Figure 2.13 Coherency Index for IEEE 16 machine Test System Calculated using Method Reported in [69]	31
Figure 2.14 WAMS data captured on 25 th August 2005 at four different locations as reported in [71].....	32
Figure 2.15 Dynamic trend extracted from the signal shown in Fig. 2.14.....	33
Figure 3.1 Single machine infinite bus system with AVR and PSS	36
Figure 3.2 Pictorial representation of the proposed methodology to differentiate the sustained oscillation between (a) NO and (b) FO	40
Figure 3.3 Response of the simulated test system for (a) Case (i) and (b) Case (ii).....	42
Figure 3.4 Response of the New England Test System for (i) NO with two weakly damped modes (ii) FO with all mode damped	43
Figure 3.5 ISO-NE case 1 [44] (a) 9 th Bus Frequency and (b) its PSD	43
Figure 3.6 ISO-NE Case 4 [44] (a) 9 th bus frequency and (b) its PSD	44
Figure 4.1 A simplified two machine test system.....	47

Figure 4.2 Dissipating energy for FD is calculated for the two machine system (a) according to [43] (b) according to (4.21).	52
Figure 4.3 Effect of damping on the calculation of dissipating energy of the two machine system for Case 1 and 2.	53
Figure 4.4 Effect of FD applied on the 2 nd generator of Kundur test system all generators' (a) speed, and (b) dissipating energy.	54
Figure 4.5 Effect of FD applied on the 3 rd generator of New England test system is shown in generators' (a) speed (b) dissipating energy.....	55
Figure 4.6 Effect of FD applied on the machines of NE as discussed in Sec. 4.6.2 showing all generators' (a) speeds (b) dissipating energy	57
Figure 4.7 Effect of FD applied on the machines of NE as discussed in Sec. 4.6.3 showing all generators' (a) speeds (b) dissipating energy	57
Figure 4.8 Dissipating Energy curve for all machines for the test case F_1 reported in [44]	58
Figure 4.9 All machines' dissipating energy curve for FD applied on the 4 th machine of Kundur test system as discussed in Sec. 4.6.4(b) with standard deviation of a) 0.5, and b) 2.8 with case1 and case 2	60
Figure 5.1 Flow chart of the proposed Forced oscillation source location: A multidimensional approach	69
Figure 5.2 Variation in system response with varying frequency of FD at the 2 nd machine of Kundur test system shown in (a) Case 1 (b) Case 2 (c) Case 3 and (d) Case 4.....	70
Figure 5.3 Variation in system response with varying frequency of FD at the 2 nd machine of IEEE 68 bus test system shown in (a) Case 1 (b) Case 2 (c) Case 3 and (d) Case 4	72
Figure 5.4 Dissipating energy curve of each generator of IEEE 16 machine system when FO is applied at its 2nd machine for (a) Case 1 (b) Case 2 (c) Case 3 and (d) Case 4	74
Figure 6.1 IEEE 16 machine 68 bus test system.....	78
Figure 6.2 Angular speed variation of all machines of IEEE 16 machine test system for the stable contingency.....	79
Figure 6.3 Instantaneous amplitudes of the speed signal of IEEE 16 machine test system for the stable contingency.....	79
Figure 6.4 Plot of $\log_e A_a(t)$ vs time to estimate damping of the signals considered in Fig. 6.2.80	

Figure 6.5 Speed variation of all machines of IEEE 16 machines test system post unstable contingency (a) first 5 second (b) first 50 second of simulation	81
Figure 6.6 Instantaneous amplitudes of the speed signal of IEEE16 machine system for unstable contingency.....	82
Figure 6.7 Plot of $\log eAa(t)$ vs time to estimate damping of the signals considered in Fig. 6.5.	82
Figure 6.8 Speed variation of all machines of Kundur test system following a small signal disturbance at 1 second	83
Figure 6.9 Instantaneous amplitudes of the speed signal of Kundur test system for the unstable contingency.....	83
Figure 6.10 PSS is <i>switched-on</i> at 10 th seconds on (a) machine number 2 (b) machine number 3	84
Figure 6.11 Frequency recorded at Mumbai, Kanpur, Kharagpur and Delhi on 4 th Feb 2013	85
Figure 6.12 Oscillating trend of the Frequency recorded at four places shown in Fig. 6.11	85
Figure 6.13 Instantaneous frequency for the measurement data shown in Fig. 6.11.....	85
Figure 6.14 Equivalent generator for the group of coherent generators of <i>kth</i> area.....	87
Figure 6.15 Classical representation of the synchronous machine	88
Figure 6.16 Kundur two area test system.....	90
Figure 6.17 Kundur two area test system rotor angle oscillation for a small signal disturbance. .	90
Figure 6.18 Generator Rotor angle oscillation of estimated and COI equivalent generators of (a) Area 1 and (b) Area 2.....	92
Figure 6.19 Generator Rotor speed oscillation of estimated and COI equivalent generators of (a) Area 1 and (b) Area 2.....	92
Figure 6.20 IEEE 39 bus test system	94
Figure 6.21 Comparison of equivalent generator speed behavior in COI frame and estimated generator parameters for (a) area 1, (b) area 2, (c) area 3 and (d) area 4.....	95
Figure 6.22 IEEE 16 machine 68 bus test system.....	97
Figure 6.23 Comparison of equivalent generator speed behavior in COI frame and estimated generator parameters for (a) area 1, (b) area 2, (c) area 3 and (d) area 5 (e) area 6	97
Figure 6.24 IEEE 3 machine 9 bus system.....	103
Figure 6.25 Estimated (a) Angular variation (b) Speed (c) Xd' [pu] (d) Eg [pu] (e) Inertia constant [s] of Generator 1 using UKF technique	104

Figure 6.26 Estimated (a) Angular variation (b) Speed (c) X_d' [pu] (d) E_g [pu] (e) Inertia constant [s] of Generator 1 using UKF technique with increase in noise in measurement data105

List of Tables

Table 2.1 Estimated frequency and damping of the signal taken from Kundur test system	26
Table 2.2 Estimated frequency and damping of the signal shown in Fig. 2.9.....	27
Table 2.3 Coherency index for field measurement data shown in Fig. 2.9.....	28
Table 2.4 Constituents of Groups Indicated in Fig. 2.11	29
Table 2.5 Variation in the coherency index with the change in the analysing time window and threshold	29
Table 2.6 Determining coherency between two signal using their phase difference.....	30
Table 2.7 FDR at Different Substations in WSCC Network.....	32
Table 2.8 Coherency index among different signals shown in Fig. 2.14.....	33
Table 4.1 Slopes of each machine's dissipating energy for FD applied to machines of Kundur test system.....	54
Table 4.2 Slopes of each machine's dissipating energy for FD applied to machines of NE	56
Table 4.3 Slopes of dissipating energy of generators (Kundur test system) for FD applied at the 1 st generator considering different load models	59
Table 5.1 Ranked machine in $DCIT\omega FO$ for Kundur test system for cases discussed in Sec. 5.5.1	71
Table 5.2 KNN values for <i>Problem 1</i> for case 1	71
Table 5.3 Inter-area modes for IEEE 16 machine test system.....	72
Table 5.4 Ranked machines with significant $DCIT\omega FO$ values of IEEE 68 bus test system for all cases	73
Table 5.5 KNN values for <i>Problem 2</i> for Case 1	74
Table 5.6 KNN values for <i>Problem 2</i> for Case 2	74
Table 6.1 Constituents of groups indicated in Fig. 6.5(a).....	81
Table 6.2 DCI for 16 machine system in an unstable condition.....	82
Table 6.3 DCI for all four machines of Kundur two area system.....	84
Table 6.4 DCI for signal recorded at 4 places on 4 th Feb 2013	86
Table 6.5 Estimated impedance of the equivalent synchronous generators of two areas of Kundur test system	91

Table 6.6 Estimated impedance of the equivalent synchronous generators of two areas of Kundur test system	92
Table 6.7 Estimated impedance of the equivalent synchronous generators of IEEE 39 bus test system.....	94
Table 6.8 Estimated impedance of the equivalent synchronous generators of IEEE 39 bus test system.....	96
Table 6.9 Estimated Impedance of The Equivalent Synchronous Generators Of IEEE 39 Bus Test System	98
Table 6.10 Actual and Estimated Parameters of generators of IEEE 9 bus System using UKF .	105
Table 6.11 Error (%) in Estimating States and Parameters of Synchronous Generators with increase in noise in measurement data.....	106

List of Abbreviations and Symbols

SCADA	Supervisory Control and Data Acquisition
EMO	Electromechanical Oscillation
PMU	Phasor Measurement Unit
PDC	Phasor Data Concentrators
GPS	Global Positioning System GPS
NO	Natural Oscillation
FO	Forced Oscillation
FD	Forced Disturbance
WRT	Wavelet Ridge Technique
WAMs	Wide-Area Measurement Systems
EMD	Empirical Mode Decomposition
IMF	Intrinsic Mode Functions
ERA	Eigen Realization algorithm
SVM	Support Vector Machines
SNR	Signal to Noise Ratio
POD	Proper Orthogonal Decomposition
SVD	Singular Value Decomposition
MWRT	Multivariate Wavelet Ridge Technique
WSCC	Western Systems Coordinating Council
PES	Power Engineering Society
RTDS	Real-time Digital Simulator

FRF	Frequency Response Function
SIMO	Single Input Multiple Output
DCI_F	Disturbance Contribution Index in Frequency Domain
$DCI_F _{\omega_{FO}}$	Disturbance Contribution Index in Frequency Domain at Forced Oscillation Frequency
DCI_T	Disturbance Contribution Index in the Time Domain
$DCI_T _{\omega_{FO}}$	Disturbance Contribution Index in Time Domain At Forced Oscillation Frequency
IF	Instantaneous Frequency
IA	Instantaneous Amplitude
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
PSD	Power Spectral Density
COI	Centre of Inertia
MR	Magnitude Response
TF	Transfer Function
WPD	Wavelet Phase Difference
FDR	Frequency Disturbance Recorders
CI	Constant Impedance
CP	Constant Power
CC	Constant Current
HVDC	High Voltage Direct Current
WGN	White Gaussian Noise

ISO	Independent System Operator
NE	New England
PSS	Power System Stabilizer
LSE	Least Square Estimation
UKF	Unscented Kalman Filter
$x(t)$,	Real-Valued Measurement Data
$A_a(t)$	Instantaneous Amplitude
$\phi_a(t)$	Instantaneous Phase
$S_a(t)$	Analytic Signal
$\omega_a(t)$	Instantaneous Frequency
$\mu(t)$	Oscillatory Trend of the Signal
$r_d(t)$	Random Variation present in a Signal
$\varepsilon(t)$	Noise
$\psi(t)$	Mother Wavelet
τ	Dilated Parameter
u	Translated Parameter
$X(\omega)$	Fourier transform of the signal $x(t)$
$\alpha_{m,n}$	A Normalizing Constant in Generalized Morse wavelet
$U(\omega)$	A unit step function
m, n	Wavelet Controlling and Shaping Parameter
$c^{\{\cdot\}}$	Continuous Ridge Curve
$\hat{x}_{a,\psi}^{\{\cdot\}}(t)$	Modulated Oscillatory Signal

W_ψ	Wavelet Transform
$\mathcal{A}$	Analytic Operator
ξ	Damping Ratio
$A_a(t)$	Canonical Amplitude
$\theta_a(t)$	Canonical Phase
$\ \cdot\ $	Euclidean norm of an array
A	$N \times N$ state matrix,
$z_l(t)$	A source of low magnitude random white Gaussian noise
$G_f,$	Weights for forced oscillation
G_a	Weights for Random Disturbance Vectors
$f(t)$	Forced Oscillation Vector,
ω_f	Fundamental Frequency of External Periodic Disturbance
$'p'$	Harmonic Number
ϕ	Right Eigenvector
ψ	Left Eigenvector
λ	Eigenvalues of matrix.
$\otimes$	Convolution Operator
x_{Res}	Residual left after Extracting Dominant Pattern
$\delta(\omega)$	Impulse Response
$x_{Ext}(t)$	Extracted signal
$x_{Res}(t)$	Residual signal
E_t	Total Energy of the System

E_G	Energy Stored in the Generators
E_{Nw}	Energy Stored in the Networks
E_L	Energy Stored in the Loads
V_B	Bus Voltages
Y	Admittance Matrix
I_G	Current Injection from Generators
I_L	Currents Drawn by Loads in phasor form
p, q	Bus Numbers.
$*$	The Complex Conjugate
TE	System Total Energy
E_{NT}	Energy Contribution of Network Components
E_{LT}	Energy Contribution of Load Components
E_{GT}	Energy Contribution of Generators
n_B, n_G, n_L	The number of total buses, generator buses and load buses respectively
$Y_{pq,rd}$	The admittance matrix for the reduced network
H	Moment of Inertia of the Generator
δ	Generator Rotor Angle
ω	Generator Rotor Speed
T_m	Generator Mechanical Torque
T_e	Generator Electrical Torque
K_{Exc}	Exciter Gain
V_t	Exciter Terminal Voltage

K_D	Damping Torque Coefficient
$\hat{X}_p$	p-th Order Deviation Vector
v_X^2	Instantaneous Error
δ_T	Local Stability Level
K_{d_1}, K_{d_2}	Gains
Σ	Diagonal Matrix
$\vec{V}_k(t)$	Voltage Measurement Samples
$\vec{I}_k(t)$	Current Measurement Samples
<i>Subscript pu</i>	Per unit value of the respective variable
$E_S \angle \delta_s$	Internal EMF of synchronous generator connected to SMIB system
$V_B \angle \theta_B$	Infinite bus voltage magnitude and angle
X_T	Transmission line reactance of the transmission line connecting synchronous generator to SMIB system
$V_T \angle \theta_T$	Synchronous generator terminal voltage and its angle