

CIGRE Green Book: Power System Dynamic Modelling and Analysis in Evolving Networks

Babak Badrzadeh and Zia Emin (editors)

*ESIG Webinar
22 January 2025*

Overview of Power System Dynamic Modelling and Analysis in Evolving Networks

Key Highlights



- The 14th (16 to date) CIGRE Green Book series to date
- Among few considered as a Major Reference Work
- First Green Book led by SC C4
- At approximately 900 pages, it is the second longest Green Book published to date.
- More than 70% of the contents were newly developed.
- Original planned to be delivered in five years with up to 800 pages
- Completed in three and half years with approximately 900 pages
- With more than 50 authors, it features one of the highest author/page ratio among Green Books
- Contributions from 11 countries

Real heroes



Miguel Cova Acosta

Udaya Annakkage

Babak Badrzadeh

Hitesh Bavarva

Jean Bélanger

Yunzhi Cheng

Sébastien Dennerrière

Zia Emin

Marta Val Escudero

Lingling Fan

Inalvis Alvarez Fernandez

Ioni Fernando

Gabriel M. Gomes Guerreiro

Sorrell Grogan

Yunjie Gu

Aboutaleb Haddadi

Andrew Halley

Rasool Heydari

Andy Hoke

Qiuhua Huang

Ismail Ibrahim

Andrew Isaacs

Chavdar Ivanov

David Jacobson

Bathiya Jayasekara

Adrian Kelly

Yicheng Liao

Genevieve Lietz

Jingwei Lu

Torsten Lund

Jason M. Macdowell

Jean Mahseredjian

Hesamaldin (Sam) Maleki

Benjamin Marshall

Julia Matevosyan

Amer Mesanovic

Parag Mitra

Nilesh Modi

Ulrich Muenz

Deepak Ramasubramanian

Hani Saad

Kasun Samarasekera

Jayapalan Senthil

Alex Shattuck

Douglas Wilson

Qiang “Frankie” Zhang

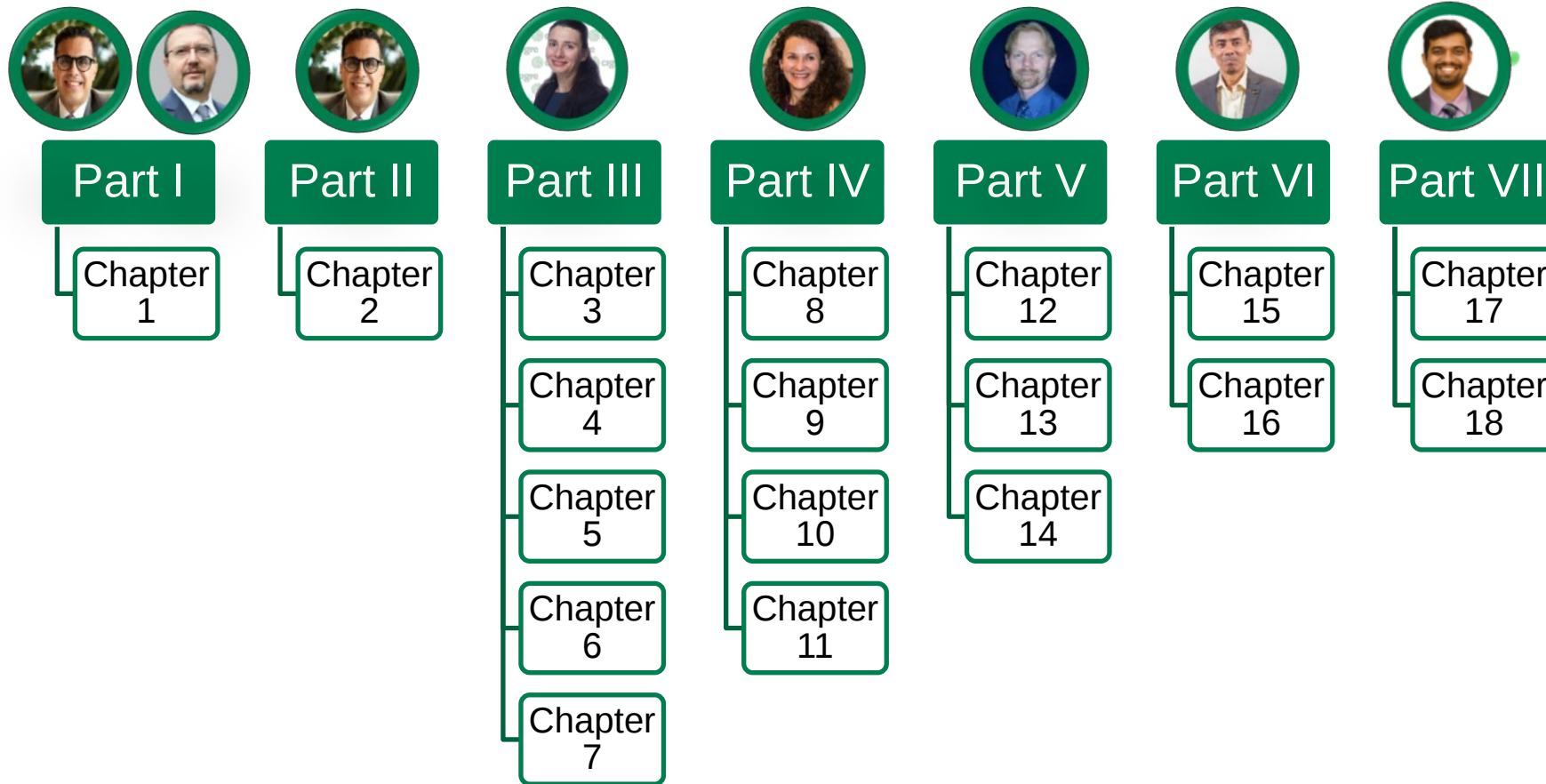
Qiming Zhang

Song Zhang

Yue Zhu

Dimitrios Zografos

Book structure



The fun part

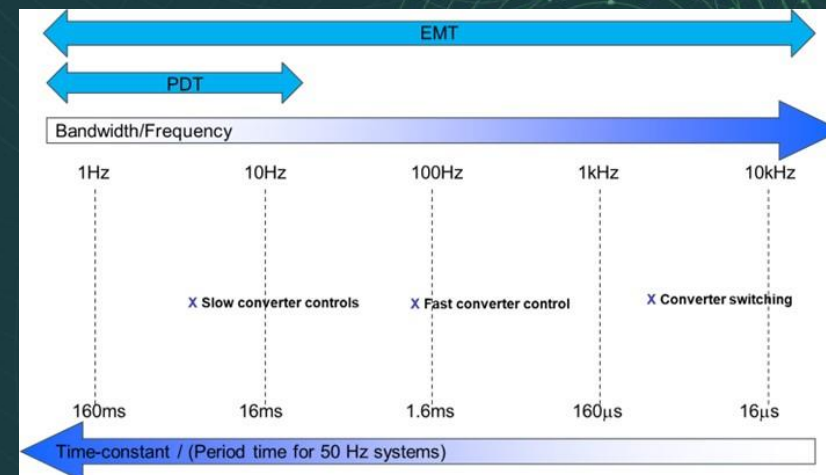
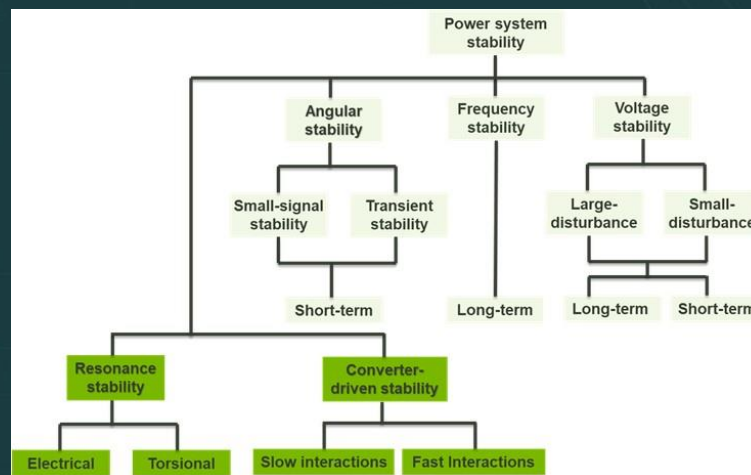
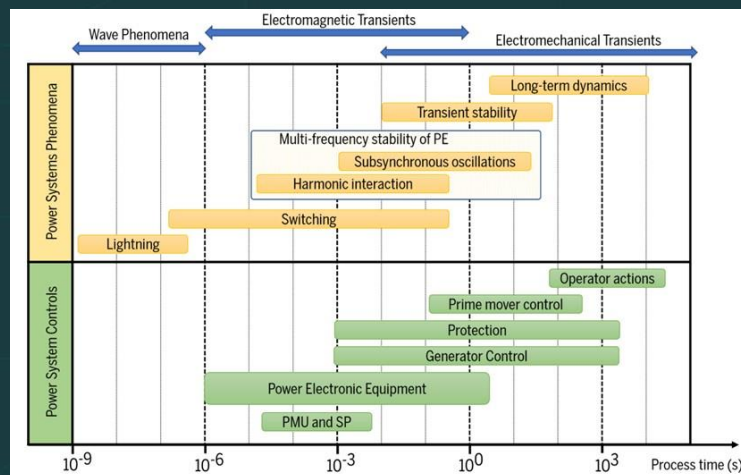


Part I – Changing Power Systems and Impact on Power System Dynamic Phenomena and Analysis Methods



Chapter 1

Changing Power Systems and Impact on Power System Dynamic Phenomena and Analysis Methods

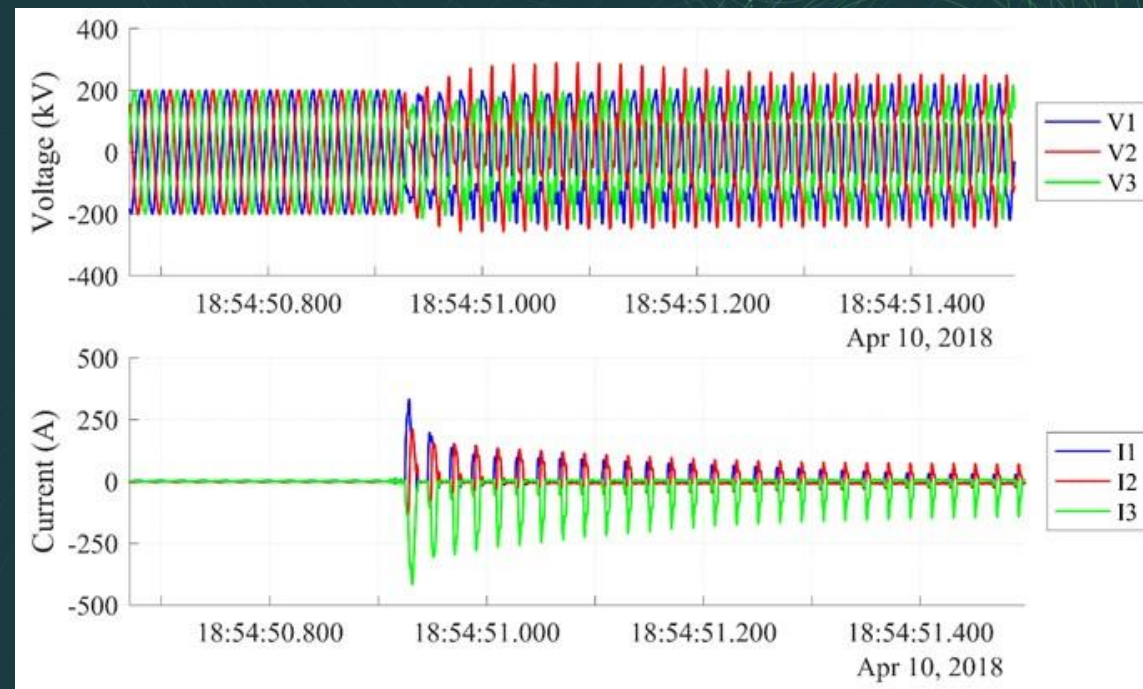
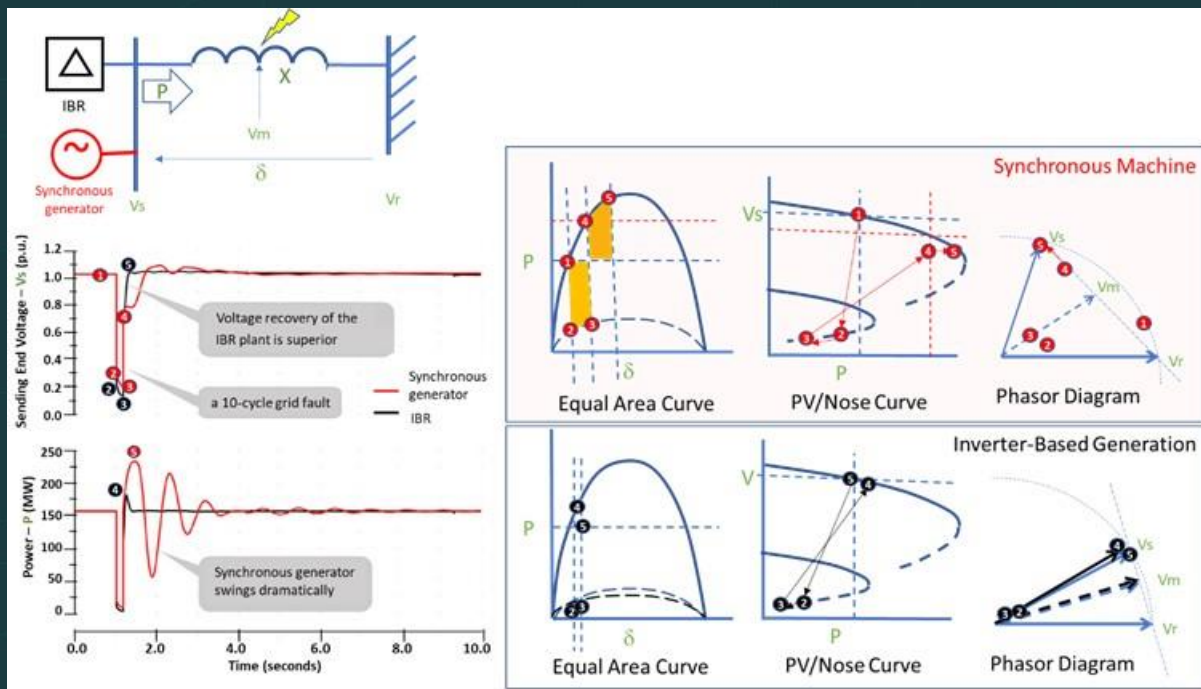


- Transition from classical to contemporary power system analysis
- Type of dynamic phenomena
- Type of tools
- Consideration on high IBR share
- Other drivers for new approaches

Part II – Power System Studies Under a High Penetration of Power Electronic Interfaced Devices

Chapter 2

Power System Dynamic Studies Under a High Penetration of Power Electronic Interfaced Devices



- Consideration in system stability analysis
- Interactions between system stability and power quality and system protection

Part III – Power System Dynamic Analysis Tools and Techniques and Their Evolution in Practice



3

Principles and Practical Considerations for the Use of Time-Domain Simulation Software Programs in Power System Dynamics Analysis

4

Practical Examples of the Use of PDT and EMT Simulation Including Their Unique Applications and Complementary Use

5

Screening Methods as Preliminary Calculations to Determine the Level and Type of Dynamic Modeling Required

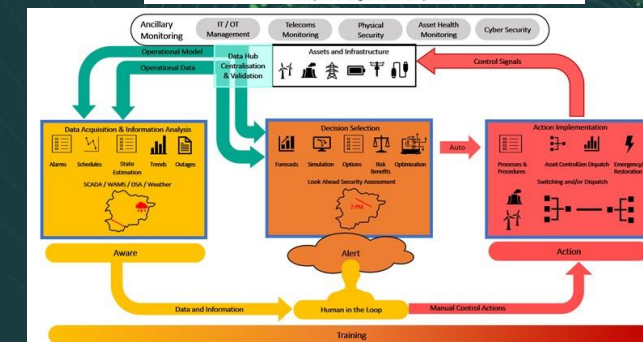
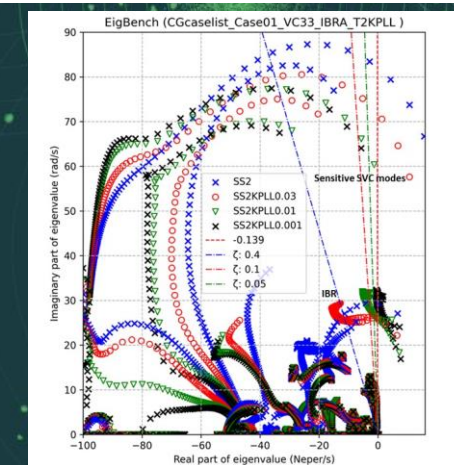
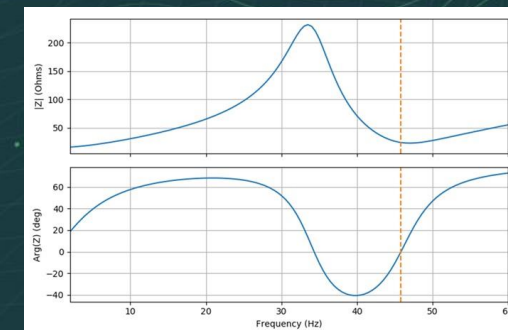
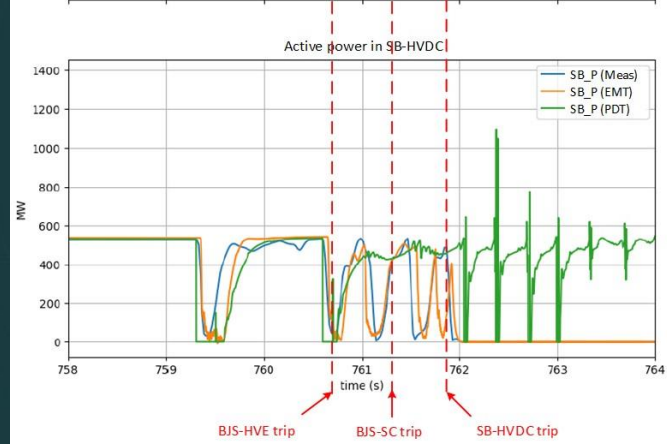
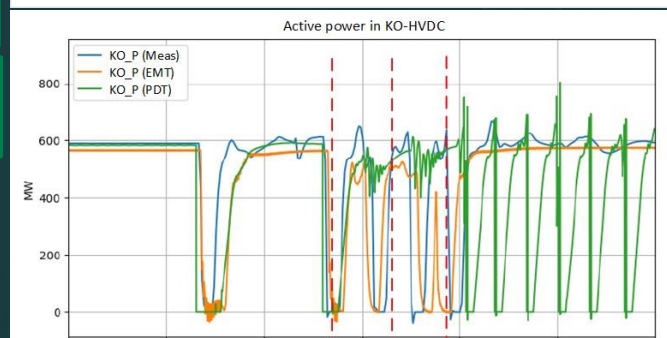
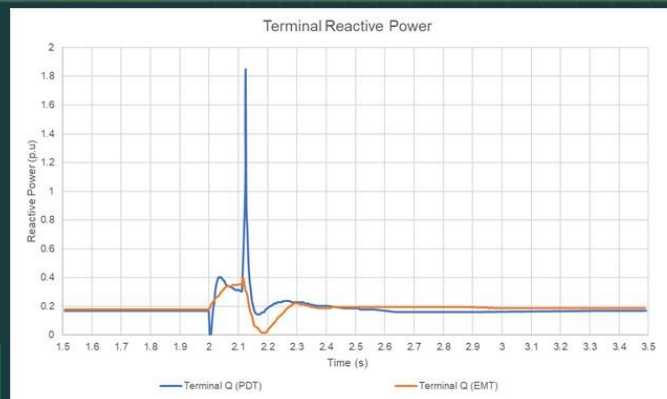
6

Linear Analysis Methods to Characterize Inherent Small-Signal Behavior of the Plant and Overall Power System

7

Operational Decision Support Tools for System Dynamic Response Awareness in Real-Time and Near-Real-Time Power System Operations

- Overview of PDT & EMT, differences, methods, real-time, co-simulation
- HVDC, system level EMT, low frequency interarea and complementary use of PDT & EMT examples
- Fault level, interaction based and other screening methods
- Eigenvalue and frequency domain (transfer function, impedance and passivity)
- WAM, state estimation and situational awareness



Part IV – Model and Data Requirements in Power Systems with a High Share of Power Electronic Interfaced Devices



8

Considerations, Challenges and Evolution in Dynamic Modeling of Synchronous Machines and Inverter-Based Resources

9

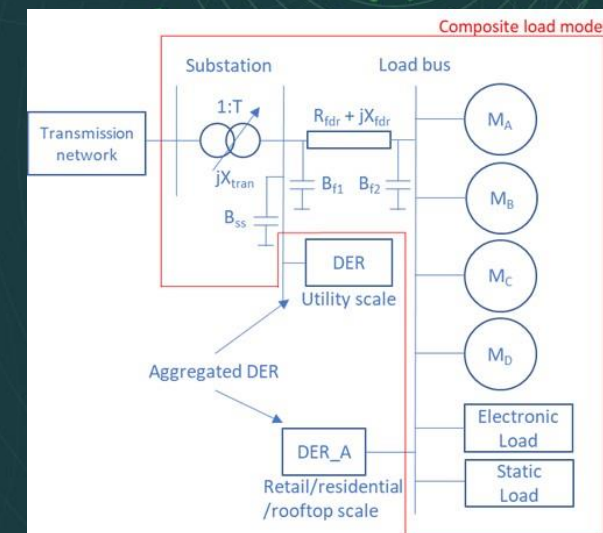
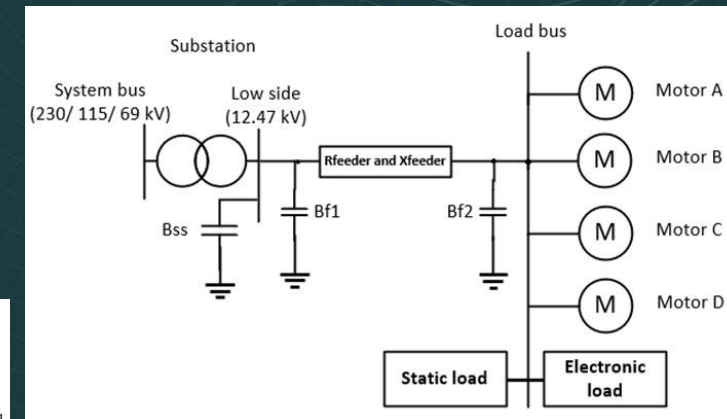
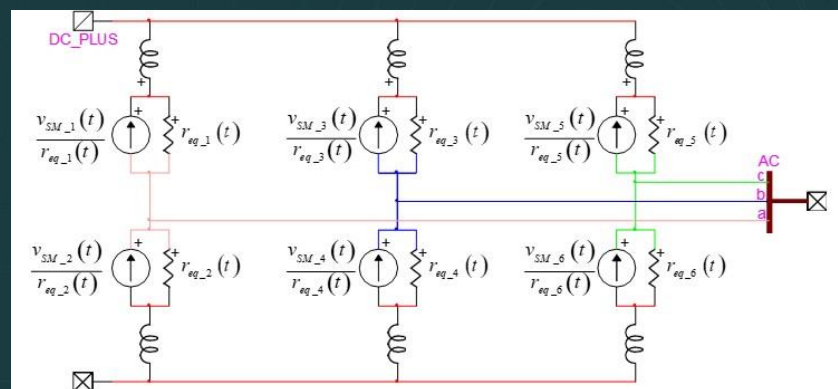
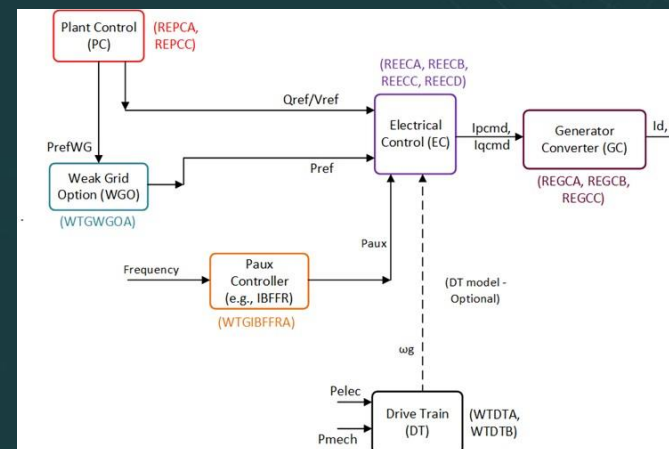
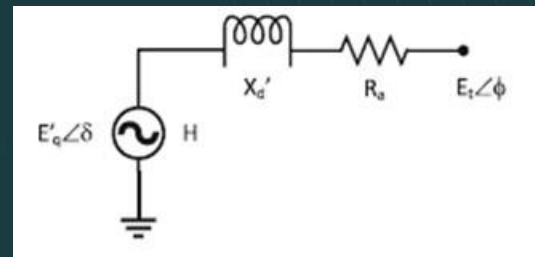
Summary of High-Voltage Direct Current (HVDC) Link Models for Operational and Planning System Dynamic Studies

10

Modeling Loads and Distributed Energy Resources with Focus on Wide-Area Power System Dynamic Performance Impact

11

Approaches in Transmission Network Modeling for EMT Dynamic Studies Including the Impact of Relevant Protection Systems



Overview of IBR and synchronous machine modelling, generic vs vendor specific

Physics based, full detailed, switchable, detailed equivalent etc for converter and upper/lower level control models

Load models, DER models

Network modelling, protection modelling

Part V – Dynamic System Study Guide from Operations to Planning

12

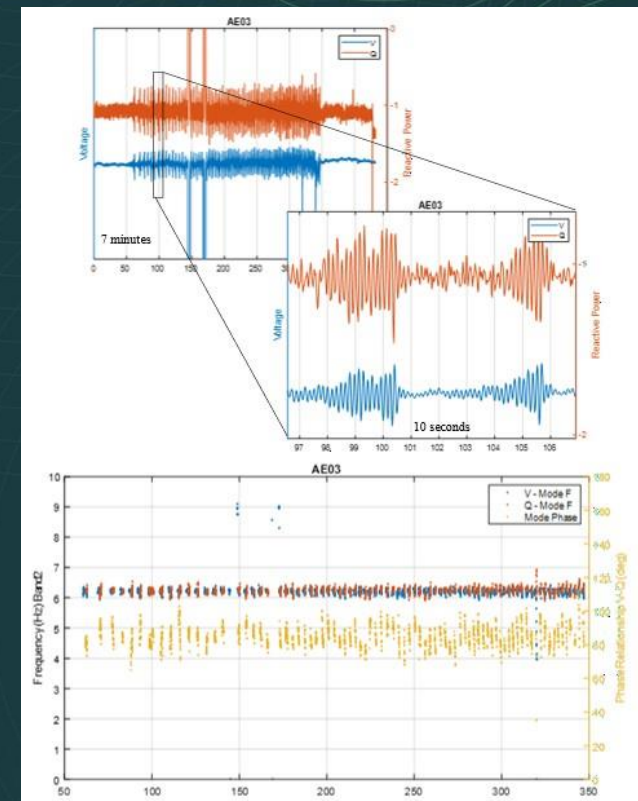
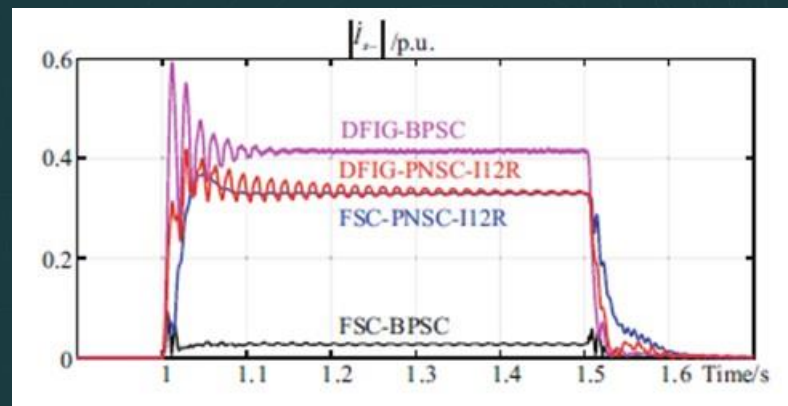
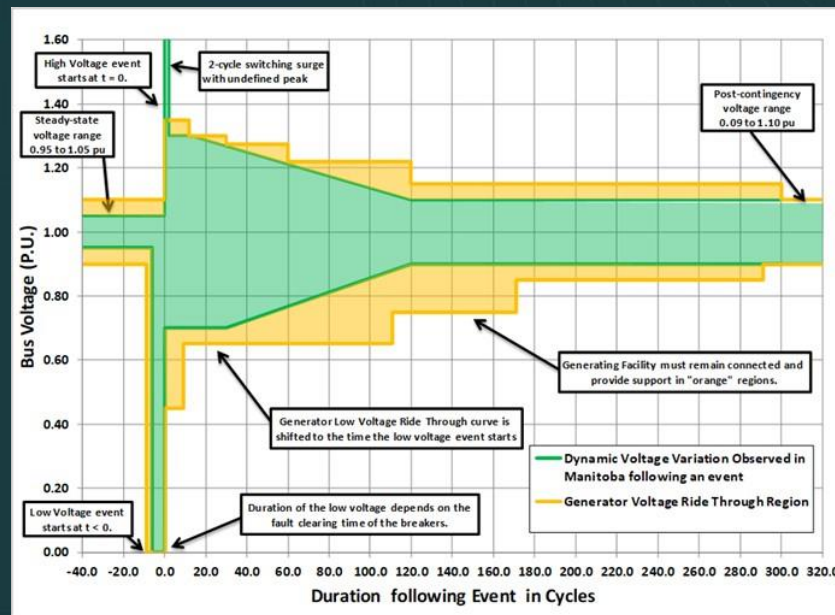
Grid Interconnection Study Procedures with Practical Examples for IBRs, HVDC and FACTS

13

Power System Planning and Operational Studies in Inverter-Dominated Networks: Interactions and Oscillation Studies, System Strength, and Inertia Determination

14

The Impact of Power System Plants Other Than Large-Scale Generation and Transmission Network on Wide-Area Power System Dynamic Performance Using Case Studies of DER, Microgrids, Industrial Power Systems, and Network Protection Systems



IBR, HVDC and FACTS interconnection studies, grid code requirements, case studies

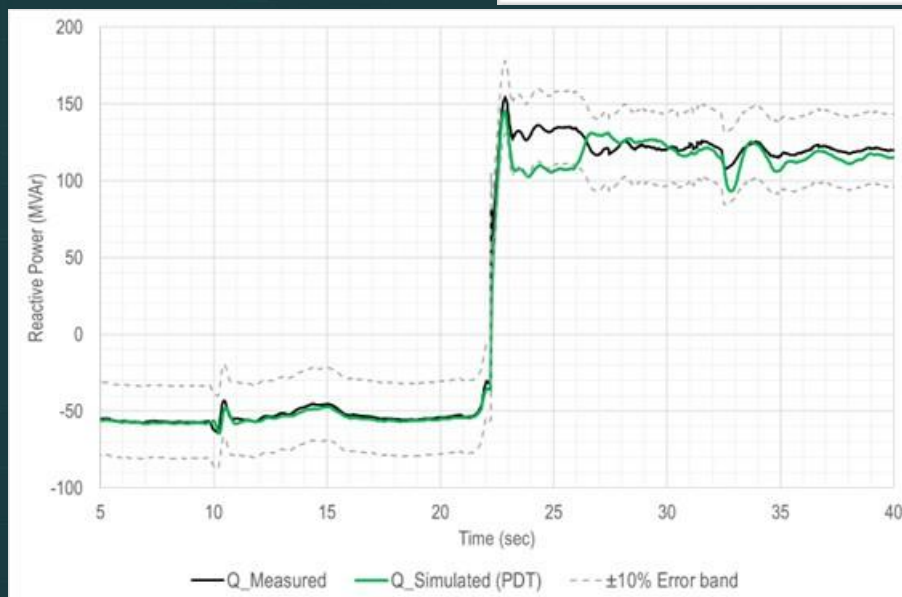
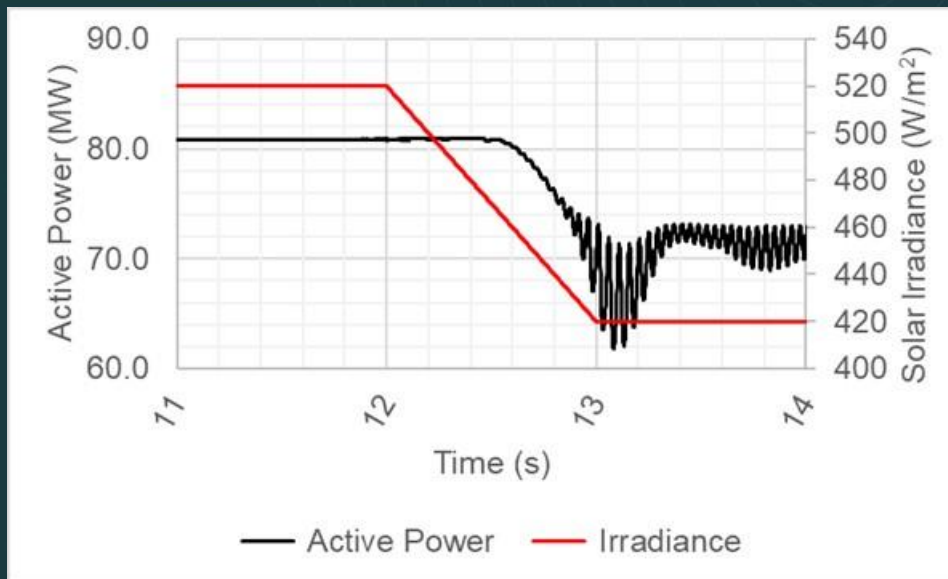
Practical examples of SSR, interaction studies and HVDC high-frequency interactions

Impact of IBR on various protection systems, impact of DER and microgrids etc

Part VI – Confidence in the Accuracy of Plant and Power System Models

- 15 Model Acceptance Testing
- 16 Power System Plant and Network Dynamic Model Validation

- Testing methodologies, general requirements and examples
- Importance of model validation, life cycle, how to get to a validated model



Part VII – Contemporary Enablers on Dynamics in Evolving Power Systems

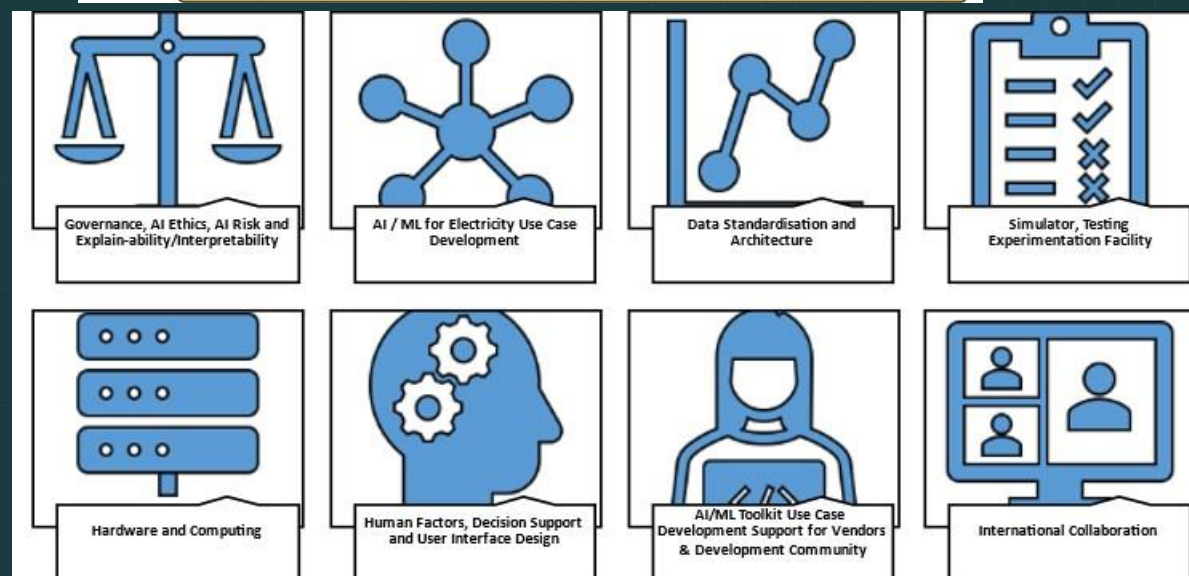
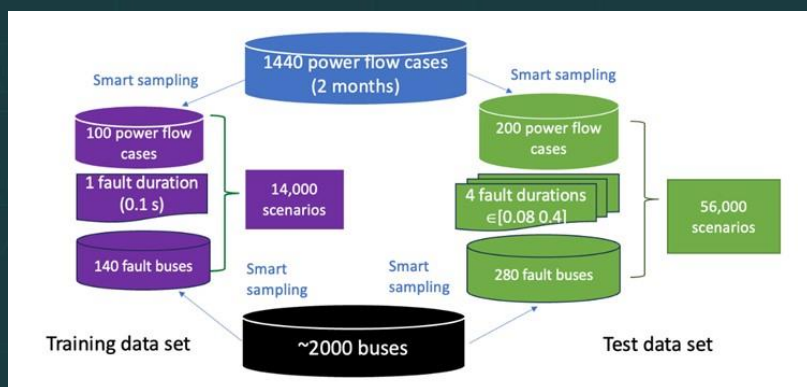
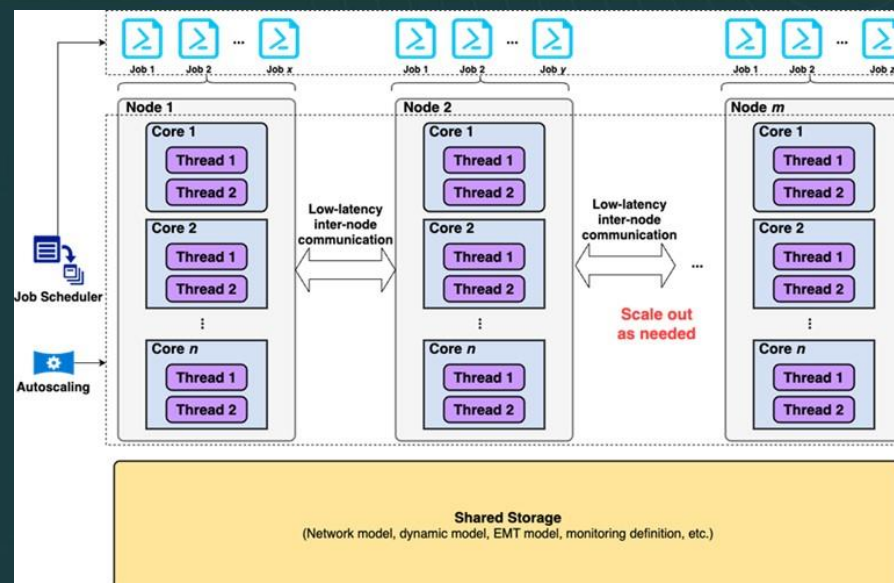
17

Computational Intelligence-Based Learning Techniques to Handle Uncertainty and Large Data Sets

18

Improving Case Creation Robustness Using Optimisation and Standardisation Techniques

- Cloud enabled scalable computing, artificial intelligence, machine learning, application examples
- Optimisation, big data analysis, standardisation, interoperability and conformity



Part I: Changing Power Systems and Impact on Power System Dynamic Phenomena and Analysis Methods

Drivers for the need to revisit power system dynamic modelling and analysis

Changing large-scale generation mix and types

Emergence of new technologies which are not well understood

Increased penetration of distributed energy resources and power electronic interfaced loads

Changing transmission and distribution networks

Increasing interactions between tools/phenomena

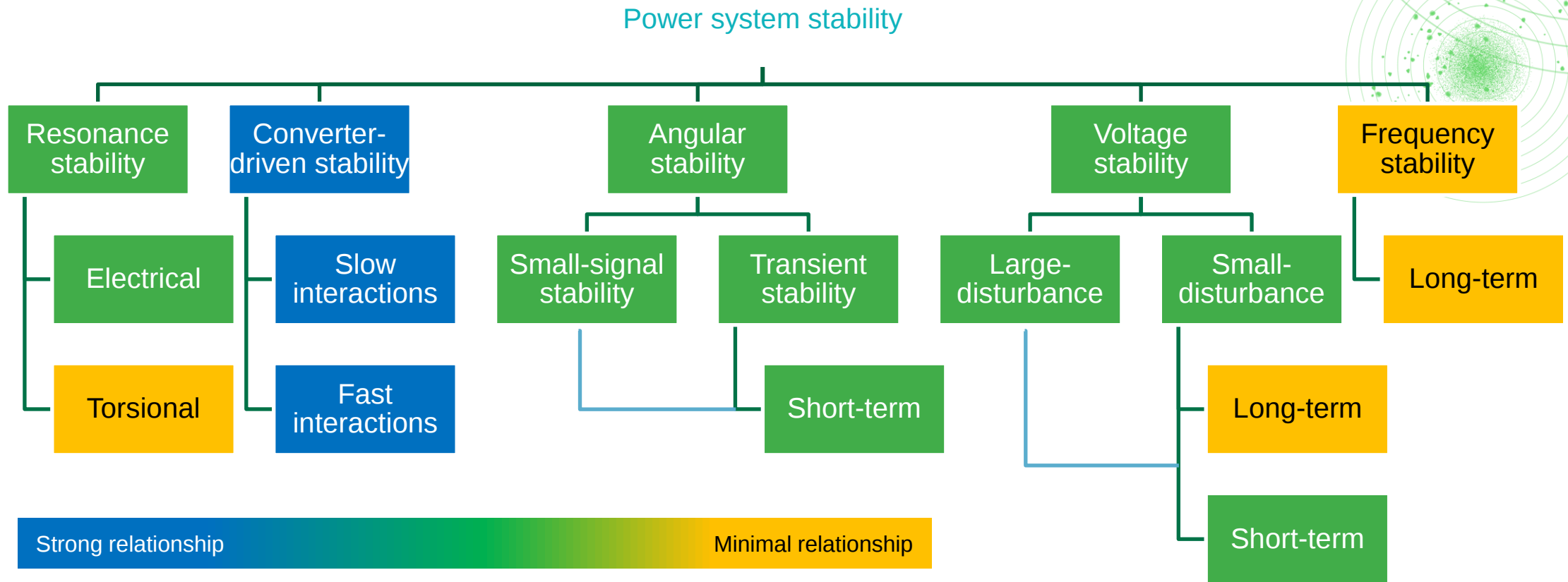
Commonly used methods cannot usually address emerging complexities

Power system phenomena

Phenomena	Typical frequency range	Circuit theory	Relation to control bandwidth	Factors influencing	Overall impact
System stability (inc. protection)	< ≈ 300 Hz	$I_F \downarrow \rightarrow \uparrow Z$ $\downarrow \text{SCR} = 1/Z \uparrow$	Within	☒ Control systems ☒ Circuitry	
Power system harmonics	>50/60 and < ≈ 10 kHz	$\uparrow \uparrow \uparrow$ $V_h = I_h \times Z_h$	Often outside	☐ Control systems ☒ Circuitry	
High-frequency transients	> ≈ 3 kHz and up to a few MHz	$L \longleftrightarrow C$	Outside	☒ Control systems ☐ Circuitry	

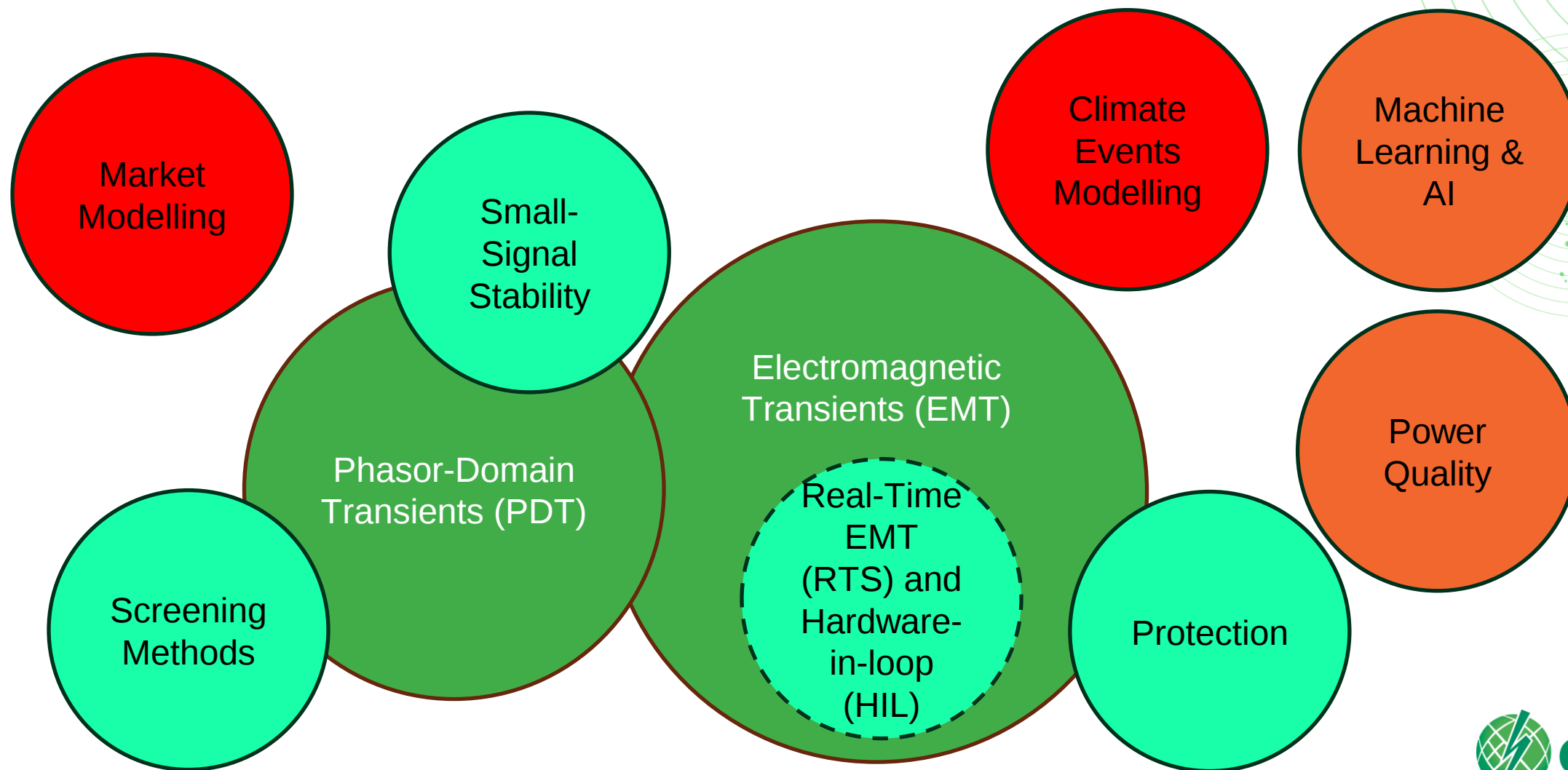
Circuitry includes transformers, lines, cables, filters and converter bridges (inc. PWM)

System strength vs system stability

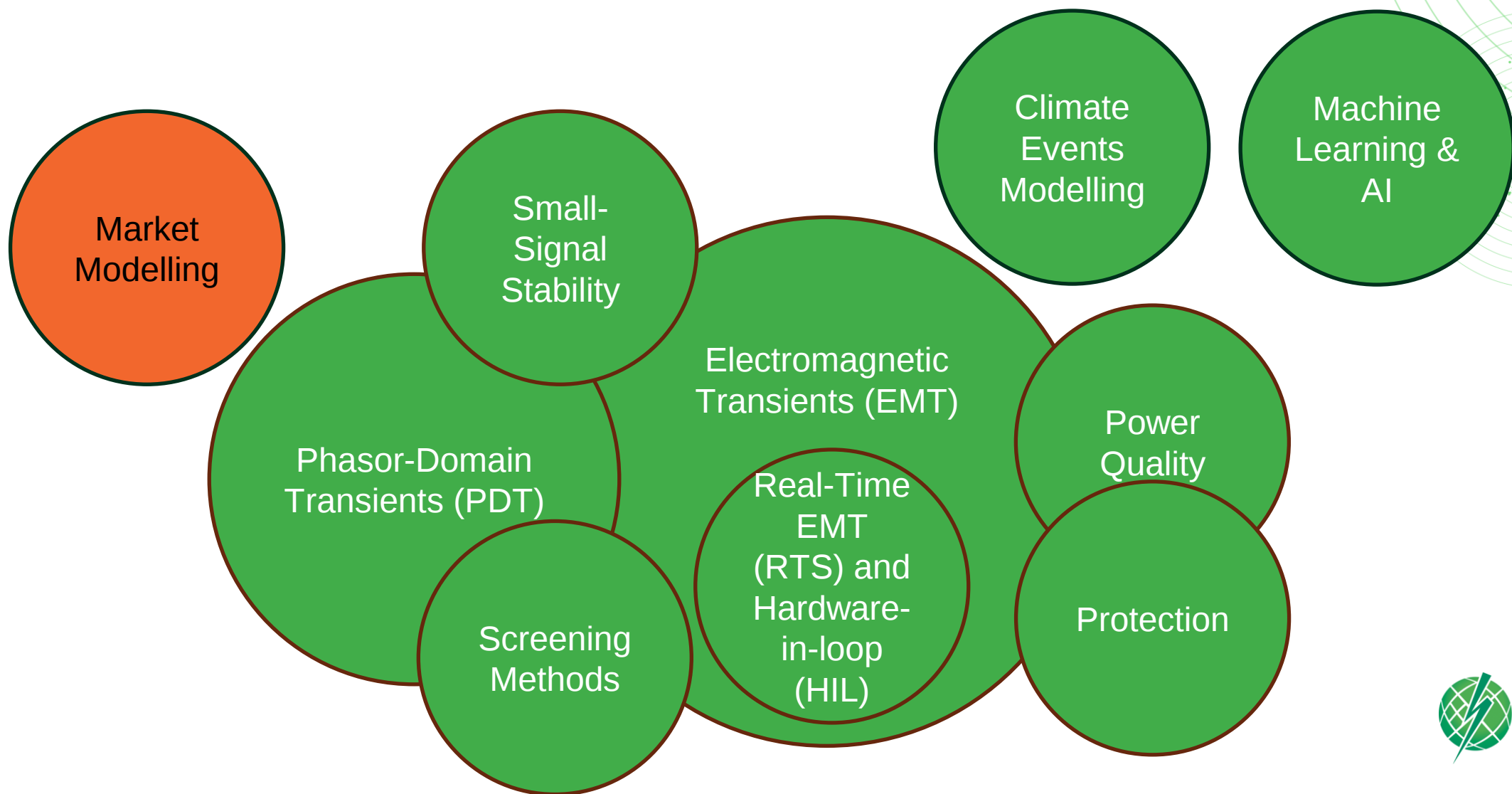


Classification of power system stability phenomena – 2020 version (IEEE TR77)

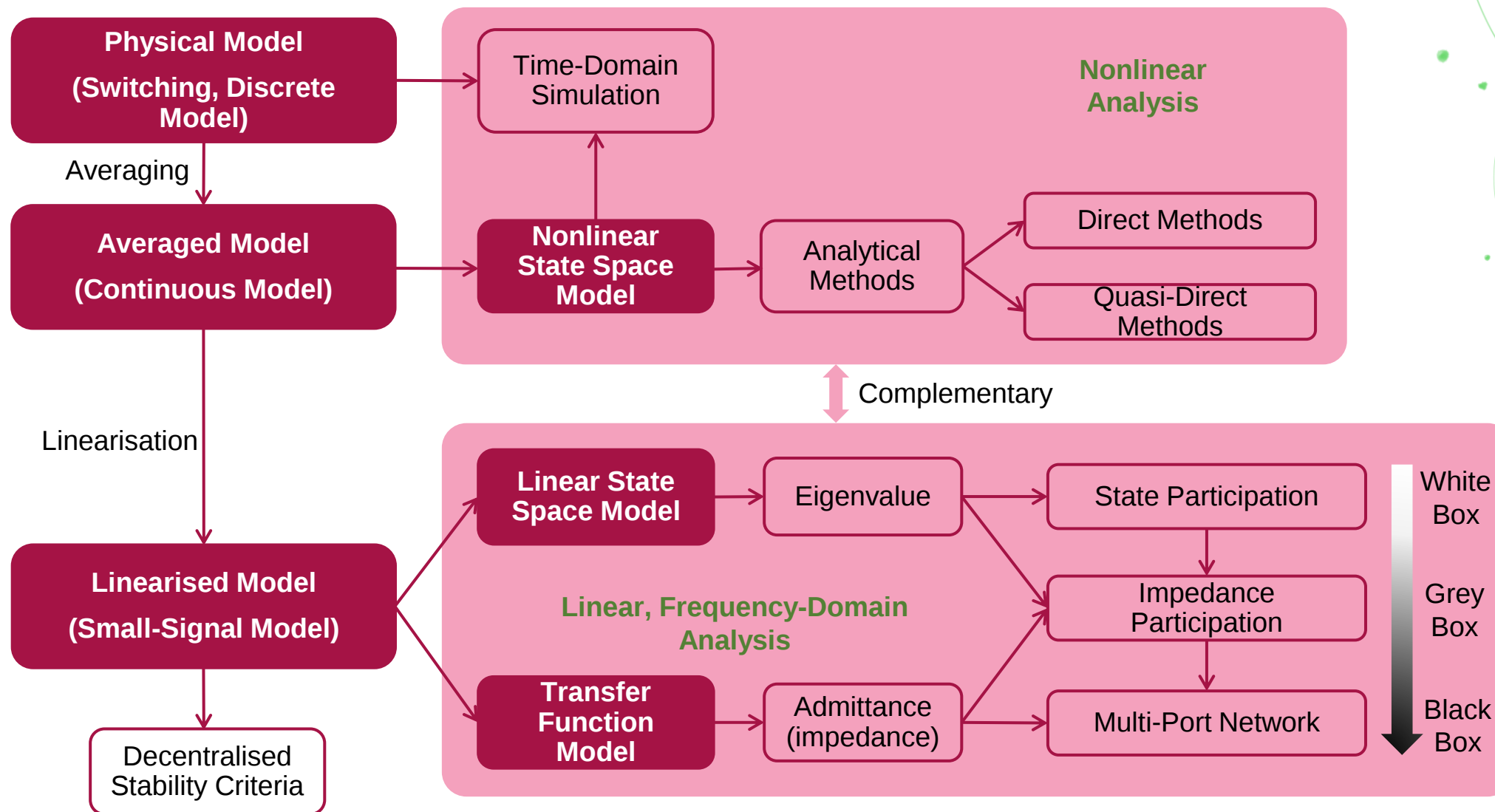
Simulation tools: today



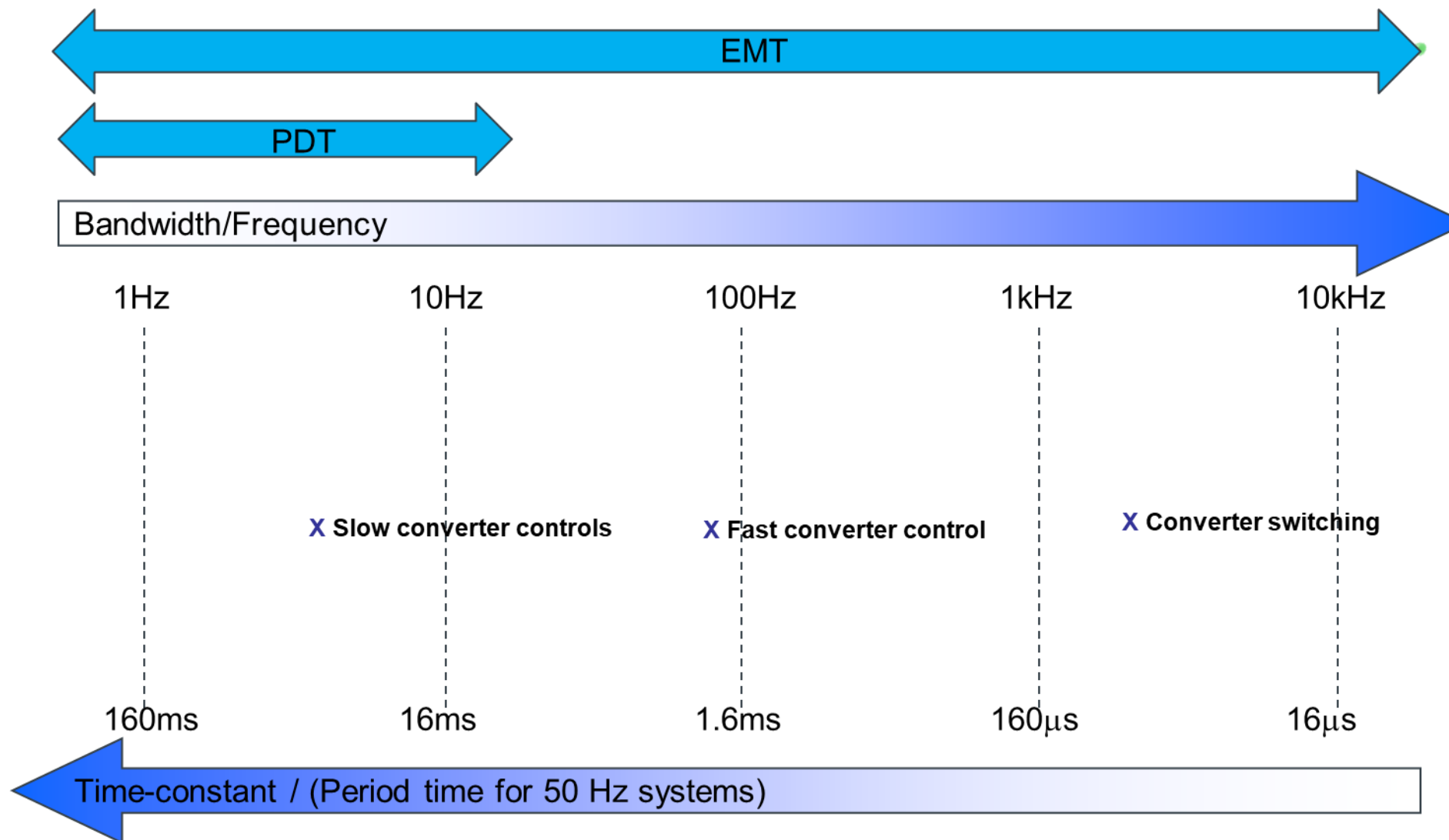
Simulation tools: moving forward



Dynamic analysis methods

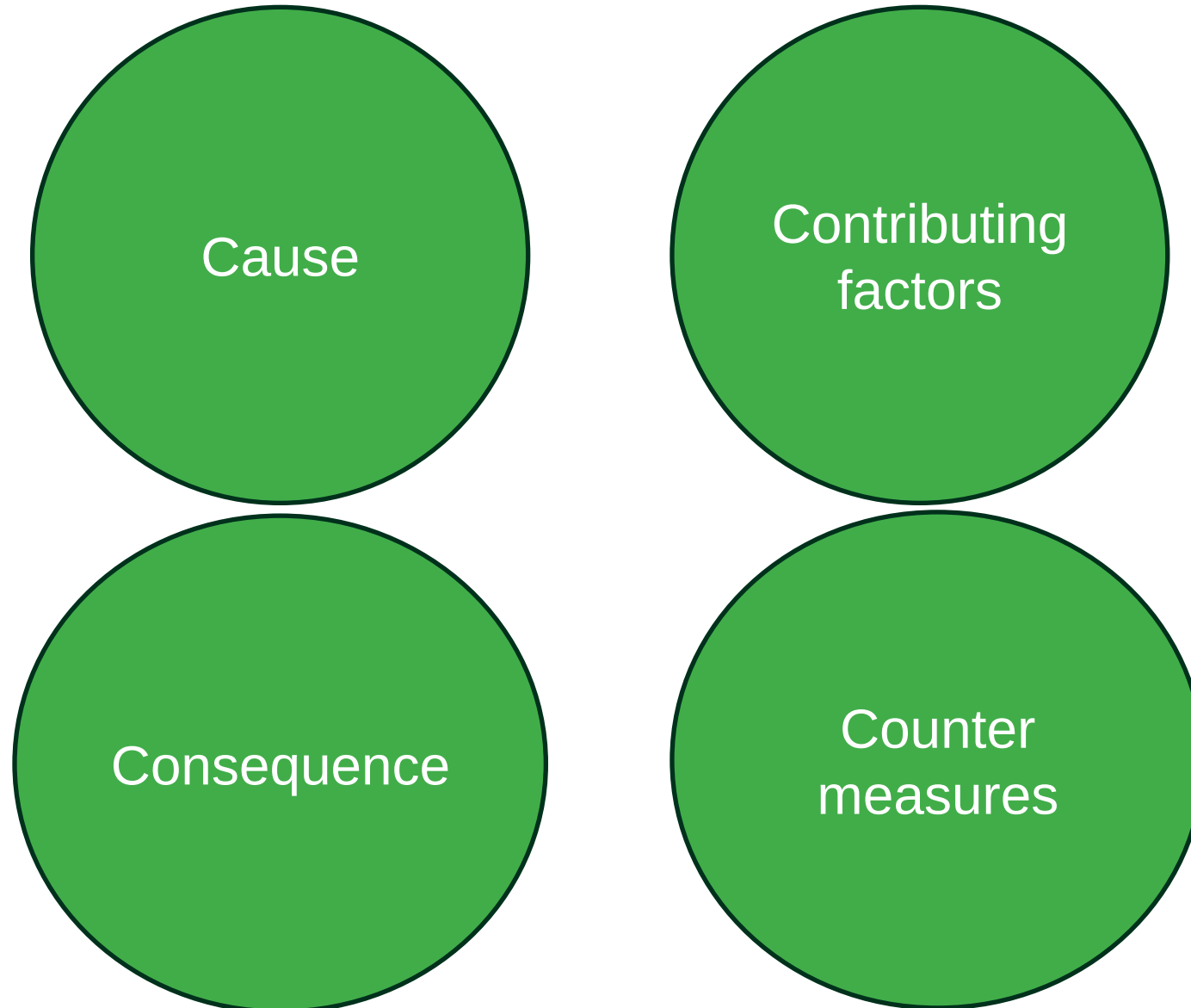


Bandwidth of phenomena/control loops in IBRs

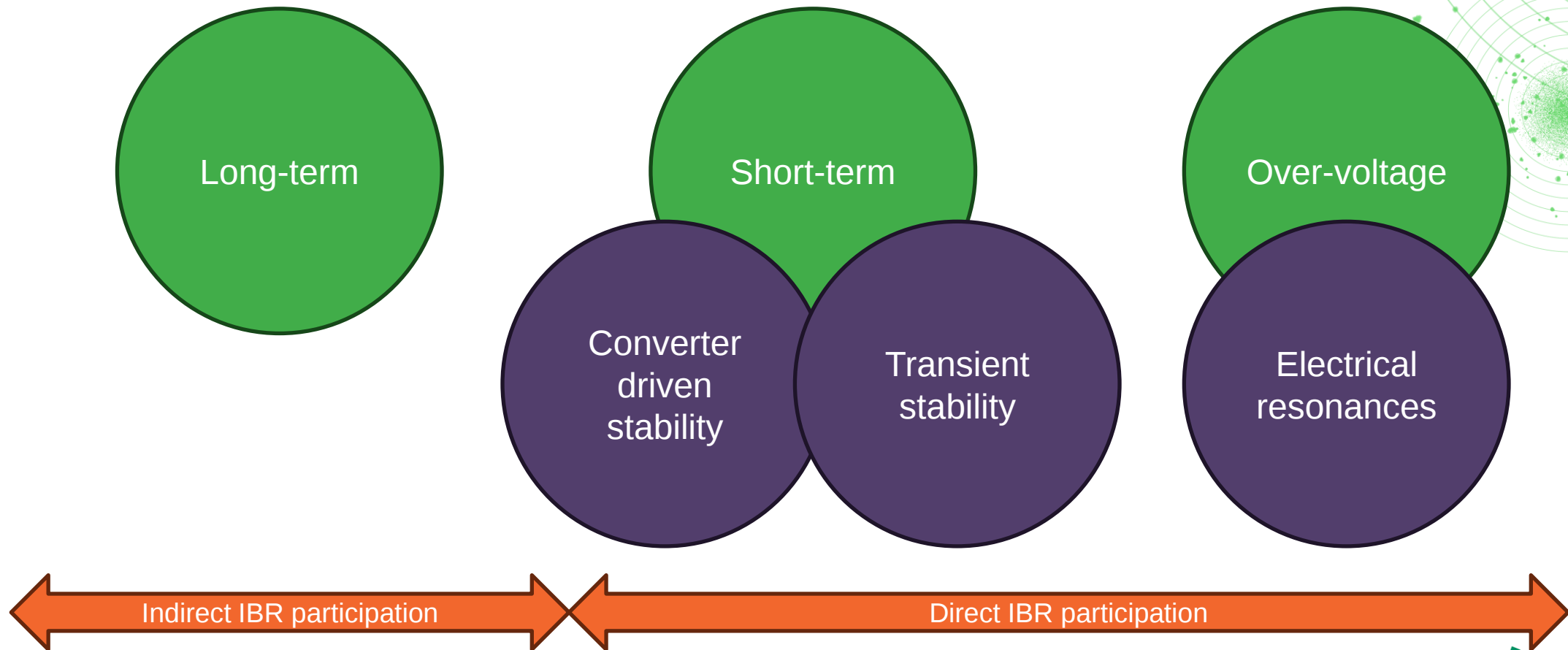


Part II: Power System Studies under a High Penetration of Power Electronic Interfaced Devices

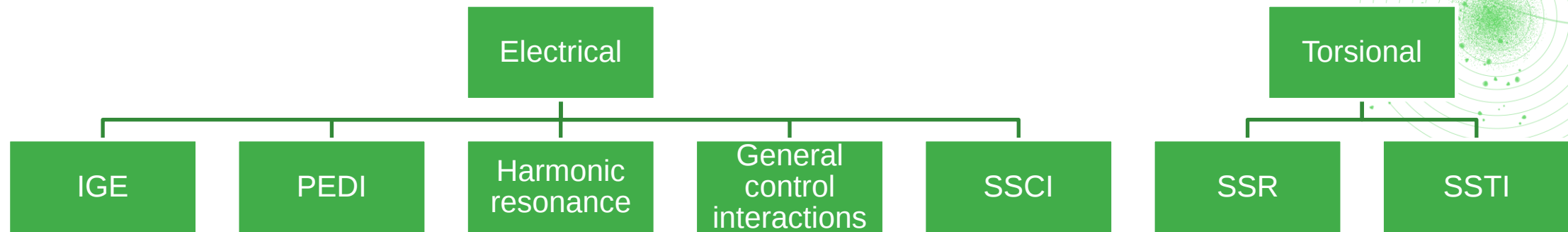
Considerations for analysing different types of system stability



Type of voltage stability

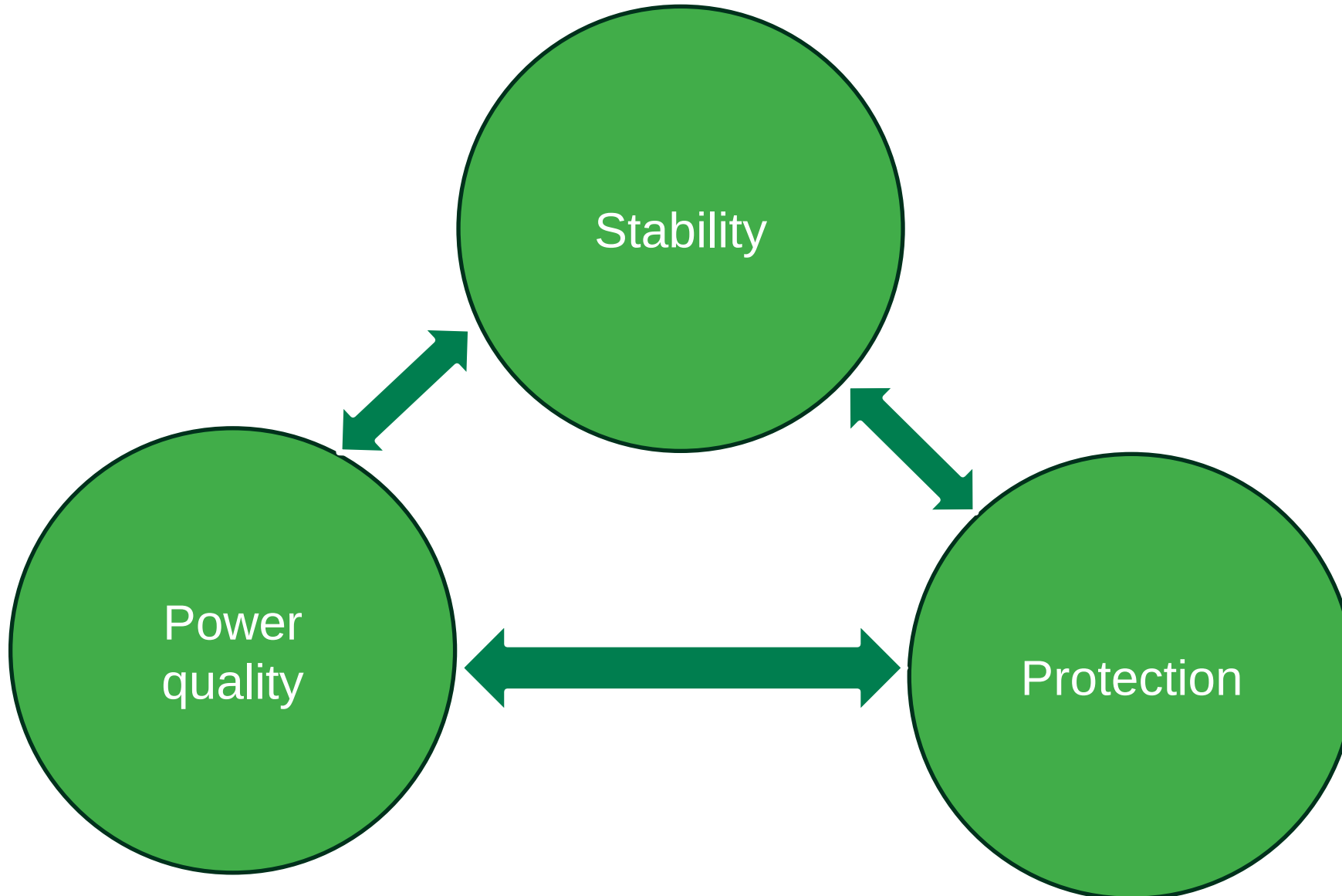


Sub-synchronous interactions

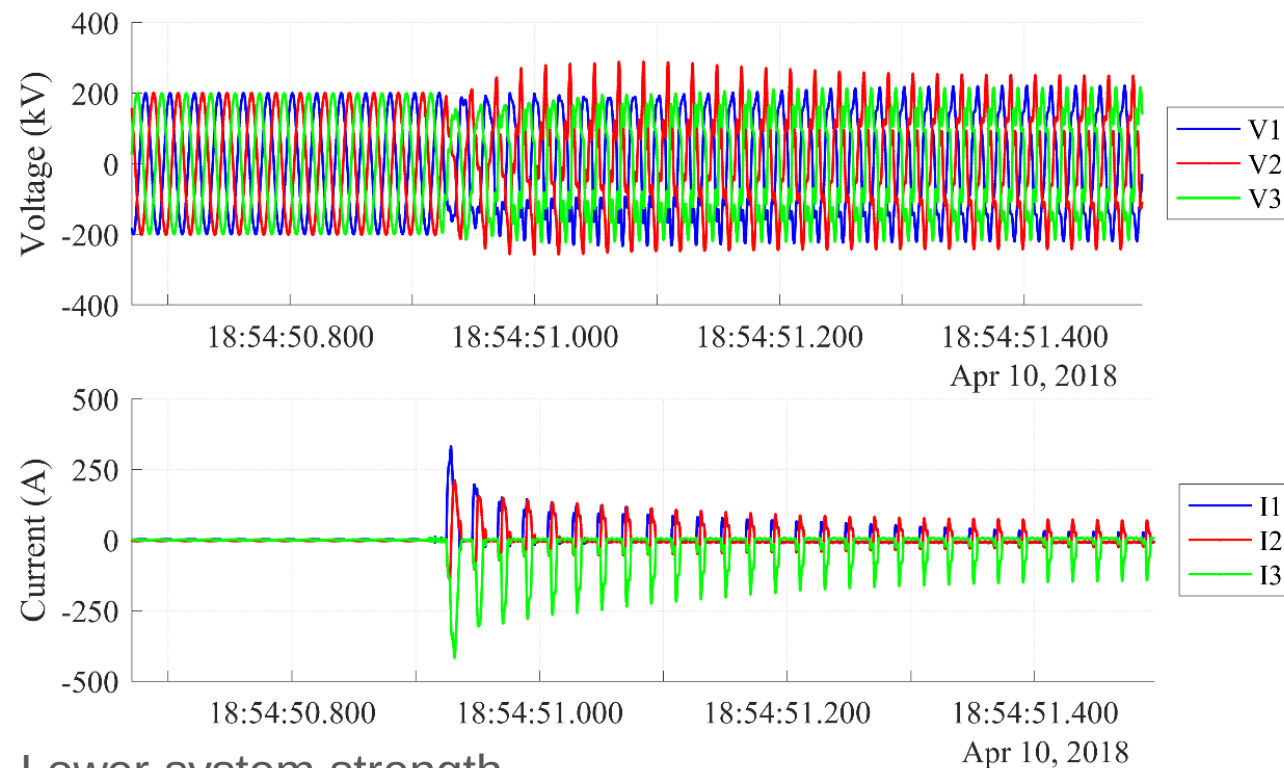


- IGE: Induction generator effect
- PEDI: Power electronics device interaction
- SSCI: Sub-synchronous control interactions
- SSR: Sub-synchronous resonance
- SSTI: Sub-synchronous torsional interactions

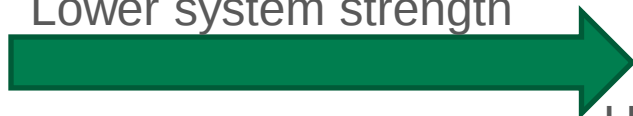
Interactions between different phenomena



Interaction between power quality and system stability



Lower system strength



Higher Thevenin impedance



Higher harmonic voltage distortion even for the same harmonic current injection

New observed phenomena

Reduced system strength conditions

Interactions involving series compensated lines

Interactions involving rotating masses of turbine generators

Interactions between multiple IBRs

Incorrect settings of slow or fast control loops used in IBRs

Selected Topics

How to obtain higher accuracy?

Using validated models

More detailed
plant models

Larger system
model

More detailed
system model

Summary of key aspects deciding the use of EMT or PDT models

Phenomena-
based

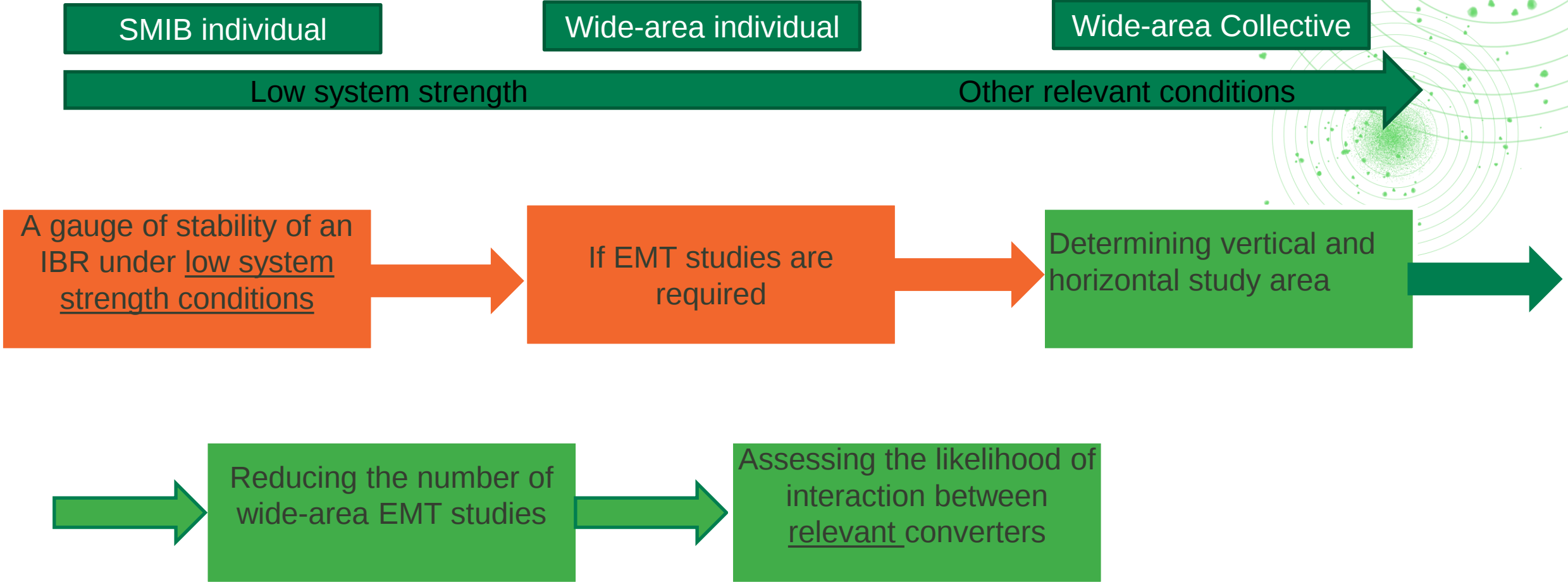
Application-
based

Screening-based

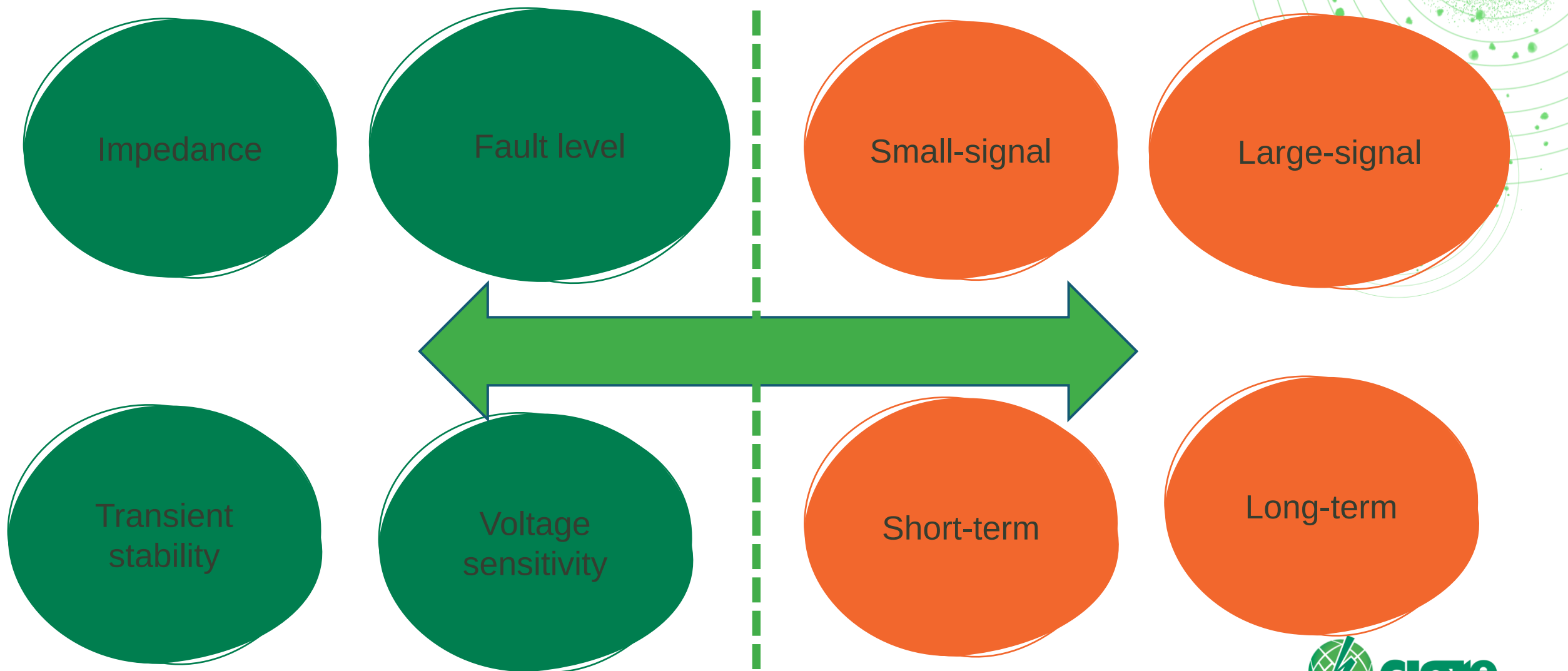
Data and model
availability-based

Models of interest are not always available

Evolution of the use of screening methods



Principles of existing screening methods



Tools and techniques to analyse interactions

EMT studies

Eigenvalue

Participation factor

Eigenvalue

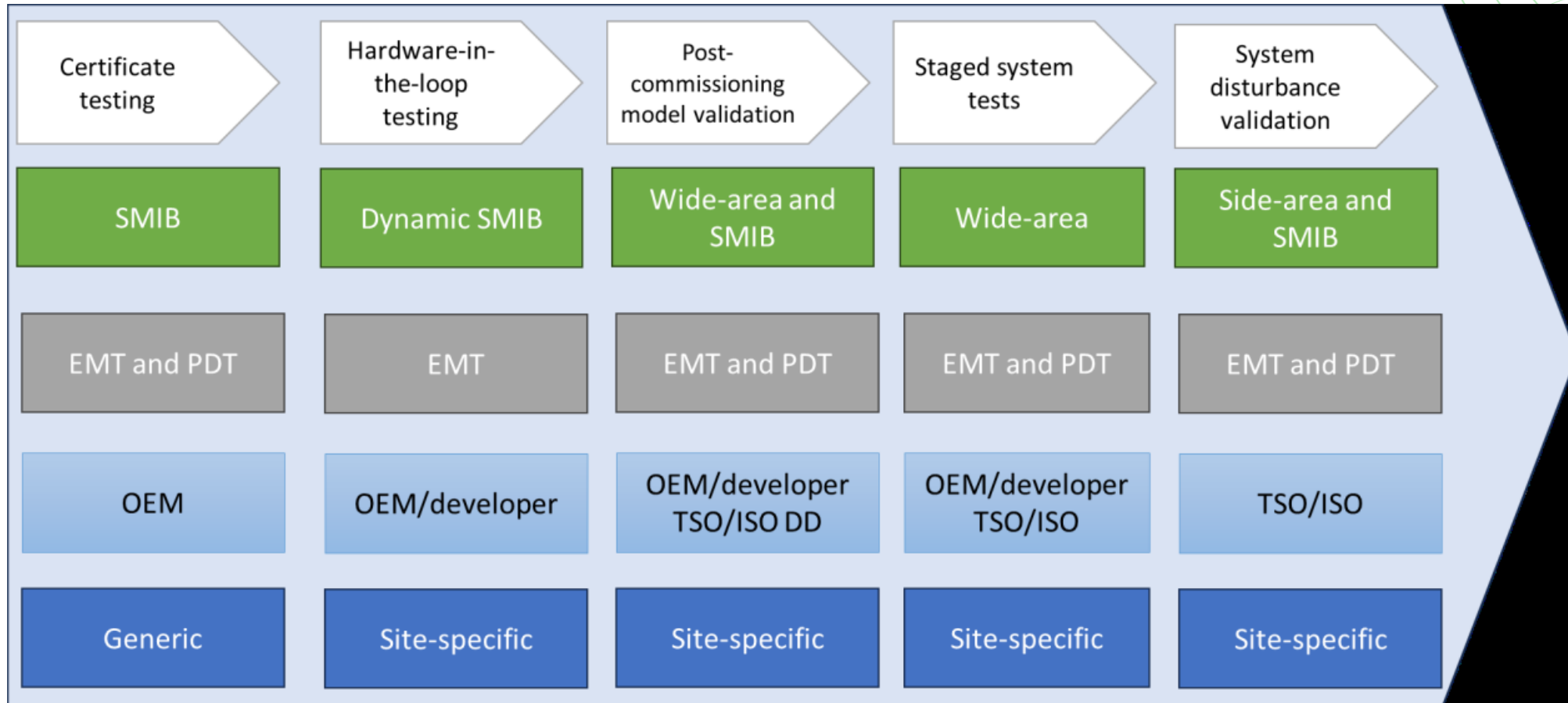
Apparent impedance

Passivity

Transfer function

Frequency domain

Model validation life-cycle



Advancing power system modelling: The push for detail and efficiency

Enhanced
modelling
techniques

Advanced
computational
tools

Collaboration and
data sharing

Standardisation
and
interoperability

Clear objectives,
processes and
success criteria

Improved
decision making
and optimisation

Screening
methods

Model validation
and testing