

**DYNAMIC FLEXIBILITY STUDIES IN
POWER SYSTEMS**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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POWER SYSTEMS**

by

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DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2023

Dedicated
to
My Parents

CERTIFICATE

This is to certify that the thesis entitled “**Dynamic Flexibility Studies in Power Systems**” submitted by **Mr. Debargha Brahma**, 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.

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Abstract

This thesis is focused to add a new paradigm in power system flexibility studies, by introducing the concept of dynamic grid flexibility (DGF). The proposed DGF framework incorporates operational flexibility with power system dynamics quantitatively, by defining two metrics – inertial index and flexibility index. These indices capture the impact of location-specific power fluctuation, which may arise due to demand variability or supply intermittency, on two system-inherent dynamic properties. The crux of the thesis is in developing these metrics of DGF using model-based and measurement-based methods, and showcasing their applications in various power system planning and operational studies. Some of the novel methods and key applications that have been discussed in this thesis are:

- 1) An analytical method of assessing the spatial distribution of inertia has been proposed. The method uses the notion of network sensitivity, to measure the locational capability of a system to resist fluctuations in bus voltage angle, and the location where these fluctuations are least is considered nearest to the center of inertia (COI).
- 2) An analytical method of calculating the capability of the system to tolerate power fluctuations due to demand variability or supply intermittency at a particular location. The flexibility index ranks the buses according to the impact of bus power injection changes on system stability. The system will exhibit the highest tolerance (or show highest flexibility) when change of injection level of a certain bus will have least impact on the damping of the most critical oscillatory mode, and this bus is designated as the most flexible bus (MFB) of the system.
- 3) Application of these indices could be instrumental for both planning and operational studies. Some of the applications that have been explored in this thesis using the information of these two indices are: optimal position for sitting of renewable energy sources (RES), impact of changing network topology and parametric variations on system dynamics, identification of coherent bus groups, mitigation strategies for the adverse effect of RES fluctuations on system stability, etc.
- 4) Using the notion of matrix perturbation theory for the first time in power system flexibility studies, a numerical-based method for calculating the metrics of DGF is proposed. The advantages of this method over its analytical counterpart are also highlighted.

- 5) A unified method with real-time capability for estimating effective nodal inertia under both ambient and transient conditions is proposed. The proposed method does not require additional noise-prone information like rate of change of frequency (ROCOF) and its threshold and rate of change of power and its threshold.

Key words: Power System Dynamics, Inertia Distribution, Power System Flexibility, Eigenvalue Sensitivity, Network Sensitivity, Center of Inertia, Coherent Bus Groups, Matrix Perturbation Theory, Condition Number, Online Inertia Estimation.

सार

यह थीसिस गतिशील ग्रिड लचीलेपन (DGF) की अवधारणा को पेश करके, बिजली प्रणाली लचीलेपन के अध्ययन में एक नया प्रतिमान जोड़ने पर केंद्रित है। प्रस्तावित DGF ढांचा दो मेट्रिक्स - जड़त्विय सूचकांक और लचीलापन सूचकांक को परिभाषित करके, मात्रात्मक रूप से बिजली प्रणाली की गतिशीलता के साथ परिचालन लचीलेपन को शामिल करता है। ये सूचकांक स्थान-विशिष्ट बिजली के उतार-चढ़ाव के प्रभाव को पकड़ते हैं, जो दो सिस्टम-निहित गतिशील गुणों पर मांग परिवर्तनशीलता या आपूर्ति रुक-रुक कर उत्पन्न हो सकता है। थीसिस का सार मॉडल-आधारित और माप-आधारित तरीकों का उपयोग करके डीजीएफ के इन मेट्रिक्स को विकसित करना और विभिन्न बिजली प्रणाली योजना और परिचालन अध्ययनों में उनके अनुप्रयोगों को प्रदर्शित करना है। इस थीसिस में जिन कुछ नवीन तरीकों और प्रमुख अनुप्रयोगों पर चर्चा की गई है वे हैं:

- 1) जड़ता के स्थानिक वितरण का आकलन करने की एक विश्लेषणात्मक विधि प्रस्तावित की गई है। यह विधि बस वोल्टेज कोण में उतार-चढ़ाव का विरोध करने के लिए सिस्टम की स्थानीय क्षमता को मापने के लिए नेटवर्क संवेदनशीलता की धारणा का उपयोग करती है, और जिस स्थान पर ये उतार-चढ़ाव सबसे कम होते हैं उसे जड़ता के केंद्र (COI) के निकटतम माना जाता है।
- 2) किसी विशेष स्थान पर मांग परिवर्तनशीलता या आपूर्ति में रुकावट के कारण बिजली के उतार-चढ़ाव को सहन करने की प्रणाली की क्षमता की गणना करने की एक विश्लेषणात्मक विधि। लचीलापन सूचकांक सिस्टम स्थिरता पर बस पावर इंजेक्शन परिवर्तनों के प्रभाव के अनुसार बसों को रैंक करता है। सिस्टम उच्चतम सहनशीलता प्रदर्शित करेगा (या उच्चतम लचीलापन दिखाएगा) जब एक निश्चित बस के इंजेक्शन स्तर में परिवर्तन से सबसे महत्वपूर्ण दोलन मोड की भिगोना पर कम से कम प्रभाव पड़ेगा, और इस बस को सबसे लचीली बस (MFB) के रूप में नामित किया गया है। प्रणाली।
- 3) इन सूचकांकों का अनुप्रयोग योजना और परिचालन अध्ययन दोनों के लिए महत्वपूर्ण हो सकता है। इन दो सूचकांकों की जानकारी का उपयोग करके इस थीसिस में जिन कुछ अनुप्रयोगों का पता लगाया गया है वे हैं: नवीकरणीय ऊर्जा स्रोतों (RES) की स्थिति के लिए इष्टतम स्थिति, बदलते नेटवर्क टोपोलॉजी का प्रभाव और सिस्टम गतिशीलता पर पैरामीट्रिक विविधताएं, सुसंगत बस समूहों की पहचान, सिस्टम स्थिरता आदि पर आरईएस उतार-चढ़ाव के प्रतिकूल प्रभाव के लिए शमन रणनीतियाँ।

- 4) पावर सिस्टम लचीलेपन के अध्ययन में पहली बार मैट्रिक्स गड़बड़ी सिद्धांत की धारणा का उपयोग करते हुए, DGF के मैट्रिक्स की गणना के लिए एक संख्यात्मक-आधारित विधि प्रस्तावित है। इसके विश्लेषणात्मक समकक्ष की तुलना में इस पद्धति के लाभों पर भी प्रकाश डाला गया है।
- 5) परिवेशीय और क्षणिक दोनों स्थितियों के तहत प्रभावी नोडल जड़ता का आकलन करने के लिए वास्तविक समय क्षमता वाली एक एकीकृत विधि प्रस्तावित है। प्रस्तावित विधि में अतिरिक्त शोर-प्रवण जानकारी की आवश्यकता नहीं होती है जैसे आवृत्ति के परिवर्तन की दर (ROCOF) और इसकी सीमा और शक्ति के परिवर्तन की दर और इसकी सीमा।

मुख्य शब्द: पावर सिस्टम डायनेमिक्स, इनर्टिया डिस्ट्रीब्यूशन, पावर सिस्टम फ्लेक्सिबिलिटी, आइजेनवैल्यू सेंसिटिविटी, नेटवर्क सेंसिटिविटी, सेंटर ऑफ इनर्टिया, सुसंगत बस समूह, मैट्रिक्स पार्टर्बेशन थ्योरी, कंडीशन नंबर, ऑनलाइन इनर्टिया एस्टीमेशन।

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LIST OF ABBREVIATIONS AND SYMBOLS

COI	Centre of Inertia
DAE	Differential Algebraic Equations
DGF	Dynamic Grid Flexibility
FD	Frequency Divider
FLOP	Floating Point Operations
MFB	Most Flexible Bus
MPT	Matrix Perturbation Theory
NETS	New England Test System
NRPG	Northern Regional Power Grid
NYPS	New York Power System
ODE	Ordinary Differential Equations
PMU	Phasor Measurement Unit
PSS	Power System Stabilizer
PV	Photovoltaic
RES	Renewable Energy Sources
ROCOF	Rate of Change of Frequency
SG	Synchronous Generation
SPC	Synchronizing Power Coefficient
VG	Variable Generation
VSG	Virtual Synchronous Generation
AVR	Automatic Voltage Regulator
L_{index}	Localness Index
ρ	Participation Factor
δ	Rotor Angle
ω	Rotor Speed
ω_s	Rated Synchronous Speed
θ	Network Bus Voltage Angle

V	Network Bus Voltage Magnitude
E	Machine Internal Voltage Magnitude
Y	Bus Admittance Matrix, $Y = G + jB$
H	Machine Inertia Constant / Effective Inertia
D	Machine Speed Damping
A_{sys}	State Matrix
λ	Eigenvalues of the State Matrix
ψ, w	Left Eigenvector
ϕ, v	Right Eigenvector
F_{index}, F	Flexibility Index
P_L	Active Power Loading Level
P_{gen}	Generator Active Power Output
Q_{gen}	Generator Reactive Power Output
x	State Vector
u	Input Vector
x_d'	d-axis Transient Reactance
J	Power-flow Jacobian Matrix
C	Sensitivity matrix
I_{index}	Inertial Index
vec	Vectorization Operator
K	Stiffness Matrix
M	Diagonal matrix $M = 2H/\omega_s$
A_s	Symmetric and Semi-definite Matrix $A_s = -M^{-1}K$
β	Eigenvalues of A_s
I_g	Generator Current Injection
ξ	Damping Ratio
P_ϵ	Perturbation Matrix
S	Right Eigenvector Matrix
Λ	Diagonal Matrix with Eigenvalues as Diagonal Entries

κ	Condition Number
τ	Relative Condition Number
K_a	Exciter Gain
T_a	Exciter Time Constant
I	Identity Matrix
A_u	Upstream Distribution Matrix
Z	Weighting Matrix
$TA_1, TA_2, TB_1,$ TB_2, τ_1, τ_3	Gradient terms associated with $\partial E / \partial P$
$TA_3, TA_4, TB_3,$ TB_4, τ_2, τ_4	Gradient terms associated with $\partial \delta / \partial P$