LOW-FREQUENCY OSCILLATION MONITORING:

EXTRACTION, CHARACTERIZATION, ESTIMATION AND SOURCE LOCALIZATION

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by

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न गुरुर अधिकं तत्वं न गुरुर अधिक तपः ।
तत्व ज्ञानात परं नास्ति तस्मै श्री गुरवे नमः ॥

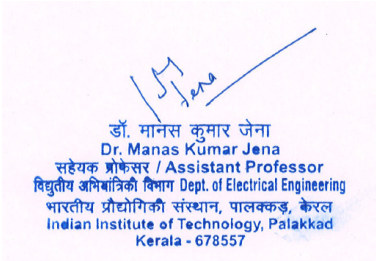
----- श्री गुरु स्तोत्रम्

No theory is more than the Master, No spiritual Work is more than the Master, There is nothing beyond deep knowledge, but there is Master whom we pray.

----- Shri Guru Strotram

CERTIFICATE

This is to certify that the thesis entitled **'LOW-FREQUENCY OSCILLATION MONITORING: EXTRACTION, CHARACTERIZATION, ESTIMATION AND SOURCE LOCALIZATION'**, being submitted by **Arup Anshuman** to **Indian Institute of Technology, Delhi** is a record of bonafide research work carried out under my supervision and I consider it worthy for consideration of the award of the degree **Doctor of Philosophy** in Electrical Engineering. The results obtained here have not been submitted to any other University or Institute for the award of any degree or diploma.



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— Arup Anshuman

Abstract

Real-time monitoring of oscillation events provides enhanced wide-area situational awareness to the system operator. This thesis focuses on the impact of low-frequency oscillations on power system stability, providing crucial insights to operators by visualizing these low-frequency modes with appropriate characterizations. In the initial phase, a novel adaptive signal processing approach is introduced to extract oscillatory modes from the signal using the "Frequency Partition-Based Mode Extraction (FPBME)" algorithm. These modes are then analyzed and classified as governor, inter-area, and local modes through a unique energy-preserving "Energy-Based Mode Detection and Classification (EBMDC)" algorithm. Instantaneous Energy (IE) and Instantaneous Frequency (IF), serving as nonlinear characterizations, are carried out using a window selection algorithm in the subsequent phase. This aids in better estimation of the damping ratio and frequency of oscillatory modes through traditional linear techniques such as Prony Analysis (PA), Matrix Pencil (MP), and Eigensystem Realization Algorithm (ERA).

In the latter part, the implementation of mode extraction and modal estimation algorithms is extended to larger systems through the concept of dynamic coherency. This work aims to establish a robust analysis platform for oscillatory stability by capturing a condensed set of independent spatiotemporal patterns utilizing frequency deviation signals at the buses following disturbances. Measurements available at the buses of the system are organized through the conjunction of two innovative algorithms employed sequentially: the linear Temporal Energy-based Karhunen Loeve Decomposition (TEKLD) algorithm and the non-linear Coherence-assisted Dynamic Time Warping (CDTW) algorithm. Finally, the thesis proposes a method for identifying the source location of sustained forced oscillations (FO), both in conventional and inverter-integrated systems, utilizing a complex dissipating energy technique.

Key Words: Low-Frequency Oscillations, Modal Extraction, Modal Estimation, Dynamic Coherency and Source Oscillation

सार

समयागतिक दोलनों का निष्कर्षण और दृश्यावलोकन गतिविधायुक्त प्रतिमानों की प्रत्याशा, अनुमान, तथा प्रारूप न्यूनीकरण हेतु पावर सिस्टम संचालकों के लिए काफी सूचनात्मक रहा है| यह शोधप्रबंध कम आवृत्ति वाले दोलनों का पावर सिस्टम के स्थिरता पर प्रभाव को व्याखित करता है, ताकि पावर सिस्टम संचालकों को लघुआवृत्ति वाले दोलनों को सही प्रतिमानों के साथ दर्शित करने में सहाय्यता मिले| प्रारम्भ में, एक अभिनव अनुकलनीय सिग्नल संसाधन को प्रस्तुत किया है, जिसको "आवृत्ति विभाजन आधारित मोड निष्कर्षण (FPBME)" नामक प्रक्रिया द्वारा दोलन मोड्स को सिग्नल्स से निष्कर्षित करता है| तत्पश्चात उन दोलन मोड्स को "ऊर्जा आधारित मोड परिचिति एवं वर्गीकरण (EBMDC)" नामक अल्गोरिथम द्वारा गवर्नर, अन्तर-क्षेत्रीय, एवं स्थानिक मोड्स में विश्लेषित तथा वर्गीकृत किया गया है| तात्कालिक ऊर्जा और तात्कालिक आवृत्ति, जो की अरेखीय परिमाण लक्षीकृत करते हैं, उनको पट्टिका चयन प्रक्रिया द्वारा अनुवर्ती चरण में प्राप्त किया गया है| प्रोनी विश्लेषण (PA), मैट्रिक्स पेंसिल (MP), एवं आइगन सिस्टम रियलाइज़ेशन (ESR) जैसे पारंपारिक रेखीय एल्गोरिद्म्स द्वारा धीमीकरण अनुपात और दोलनों की आवृत्ति को सही ढंग से अनुमानित करने में यह विशेषरूप से मदद कर सकता है|

प्रबंध के अगले चरण में, दोलन निष्कासन तथा अनुमान के एल्गोरिदम्स को बड़े पैमाने पर प्रणाली में कार्यान्वित करने की गतिशील सुसंगतता की संकल्पना पर आधारित एक विधि को प्रकाशित किया है| यह कार्य स्वतन्त्र समयागतिक तथा स्थानागतिक प्रारूपों को संग्रहित करके दोलनस्थिरता के ठोस विश्लेषण को एक मंच प्रस्थापित करता है, जो सिस्टम्स में गड़बड़ी के बाद मिलने वाले आवृत्ति विचलन सिग्नल्स को उपयुक्त करता है| सिस्टम की बसों में उपलब्ध मापों को "रैखिक अस्थायी ऊर्जा-आधारित करहुनेन लोवे अपघटन (TEKLD)" एवं "गैर-रैखिक जुटना-सहायता प्राप्त गतिशील समयतान (CDTW)" नामक दो अभिनव एल्गोरिदम्स द्वारा अनुक्रमिक रूप से संगठित किया गया है| अंततः इस प्रबंध में, एक जटिल अपव्यय ऊर्जा तकनीक का उपयोग करके निरंतर दबाववशित दोलनों के स्रोत को खोजने हेतु एक प्रक्रिया प्रकाशित की गयी है, जो की परंपरागत तथा इन्वर्टर आधारित पावर सिस्टम्स में भी उपयुक्त हो सकती है|

प्रमुख शब्द: गतिशील सुसंगतता, कम आवृत्ति दोलन, मोडल निष्कर्षण, मोडल अनुमान, और स्रोत स्थानीयकरण.

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Nomenclature

Acronyms/Abbreviations

AM Amplitude Modulated

CDEF Complex Dissipative Energy Function

CDTW Coherence-assisted Dynamic Time Warping

COI Center of Inertia

CWT Continuous Wavelet Transform

DFT Discrete Fourier Transform

EBMDC Energy-based Mode Detection and Classification

EDA Energy Decomposition Algorithm

EMD Empirical Mode Decomposition

ERA Eigensystem Realization Algorithm

EWT Empirical Wavelet Transform

FFT Fast Fourier Transform

FM Frequency Modulated

FO Forced oscillations

FPBME Frequency partition-based mode extraction

FPS Frames per second

FS Fourier Spectrum

HHT Hilbert-Huang Technique

HSA Hilbert Spectral Analysis

IAM Inter-Area Mode

IBR Inverter Based resources

IDI Inertia Distribution Index

IDM Inertia distribution Monitoring

IE Instantaneous Energy

IF Instantaneous Frequency

IP Instantaneous Phase

IPP Independent Power Providers

ISO-NE Independent System Operator-New England

KLD Karhunen Loeve Decomposition

LFO Low Frequency Oscillations

LM Local Modes

MMC Multi-Modal components

MP Matrix Pencil

MSST Multisynchrosqueezing transform

NASPI North American Synchrophasor Initiative

NETS New-England Test System

NYPS New York Power System

OEM Original equipment manufacturer

OSM Oscillatory stability management

PA Prony Analysis

PDC Phasor data concentrator

PMU Phasor Measurement Unit

PSS Power System Stabilisers

SCADA Supervisory Control And Data Acquisition

STFT Short-Time Fourier Transform

TEKLD Temporal Energy-based Karhunen Loeve Decomposition

TFR Time-Frequency Representation

UTS Univariate Time Series

WECC Western Electricity Coordinating Council