ANALYSIS AND ENHANCEMENT OF SMALL-SIGNAL DYNAMICS IN INVERTER DRIVEN POWER SYSTEMS

AKSHITA SHARMA

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

ANALYSIS AND ENHANCEMENT OF SMALL-SIGNAL DYNAMICS IN INVERTER DRIVEN POWER SYSTEMS

by

AKSHITA SHARMA

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfillment of requirements of degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

Dedicated to *My Parents*

CERTIFICATE

This is to certify that the thesis entitled **'ANALYSIS AND ENHANCEMENT OF SMALL-SIGNAL DYNAMICS IN INVERTER DRIVEN POWER SYSTEMS'**, being submitted by **Akshita Sharma** 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.

Prof. Bijaya Ketan Panigrahi
Department of Electrical Engineering,
Indian Institute of Technology Delhi,
New Delhi - 110016, India.

Date:

Acknowledgments

In this moment of reflection, I find myself overwhelmed with gratitude for the incredible individuals who have been instrumental in bringing this thesis to fruition.

First and foremost, I am immensely grateful to my supervisor, Prof. B. K. Panigrahi, for his guidance, support, and invaluable insights throughout the research process. His dedication to fostering intellectual curiosity and scholarly excellence has been a constant source of inspiration. I am thankful to him for the freedom of research he provided during the entire duration, which made me an independent and broad thinker.

I extend my heartfelt thanks to the doctoral research committee members viz. Prof. Shubhendu Bhasin, Prof. Sumit Pramanick, and Prof. S.K. Chattopadhyay. Their insightful feedback and genuine interest in my work have enriched the depth and quality of this thesis. I am forever indebted to IIT, Delhi for providing the resources and environment conducive to academic exploration.

I also thank the Ministry of Human Resource Development (MHRD), Government of India, for providing the financial support to complete the Doctoral program at IIT Delhi successfully.

I am truly fortunate to have met Dr. Pankaj D. Achlerkar at IIT Delhi, who has been my senior mentor and wonderful collaborator since then. His presence has been a beacon of light, guiding me through all the challenges and uncertainties of this prolonged journey.

I want to convey my sincere appreciation to the cherished people in my life: my friends and family for being my biggest support system. Their patience, encouragement, and understanding during the highs and lows of this journey have made all the difference.

Finally, it is imperative to convey that words fall short of capturing the depth of gratitude I harbor for my parents. Their unyielding support, empathetic understanding, and countless sacrifices have been the cornerstones of my journey. Their relentless aspiration for my success has consistently propelled me to strive for excellence throughout my professional as well as personal journey.

— Akshita Sharma

Abstract

The growing penetration of inverter-based energy resources in power grids is causing continuous decrease in grid strengths, various new oscillation modes, systems interactions, and instability issues. Lack of detailed electromagnetic transient (EMT) models of individual inverters, lack of modeling and analysis experience with inverters with heterogeneous technologies, and lack of traceability of observed oscillatory modes are some challenges faced by system operators. On the contrary, key issues faced by inverter manufacturers include a lack of clear design guidelines from system operators in terms of output impedance and contribution to system interactions. To address some of the issues, this work firstly analyzes a single inverter-to-grid interface. Its model in time and frequency domains is carried out to develop an easily implementable optimal state-feedback control solution based on the linear quadratic regulator concept. Further, the work is extended to generic power systems with multiple heterogeneous inverters, where the small-signal modeling inaccuracies are identified and resolved by eliminating the need for fictitious parameters. The system interactions amongst inverters, loads, and grid are analyzed and indicators are proposed to quantify them. All propositions are validated from theory, by offline and real-time simulation case studies, and on the laboratory-scale power hardware-in-loop (PHIL) setup. Potential applications include accurate stability analysis, dynamic aggregation, coherency detection, oscillation source detection, new resource integration compliance studies, etc. This work would be a crucial asset for original equipment manufacturers (OEMs) as well as power system operators.

Key Words: Inverter-based Resources (IBRs), Small-Signal Stability, Weak Grid, Dynamic Aggregation, System Interactions.

सारांश

पावरग्रिड में इन्वर्टर-आधारित ऊर्जा संसाधनों के बढ़ते प्रमाण से ग्रिड की प्रबलता में कमी, विभिन्न नए दोलन मोड, सिस्टम इंटरैक्शन और अस्थिरता के मुद्दों में लगातार बढ़ोतरी दिखाई देती है| अलग-अलग इन्वर्टर के विस्तृत विद्युत-चुम्बकीय क्षणिक मॉडल का अभाव, विषम प्रौद्योगिकियों वाले इन्वेर्टर्स के साथ मॉडलिंग और विश्लेषण के अनुभव की कमी, देखे गए दोलन मोड के अनुमार्गणीयता की कमी, यह सिस्टम परिचालकों द्वारा सामना की जाने वाली कुछ चुनौतियां हैं। इसके विपरीत, इन्वर्टर निर्माताओं द्वारा सामना किए जाने वाले प्रमुख मुद्दों में आउटपुट प्रतिबाधा और सिस्टम इंटरैक्शन में योगदान के संदर्भ में सिस्टम ऑपरेटरों से स्पष्ट डिजाइन दिशानिर्देशों की कमी शामिल है। इनमें से कुछ प्रमुख मुद्दों को हल करने के लिए, यह शोध प्रबंध सबसे पहले ग्रिड इंटरफ़ेस के लिए एक अकेले इन्वर्टर का विश्लेषण करता है। समय तथा आवृत्ति डोमेन में इसका मॉडल रैखिक द्विघात नियामक अवधारणा के आधार पर आसानी से कार्यान्वयन योग्य इष्टतम अवस्था-प्रतिक्रिया नियंत्रण आधारित समाधान विकसित करने के लिए किया गया है। शोध के अगले काम में, कई विषम इन्वेर्टर्स के साथ जुड़े हुए सामान्यीकृत विद्युत् प्रणाली को ध्यान में लिया गया है, जहां छोटे-सिग्नल मॉडलिंग अशुद्धियों की पहचान की को ध्यान में लिया गया है और काल्पनिक प्रतिमानों की आवश्यकता को समाप्त करके हल बताया गया है। इन्वर्टर, लोड और ग्रिड के बीच सिस्टम में हो रहे परस्पर संबंधों का विश्लेषण किया गया है और उन्हें निर्धारित करने के लिए संकेतक प्रस्तावित किए हैं। सभी प्रस्तावों को सिद्धांत से, ऑफ़लाइन और वास्तविक समय सिमुलेशन केस-स्टडी और प्रयोगशाला-पैमाने पर पावर हार्डवेयर-इन-लूप (फिल) सेटअप पर मान्य किया जाता है। इस शोध कार्य के संभावित अनुप्रयोगों में सटीक स्थिरता विश्लेषण, गतिशील एकत्रीकरण, समन्वय का पता लगाना, दोलन स्रोत का पता लगाना, नए संसाधन एकीकरण अनुपालन अध्ययन आदि शामिल हैं। यह काम मूल उपकरण निर्माताओं (ओईएम) के साथ-साथ बिजली प्रणाली ऑपरेटरों के लिए एक महत्वपूर्ण संपत्ति होगी।

प्रमुख शब्द: इन्वर्टर आधारित संसाधन (आईबीआर), लघु-सिग्नल स्थिरता, निर्बल ग्रिड, डायनेमिक एकत्रीकरण, सिस्टम इंटरैक्शन|

Contents

List of Figures

List of Tables

Nomenclature

Acronyms/Abbreviations

AC Alternating Current

ARE Algebraic Riccati Equation

CHIL Controller Hardware-in-Loop

CIGRE Conseil International des Grands Réseaux Electriques (International Council on Large Electric Systems)

DC Direct Current

DG Distributed Generator

EMT Electromagnetic Transient

FACTS Flexible Alternating Current Transmission Systems

FFT Fast Fourier Transform

GFL Grid Following

GFM Grid Forming

HIL Hardware-in-Loop

HVDC High Voltage Direct Current

HVRT High Voltage Ride Through

IBR Inverter Based Resource

IEEE Institute of Electrical and Electronics Engineers

IGBT Insulated Gate Bipolar Transistor

LQR Linear Quadratic Regulator

LTI Linear Time-Invariant

LTP Linear Time-Periodic

LVRT Low Voltage Ride Through

MATLAB *MATrix LABoratory*

MIMO Multiple Input Multiple Output

NERC North-American Electric Reliability Corporation

OEM Original Equipment Manufacturer

PCC Point of Common Coupling

PHIL Power Hardware-in-Loop

PI Proportional Integral

PLL Phase Locked-Loop

PoI Point of Interconnection

RCP Rapid Control Prototyping

RMS Root Mean Square

SCR Short Circuit Ratio

SISO Single Input Single Output

SRF Synchronous Reference Frame

VSC Voltage Source Converter

List of Suffixes/Superscripts

$(\cdot)^{\text{IBR,G}}$ IBR to Grid interaction

$(\cdot)^{\text{IBR,L}}$ IBR to Load interaction

$(\cdot)^{\text{IBR}}$ IBR to IBR interaction

$(\cdot)_{\alpha\beta}$ Stationary $\alpha\beta$ reference frame

$(\cdot)_{abc}$ Natural abc reference frame

$(\cdot)_{DQ}$ Global DQ reference frame

$(\cdot)_{dq}$ Local dq reference frame