EMT Power System Modeling Seminar

NEDO (Human Resource Development for Future Power System Planning and Operation) - **1st Session**

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- Classical Power System Dynamics
  - Synchronous Generator (SG) dominated network

- Modern Power System Dynamics
  - Networks with high Inverter-Based Resource (IBR) penetration

- Power System Dynamic Modelling and Simulation Tools
  - Phasor Domain Transients (PDT) vs Electromagnetic Transients (EMT)
  - Examples of comparative study results

- Building Large Scale EMT Dynamic Stability Capability

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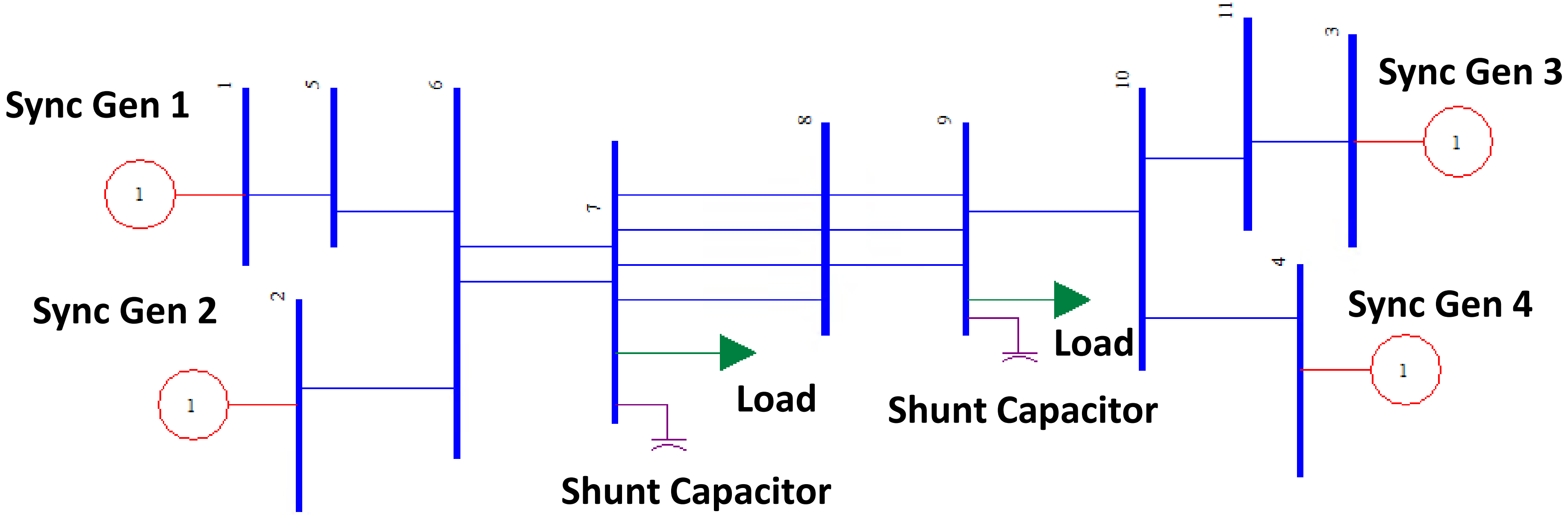
Classical Power System Dynamics

Synchronous Generator Dominated Networks

Classical Power Systems Network - Configuration

- Classical power systems network consists of mainly SG, electrical circuits and loads.
- SG produces and converts mechanical energy to electrical energy, and deliver the energy via transmission circuits.
- Dynamic stability of the network is key to ensure reliable and safe energy delivery.



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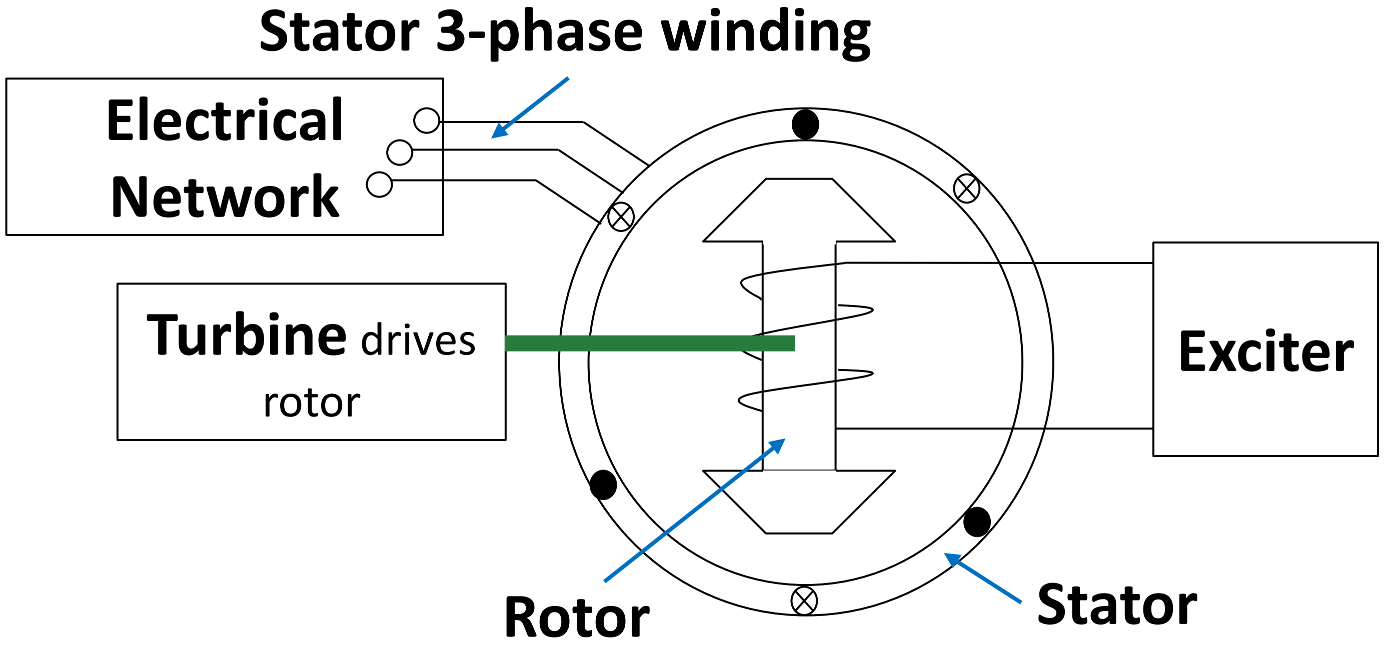
How SG produce Electricity? The Basics

- Exciter applies DC current to magnetize rotor (creates magnetic field).
- Turbine creates mechanical torque and rotates rotor (creates rotating magnetic field).
- AC voltages across stator windings induced by rotating magnetic field (Faraday's law), producing electrical power when connecting to electrical network.



$$P_m - P_e = \frac{H}{\pi f}\frac{d^2\delta}{dt^2}$$

Pm: mechanical power
Pe: electrical power
H: inertia constant
f: system frequency
δ: power angle
t: time

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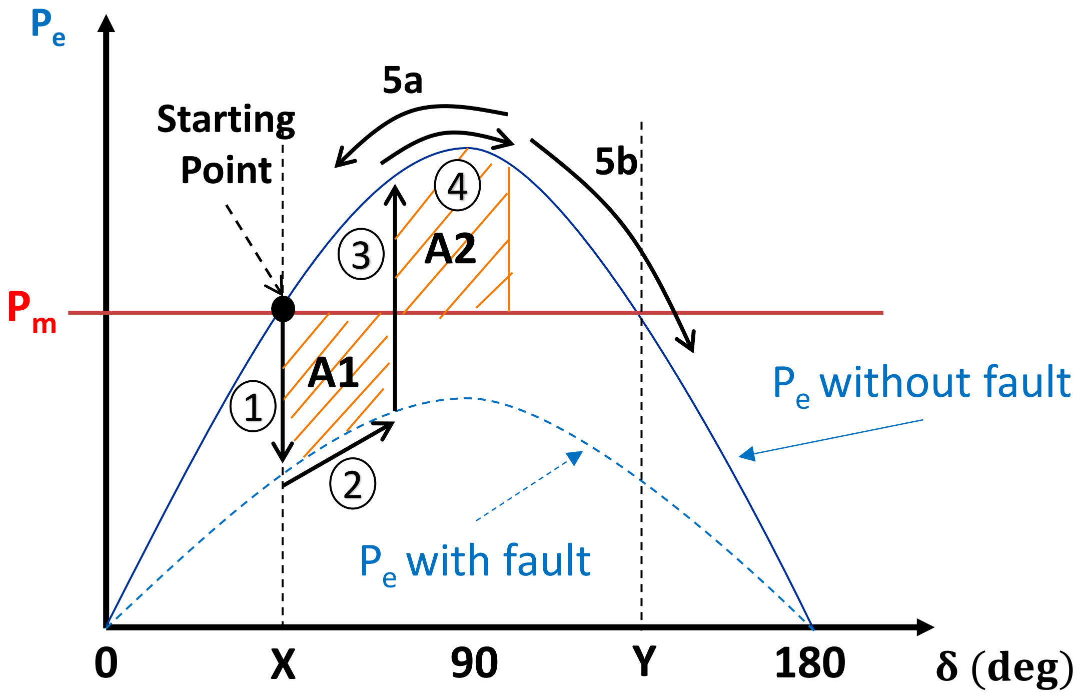
Classical Power Systems Network – Dynamic Stability

- Electromechanical Transients occur when there is imbalance between electrical and mechanical energy in SG.
- Power-Angle Equal Area Criteria is a common and simplified way to assess angular stability.



Initially $P_m = P_e$, angle $\delta = X$

Stage 1: A fault occurs, electrical power P_e decreases and smaller than mechanical power P_m

Stage 2: During the fault, $P_m > P_e$ therefore rotor accelerates and rotor angle δ increases.

Stage 3: Fault is cleared. P_e jumps to the level higher than P_m due to δ advancement. Area A1 represents the total kinetic energy gained by the rotor during the fault.

Stage 4: Rotor decelerates as $P_e > P_m$, and δ keeps increasing. Area A2 represents the kinetic energy dissipates by the rotor.

Stage 5a: Area A2 = A1 before δ reaches point Y, δ starts to decrease. **System is stable**.

Stage 5b: δ increases beyond point Y before A2=A1, rotor accelerates again. **System is unstable**.

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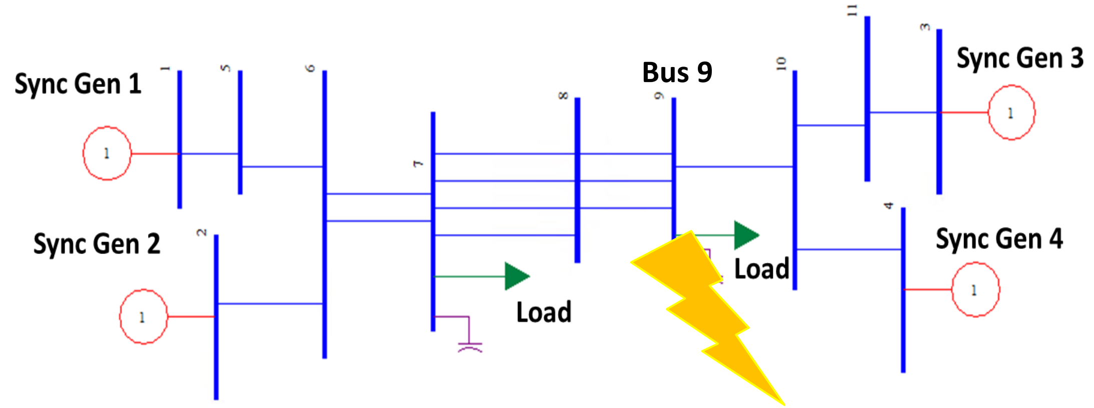
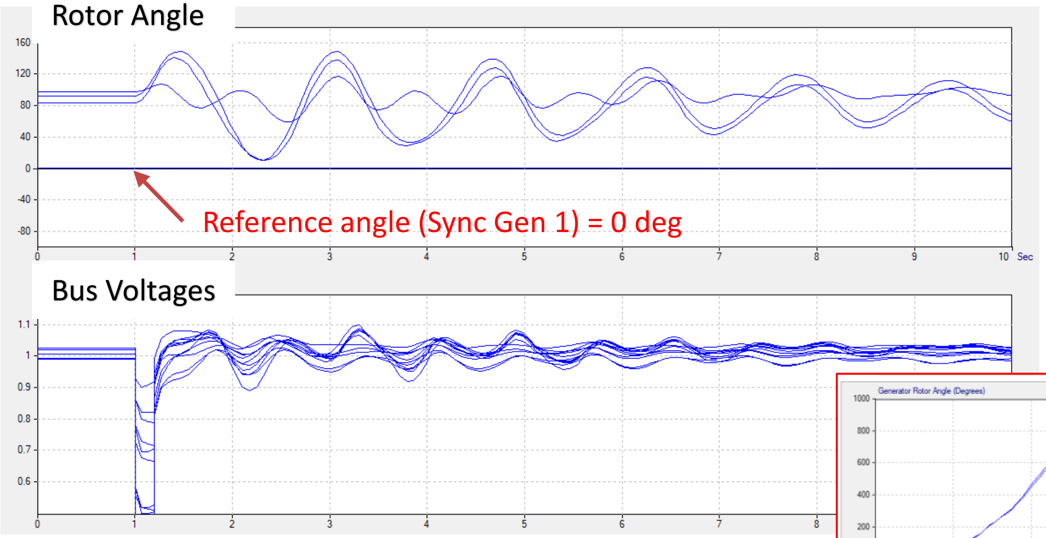
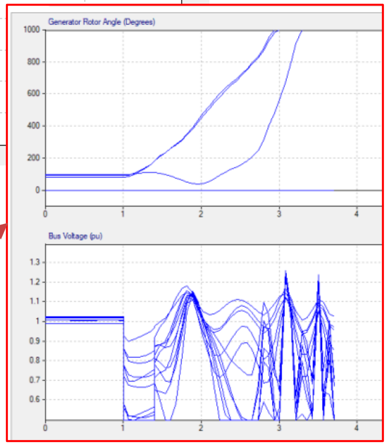
Case Study: 3-Phase Fault Event

- 3-phase-to-ground fault applied at Bus 9 at t = 1s, cleared at t = 1.2s
- Rotor angle of SG 1 is used as the reference.
- System is stable after the fault as the rotor angles oscillates but are gradually damped.





unstable if fault cleared at 1.4s
(critical clearing time = 400ms)



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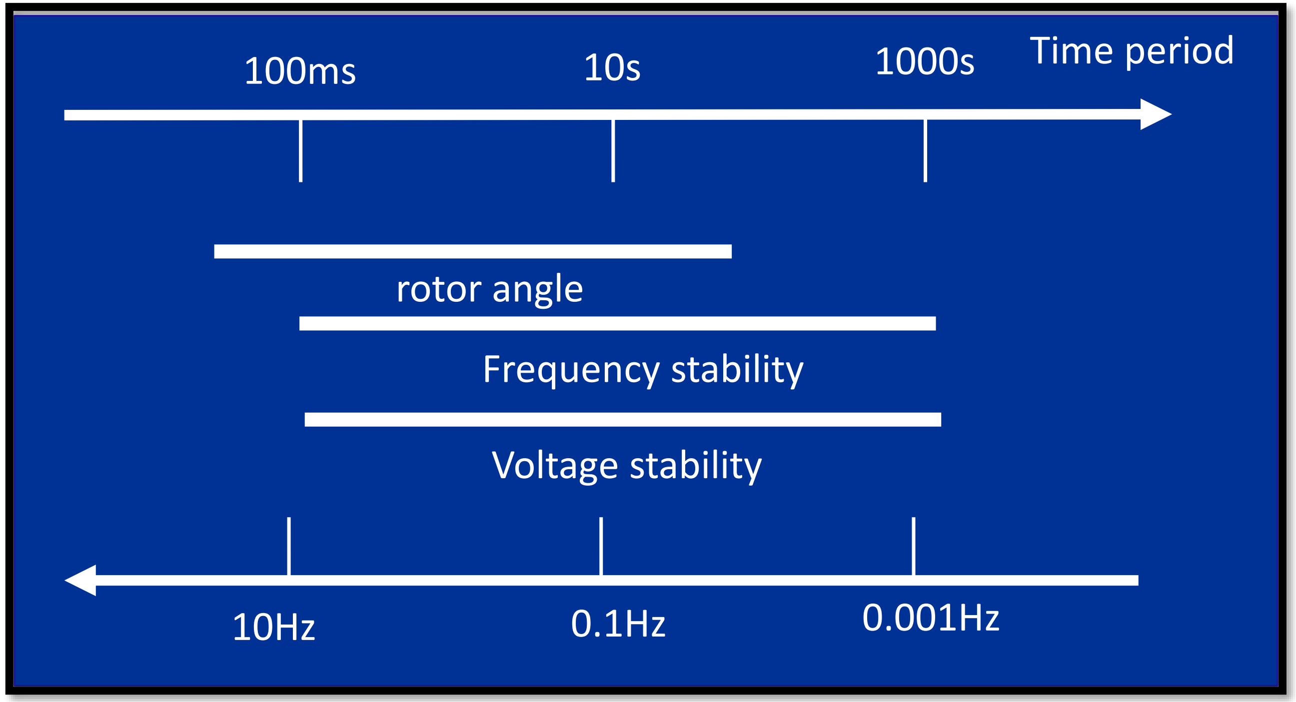
Classical Dynamic Stability Types

- Angular, voltage and frequency stability are the main concerns in classical power system networks.
- All these types of stability need to be studied to prevent system becoming unstable after disturbances.



Indicative timeframe of angular, voltage and frequency stabilities in classical networks

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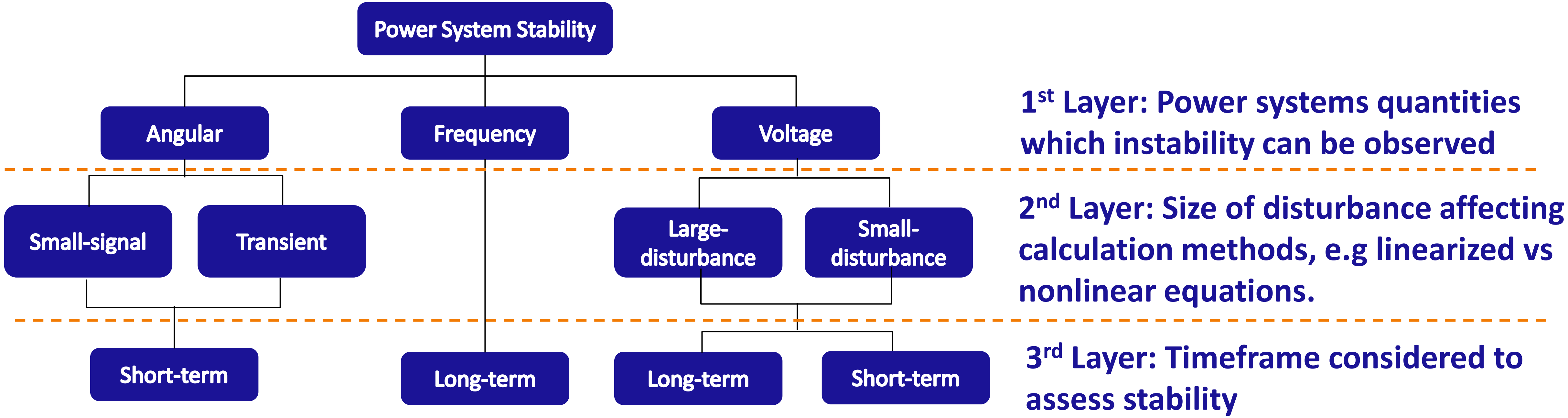
Original Classification of Dynamic Stability

- Original classification of power systems stability proposed by IEEE/CIGRE Task Force.
- Classify dynamic problems helps identify key contributing factors to instability



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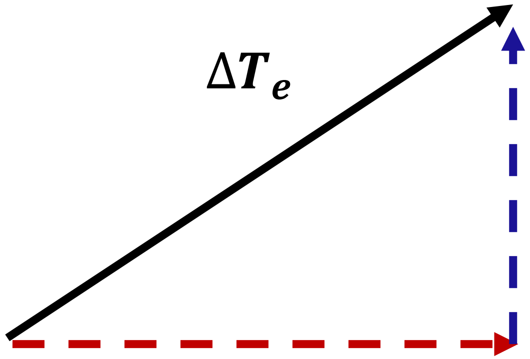
Angular Stability

- Classical definition: ability of SG to remain in synchronism following a small (small-signal stability) or large (transient stability) disturbance.
- Change in electrical torque $\boldsymbol{\Delta T_e}$ consists of change in synchronizing torque $\boldsymbol{\Delta T_s}$ and damping torque $\boldsymbol{\Delta T_D}$.
- Small-signal stability mainly driven by $\boldsymbol{T_D}$, large-signal stability mainly driven by $\boldsymbol{T_s}$.

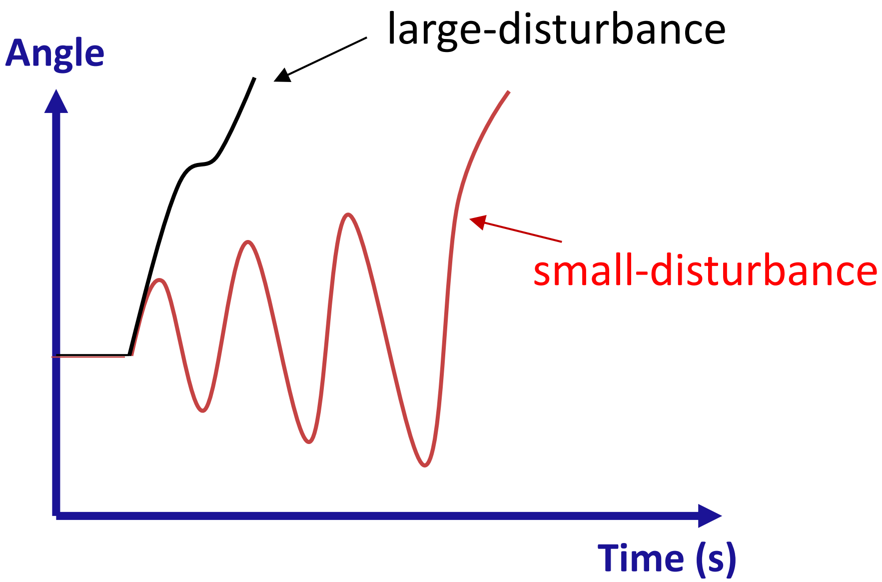


$\boldsymbol{\Delta T_D = (T_D \cdot \Delta\omega)}$

$\mathrm{T_D}$: damping torque coefficient
$\Delta\omega$: change in angular speed

$\boldsymbol{\Delta T_s = (T_s \cdot \Delta\delta)}$

$\mathrm{T_s}$: synchronizing torque coefficient
$\Delta\delta$: change in angle



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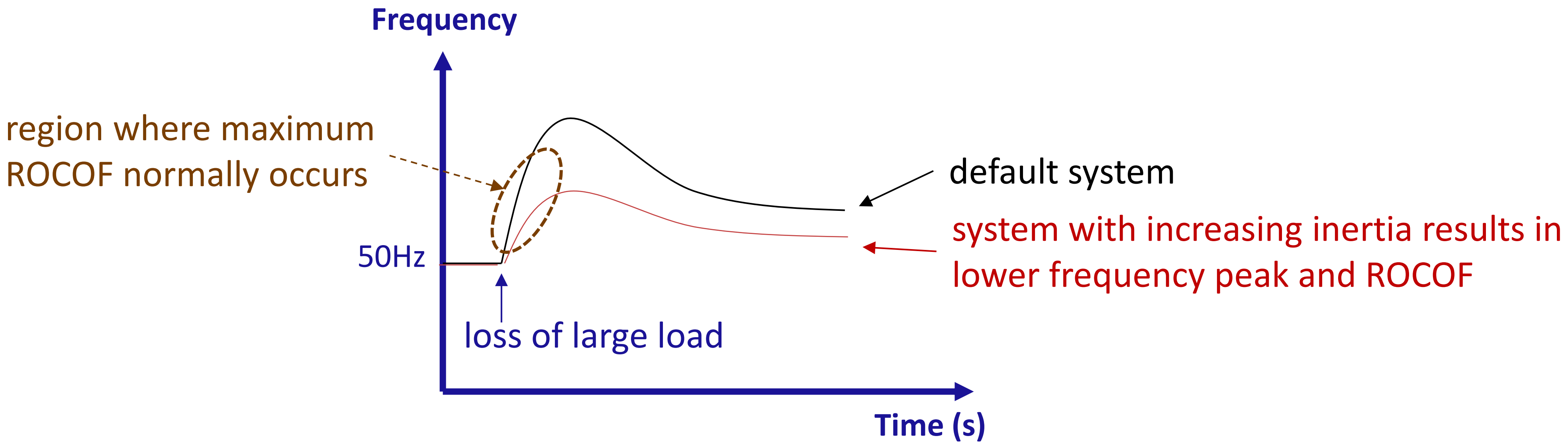
Frequency Stability

- Classical definition: ability of power system to return to equilibrium following significant imbalance between generation and load.
- Instability occurs as result of generation/load tripping by protection such as over/under-frequency, rate of change of frequency (ROCOF) relay.
- SG inertia plays key role in limiting frequency excursion and ROCOF.



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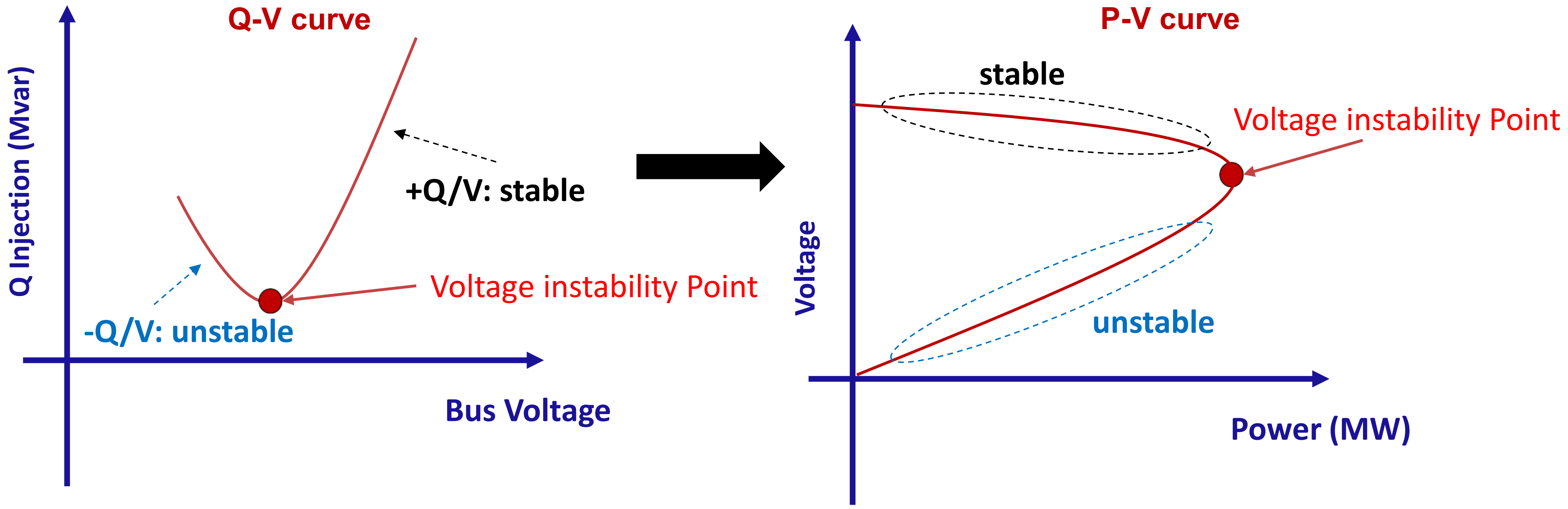
Voltage Stability

- Definition: ability of power system to maintain acceptable voltages at all busbars in the system under normal operating conditions and following either a small (i.e. gradual increase in load) or large disturbance (i.e. loss of generation).
- Instability happens when injection of reactive power injected into a bus causing decrease in voltage.



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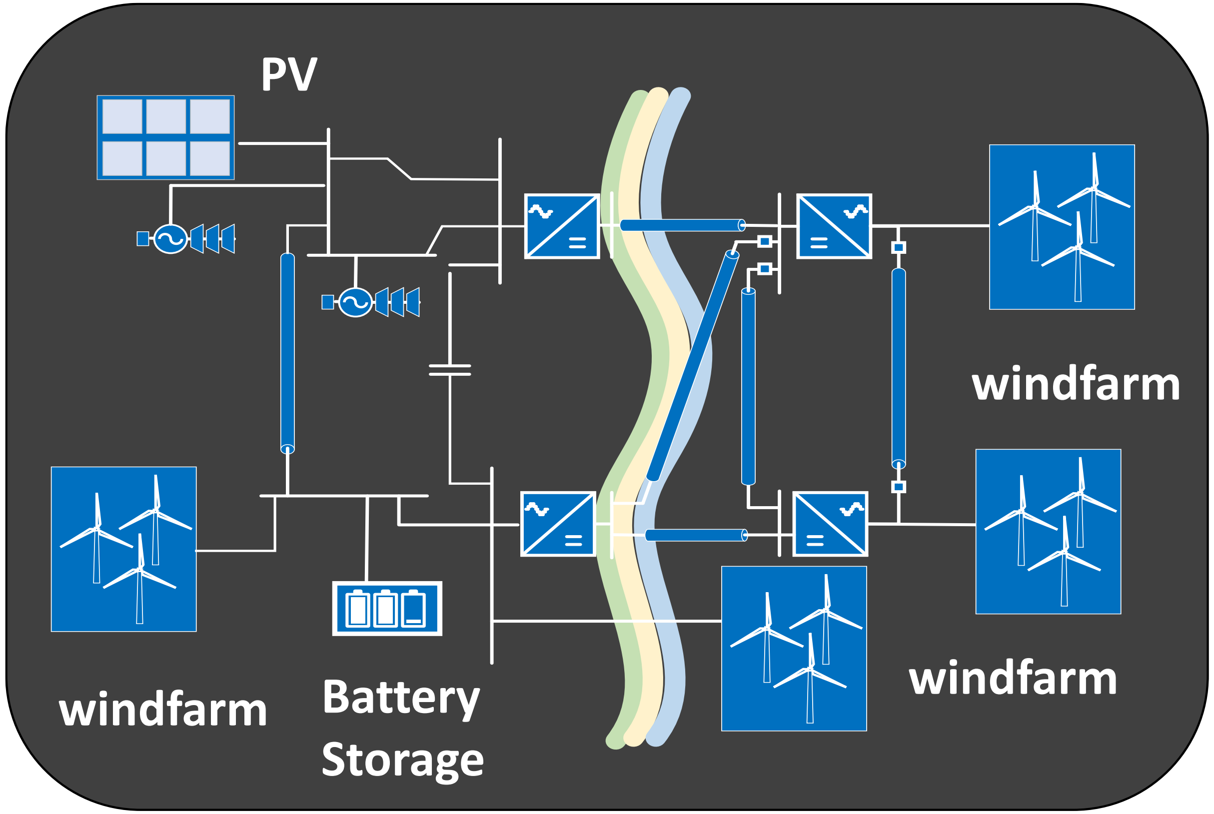
Modern Power System Dynamics

Networks with High IBR Penetration

Modern Power Systems

- Modern power systems consists of many **I**nverter-**B**ased **R**esources (IBRs), such as HVDC, windfarms, photovoltaic and battery storage units etc.
- Unlike SG, IBRs are either partially or fully-decoupled from the electrical network by power electronic converters, meaning dynamics from network do not directly or only partially transfer to the generator side, or vice versa.
- In IBR-dominated networks, system dynamics and stability can be heavily influenced by IBR controls.



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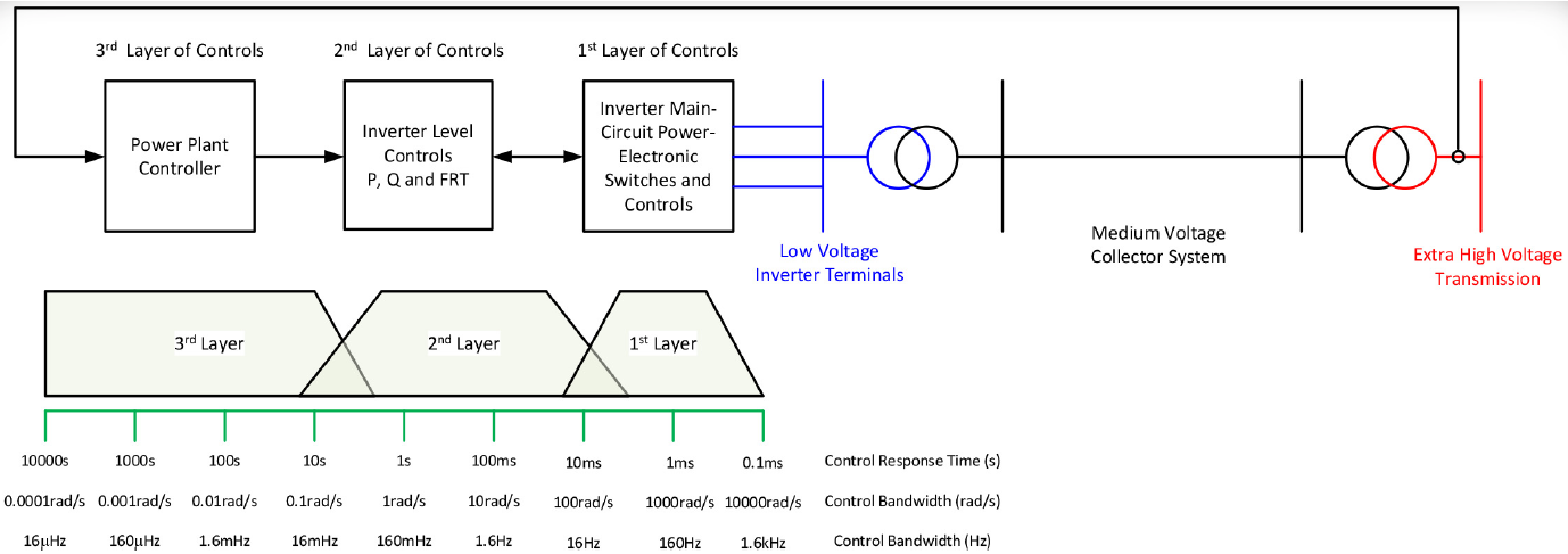
Typical IBR Control Hierarchy and Bandwidth



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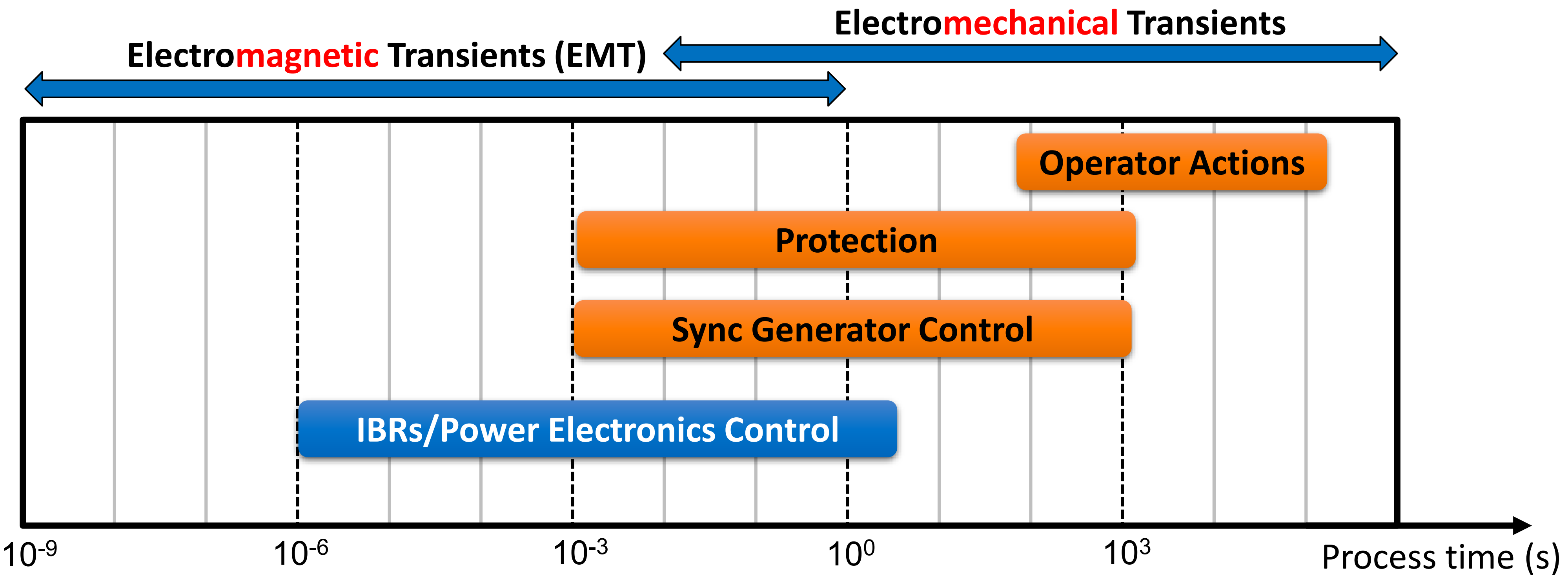
IBRs vs SG Control Bandwidth

- SG control process time typically range from 1 cycle (i.e. 20ms, 50Hz) onwards
- IBRs control bandwidth can be much faster, outside the timeframe of electromechanical transients and into the domain of electromagnetic transients.



Graph inspired from the CIGRE Green Book on "Power System Dynamic Modelling and Analysis in Evolving Networks" Eds. B. Badrzadeh & Z. Emin

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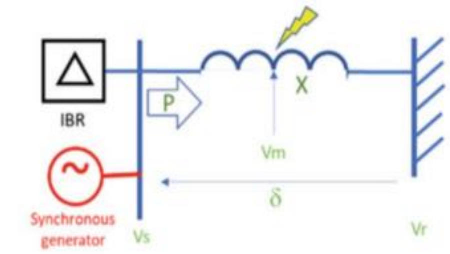
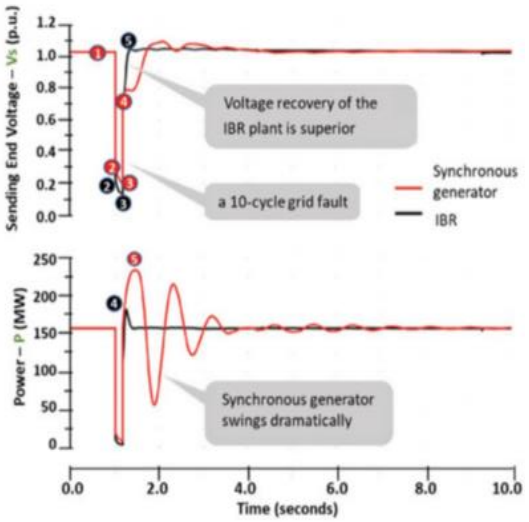
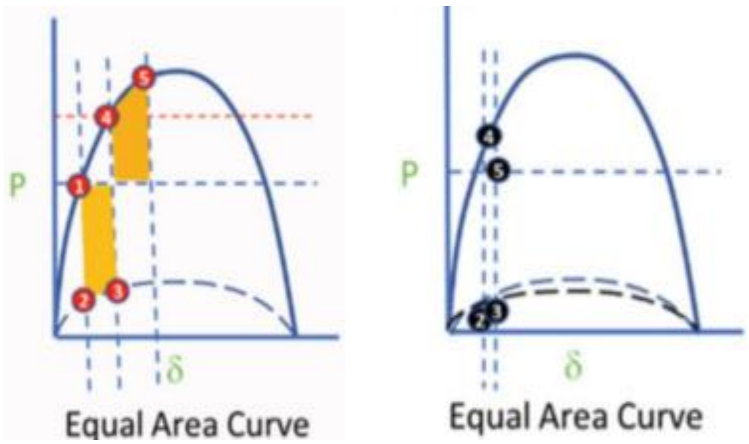
Impact of IBRs on Angular Stability

- Figure shows SG and IBR with same rating and initial dispatch connecting to an infinite bus followed by a fault on the circuit.
- With IBR, faster power and angle recovery is achieved after fault, because no dissipation of mechanical energy required. IBR controller determines angle, rather than a result of electromechanical imbalance.





Sync Gen IBR



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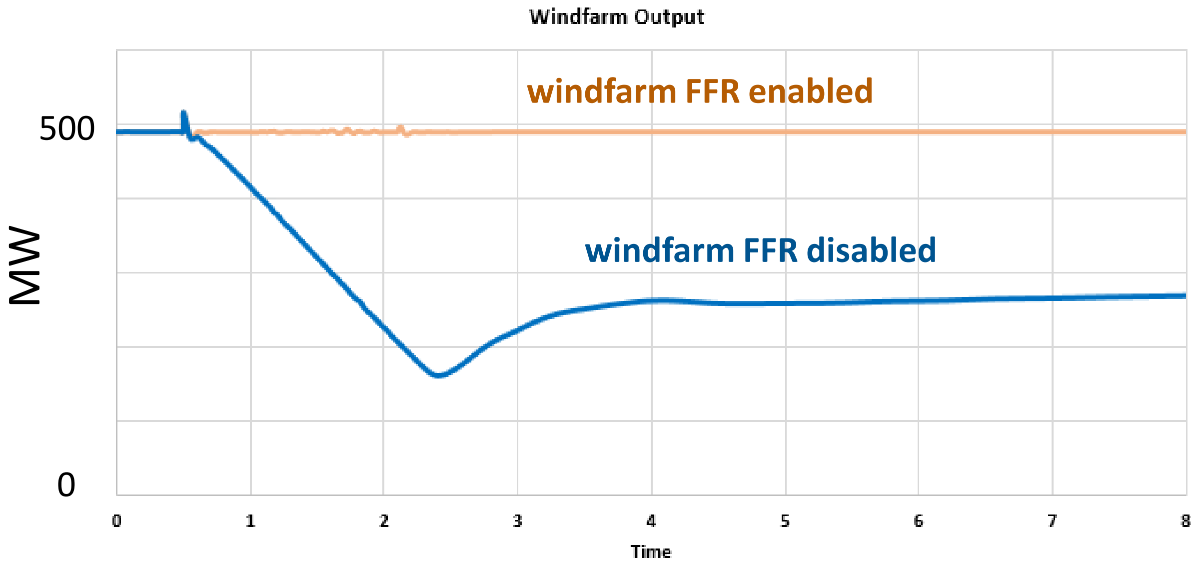
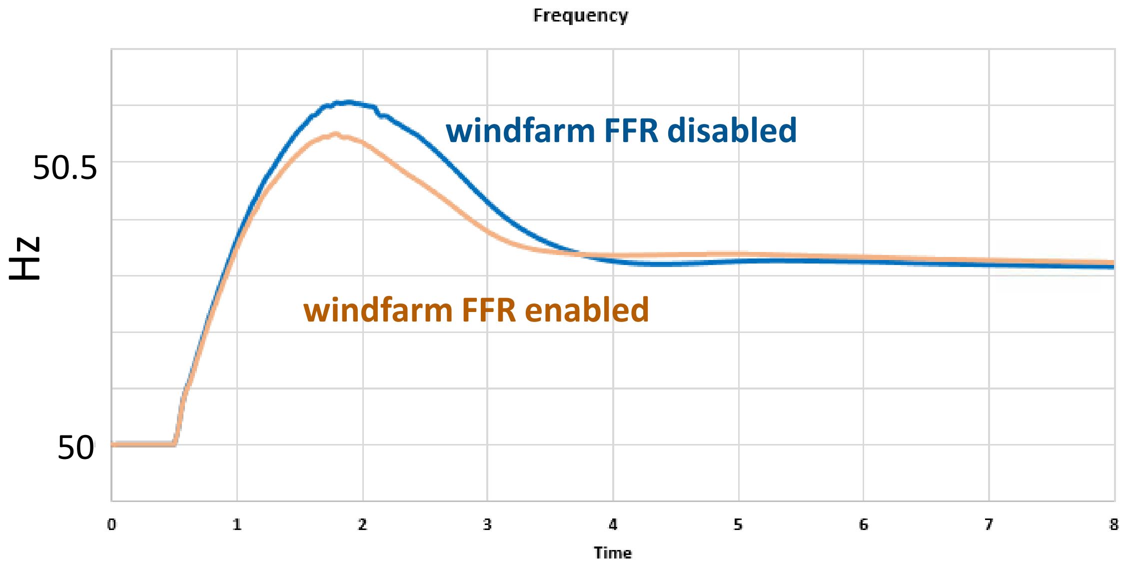
Impact of IBRs on Frequency Stability

- A disturbance can result higher frequency excursion and ROCOF in IBR dominated network due to lack of inertial response from SG.
- IBRs with Fast Frequency Response (FFR) control can assist in reducing frequency nadir or zenith, may also improve ROCOF.
- Figures compare frequency and windfarm MW output with and without enabling windfarm FFR after load loss at t = 0.5s.





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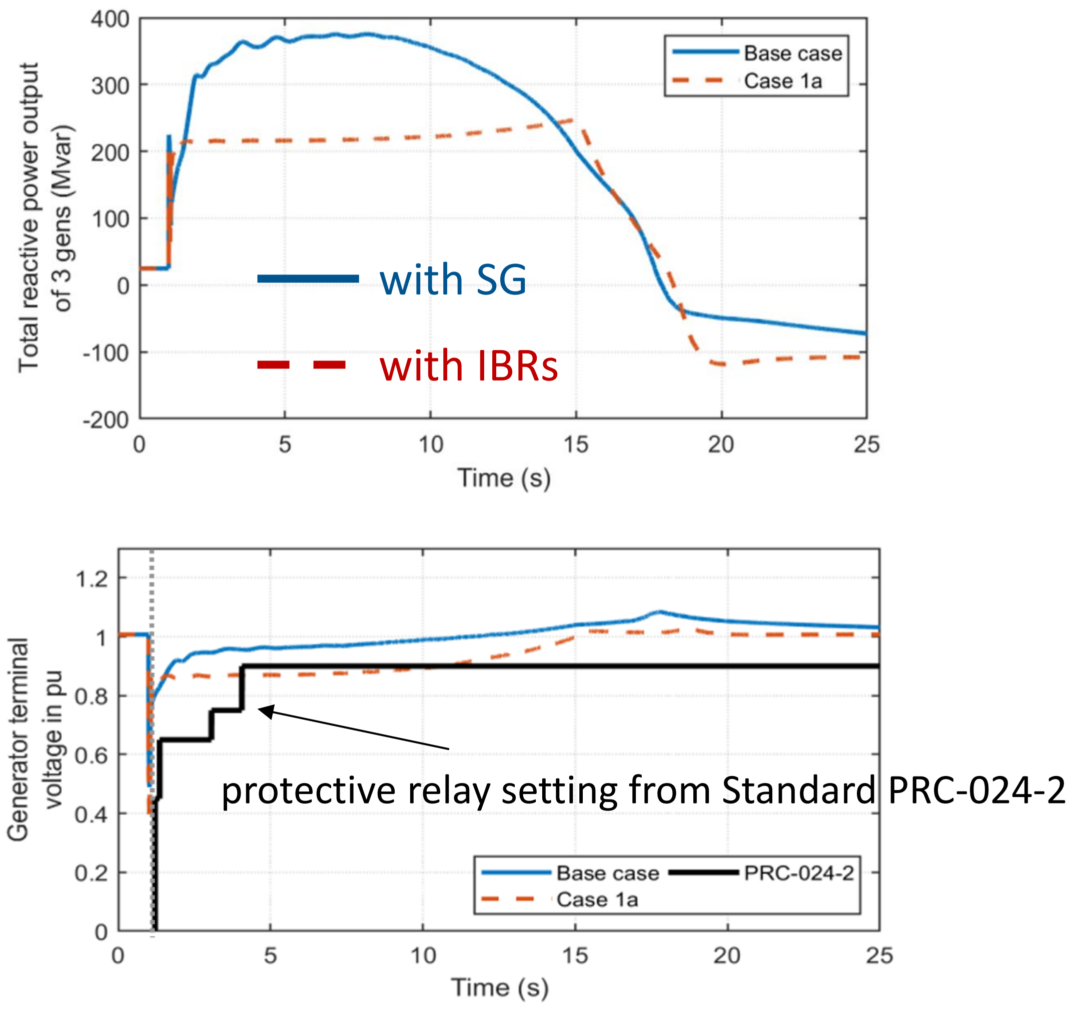
Impact of IBRs on Voltage Stability

- New voltage stability due to inappropriately tuned online voltage regulators interacting between IBRs.
- IBRs limitation on current injection could cause slow voltage recovery after a fault event, risking further device tripping.
- Figures show slower voltage recovery due to limited MVAr injection by IRBs compared to SG, potentially leading to IRBs tripping.



Figures from "Impact of Large scale Integration of Inverter-Based Resources on FIDVR", published in 2020 52nd North American Power Symposium, by L. Sundaresh et al.

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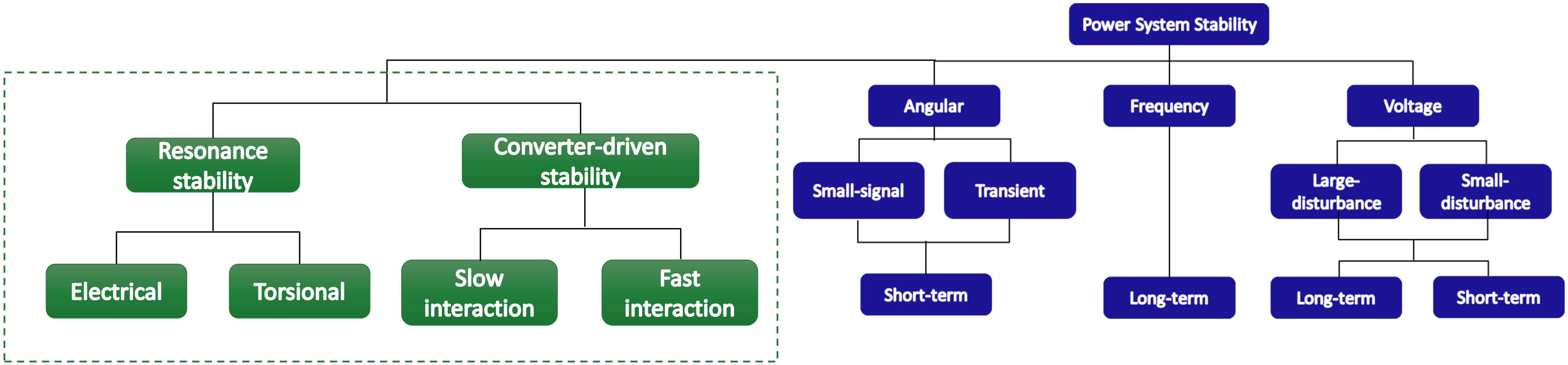
New Dynamic Phenomena

- IBRs fast control response introduce new network stability issues.
- Two new stability categories are added by IEEE Task Force: Resonance stability (also referred to as Subsynchronous Oscillations - SSO) and Converter-driven stability.



New Dynamic Stability Category

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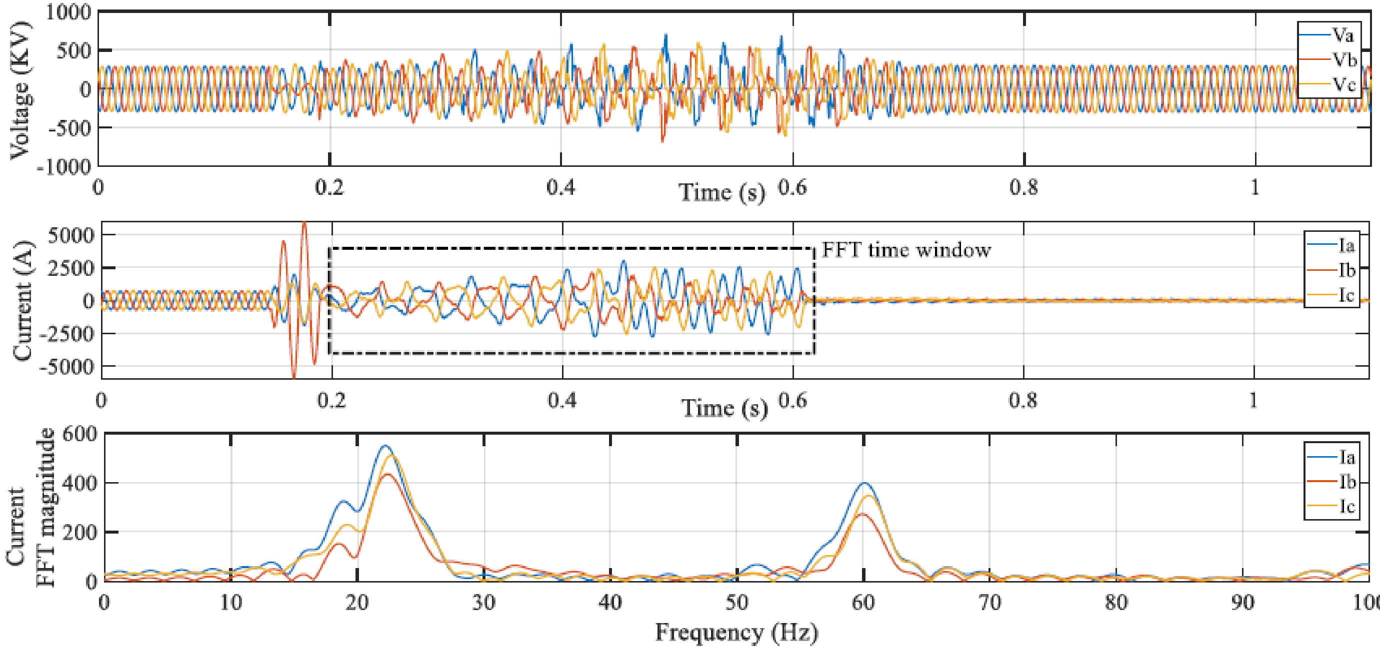
Resonance Stability (Sub-synchronous Oscillations)

- Resonance instability normally manifests itself in voltage oscillations with high amplitude and low damping. Oscillation frequency is normally below the system frequency.
- Harmonics from IBRs can interact with network resonances or other devices causing instability.



An SSO Event happened on 27th Sep, 2017 in ERCOT 375kV network. Windfarms interacted with series-connected capacitors after a fault and eventually tripped by protection. Oscillations was around 20-25 Hz.

Graph from the CIGRE Technical Brochure 909 “Guidelines for Sub-Synchronous Oscillation Studies in Power Electronics Dominated Power Systems”.

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Types of Resonance Stability

- SSO can be further divided as Subsynchronous Resonance (SSR), Subsynchronous Control Interactions (SSCI) and Subsynchronous Tortional Interactions (SSTI).
- SSR: interactions between network component, such as series-compensated line and SG drive-train (torsional mode) or excitation system (electrical).
- SSTI: interactions between IBRs control system and SG drive-train (torsional mode).
- SSCI: electrical interactions between different IBRs control systems and network.

Conventional classification of SSO

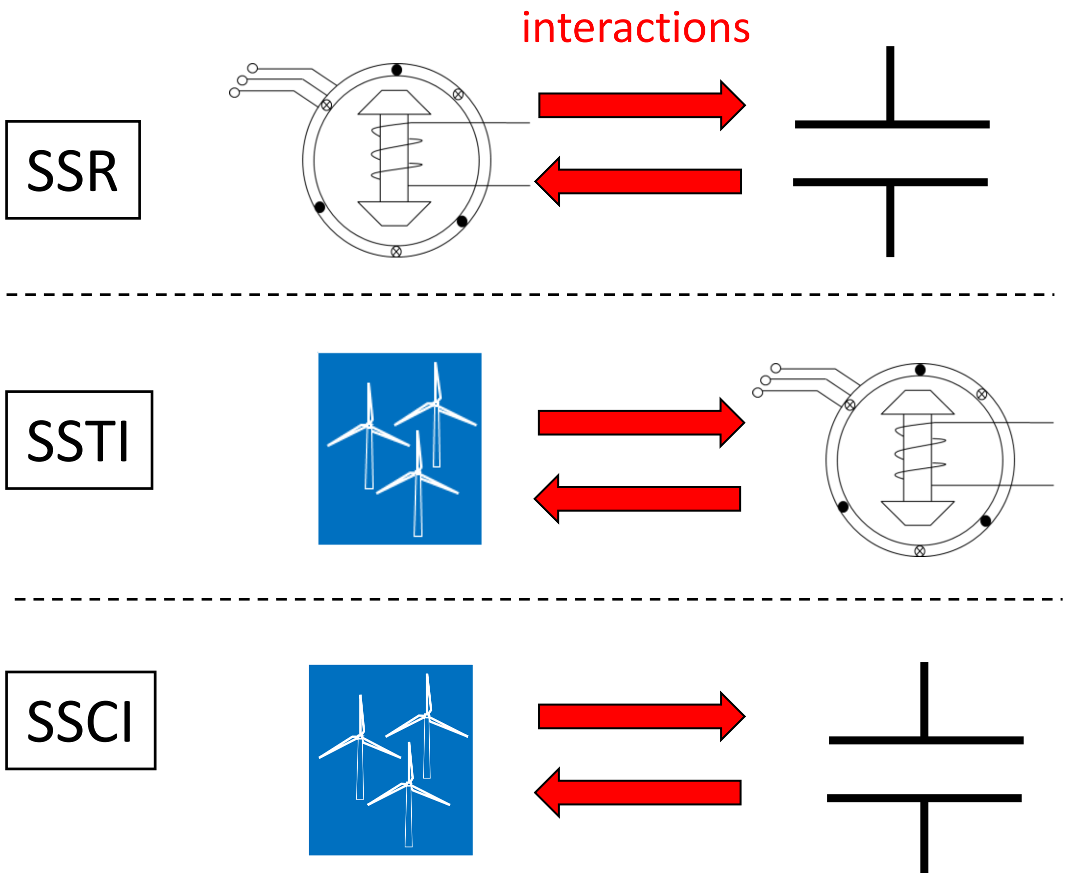

Figure inspired from the CIGRE Green Book on "Power System Dynamic Modelling and Analysis in Evolving Networks" Eds. B. Badrzadeh & Z. Emin

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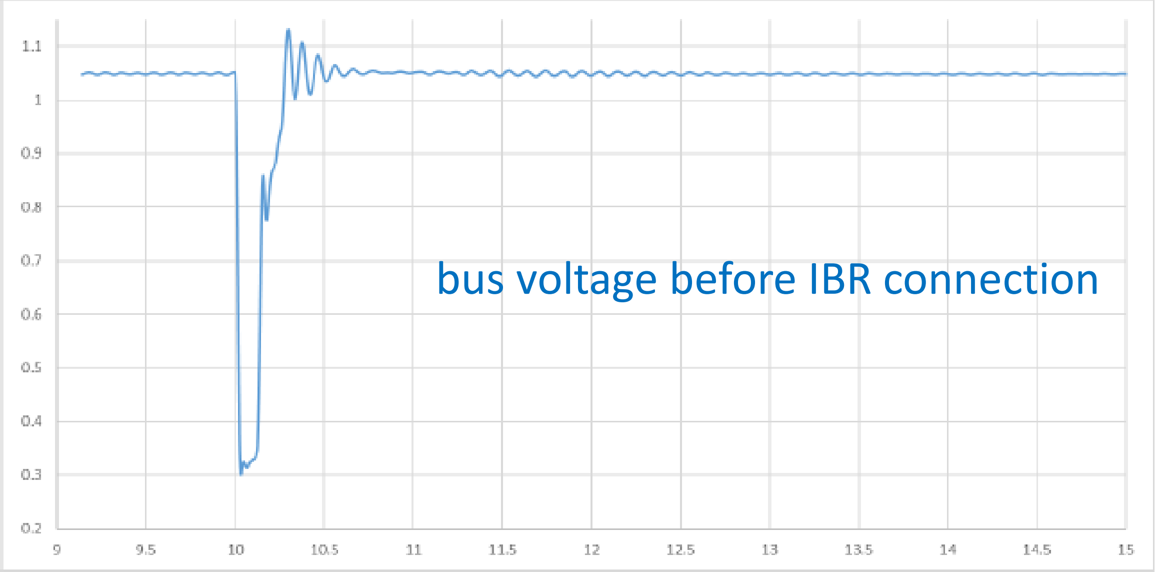
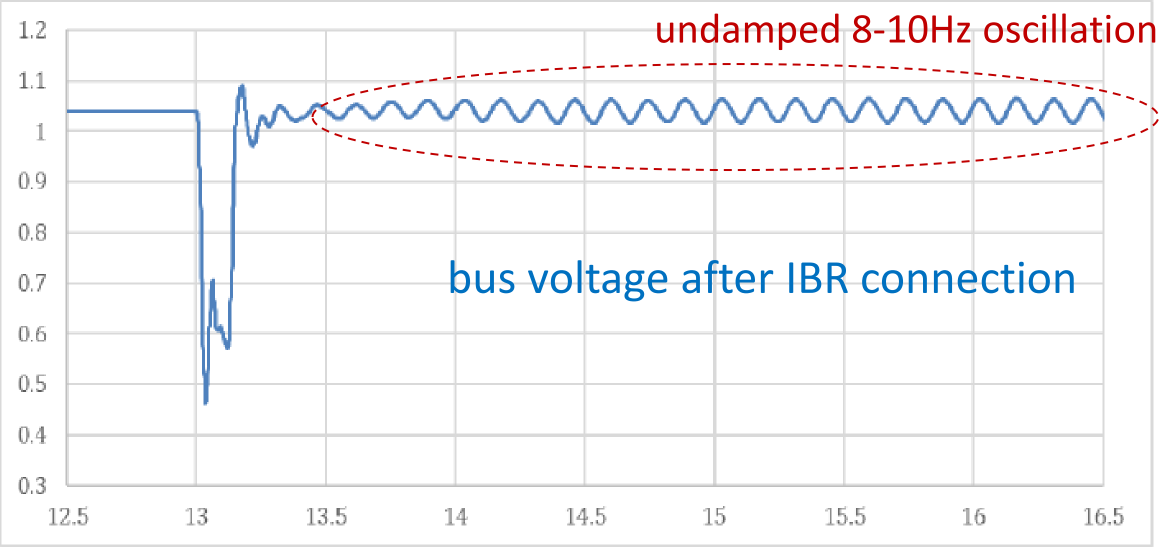
Converter-driven Stability

- Converter-driven instability occurs when system strength is low, when IBRs control system becomes unstable.
- Interactions between IRBs control system and network, or between multiple control systems.
- Figures show bus voltage in a weak network in a fault event with and without IBR connection





Graphs from the CIGRE Technical Brochure 881 “Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high penetration of inverter-connected generation”.

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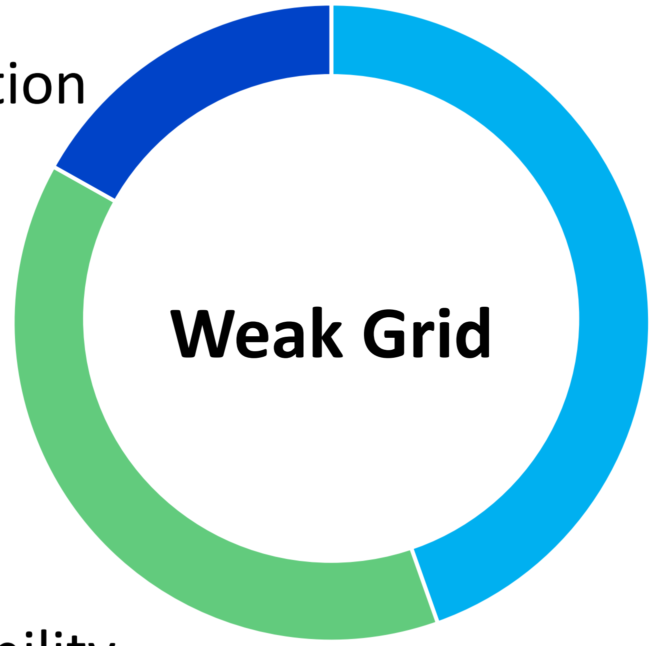
What does weak grid mean?

Low short circuit MVA

- Challenges system protection



High $\boldsymbol{\frac{\Delta V}{\Delta I}}$

high sensitivity of IBR terminal voltage to its current injection

- Challenges stable operation of conventional IBR

High $\boldsymbol{\frac{\Delta f}{\Delta t}}$

low system inertia

- Challenges frequency stability of power system

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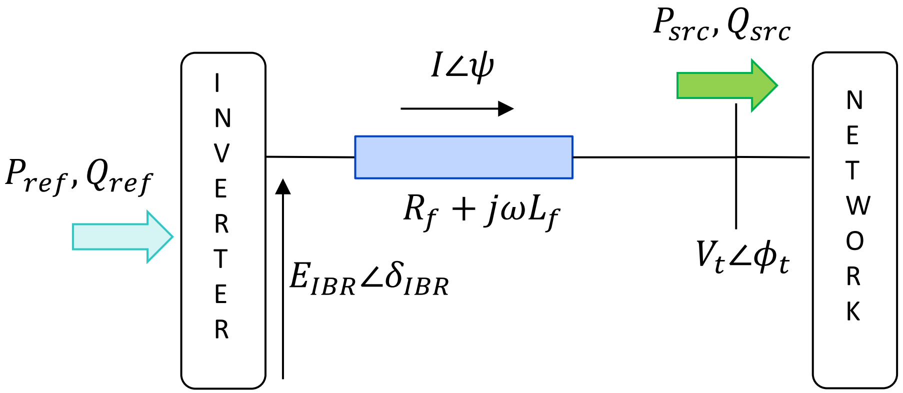
Present-day IBR current generation and weak grids…



$$\underbrace{\frac{P_{ref} - jQ_{ref}}{V_t\angle -\phi_{PLL}} = (I\angle\psi)_{ref}}_{\text{Decided by controller}} \approx \underbrace{I\angle\psi = \frac{E_{IBR}\angle\delta_{IBR} - V_t\angle\phi_t}{R_f + j\omega L_f}}_{\text{Decided by KVL* and network}}$$

- To ensure $I\angle\psi \approx (I\angle\psi)_{ref}$
  - $E_{IBR}\angle\delta_{IBR}$ must change rapidly when $V_t\angle\phi_t$ changes
- To enable a rapid change in $E_{IBR}\angle\delta_{IBR}$
  - Accurate and fast estimation of $\phi_{PLL} \approx \phi_t$
  - Accurate and fast current controller to generate $E_{IBR}\angle\delta_{IBR}$

An IBR injects controlled current

- In weak grids, for small $\Delta(I\angle\psi)$, high $\Delta(V_t\angle\phi_t)$:
  - magnitude of change can be large
  - rate of change occurs can be large
  - frequency of change can be high

Fast control loops of IBRs that help $E_{IBR}\angle\delta_{IBR}$ change rapidly can become unstable

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*KVL = Kirchhoff's Voltage Law

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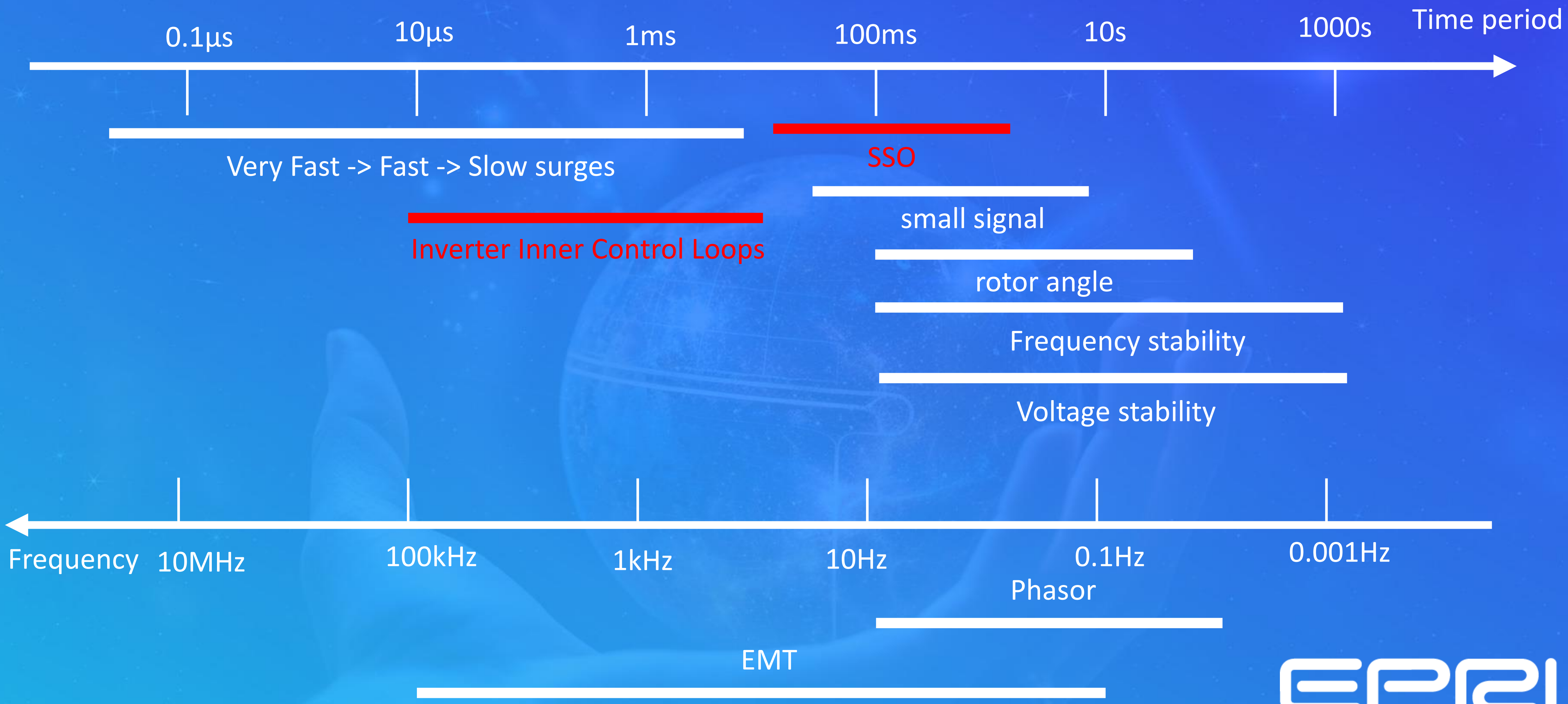
Frequency Range of Interest



Power System Dynamic Modelling and Simulation Tools

Why are dynamic simulations conducted?

- An objective of a dynamic simulation:
  - Get visibility and insight regarding dynamic characteristic response of a system

- How are dynamic characteristics represented?
  - Predominantly through use of differential equations that represent the rate at which quantities change.

- How is the above objective achieved?
  - Through numerical integration of differential equations
  - Along with solution of algebraic equations (if present)

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Two major power system dynamics simulation domains

- Phasor Domain Transient (PDT): popular industrial software including PowerFactory, PSSE, TSAT and more.
- Electromagnetic Transient (EMT): popular industrial software including ATP, EMTP, PowerFactory, PSCAD and possibly others.
- PDT and EMT use different modelling assumptions and equations to solve power systems equations.

Software names listed in alphabetical order

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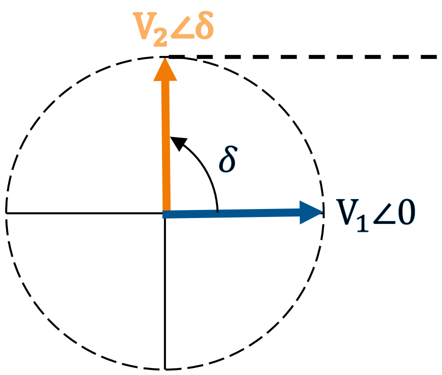
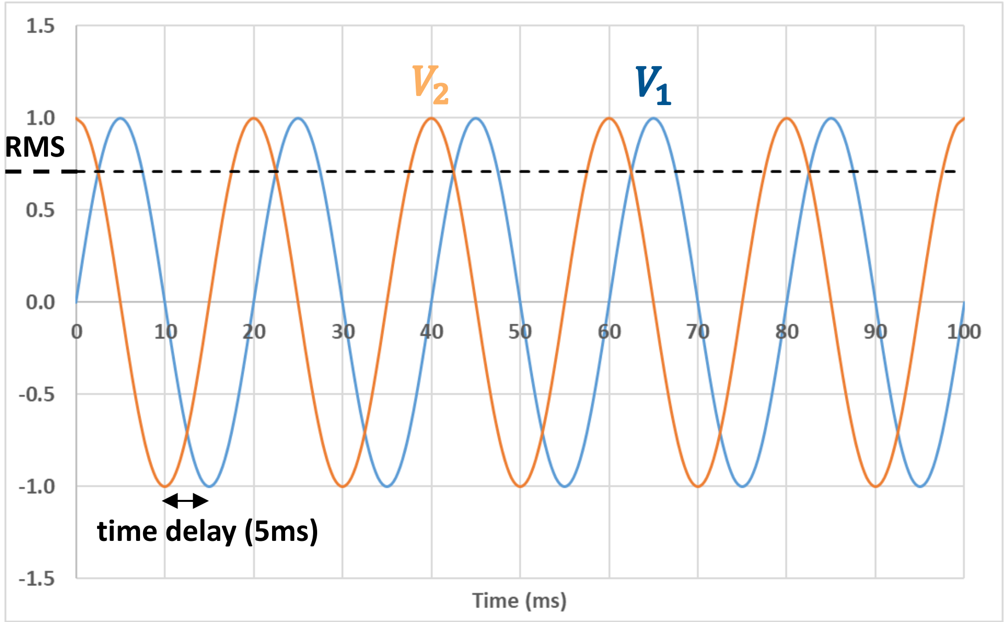
Phasor Domain Transients (PDT)

- In PDT, V and I are represented as phasors, i.e., consisting of magnitude and angle. The magnitude equals the RMS of a sinusoidal signal, while the angle represents the time delay between two sinusoidal signals in time domain.
- Network impedance is calculated at power frequency; this allows network to be modelled using algebraic equations. However, any network resonances and dynamics occur at other frequencies are ignored.
- Note PDT is also commonly termed as root-mean-square (RMS) or positive sequence, despite the differences.

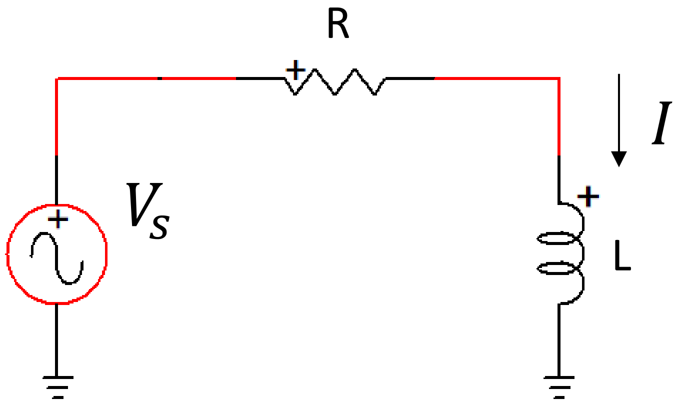
Phasor



Time domain



$$V_s = R\,I + j\omega_0 L\,I$$



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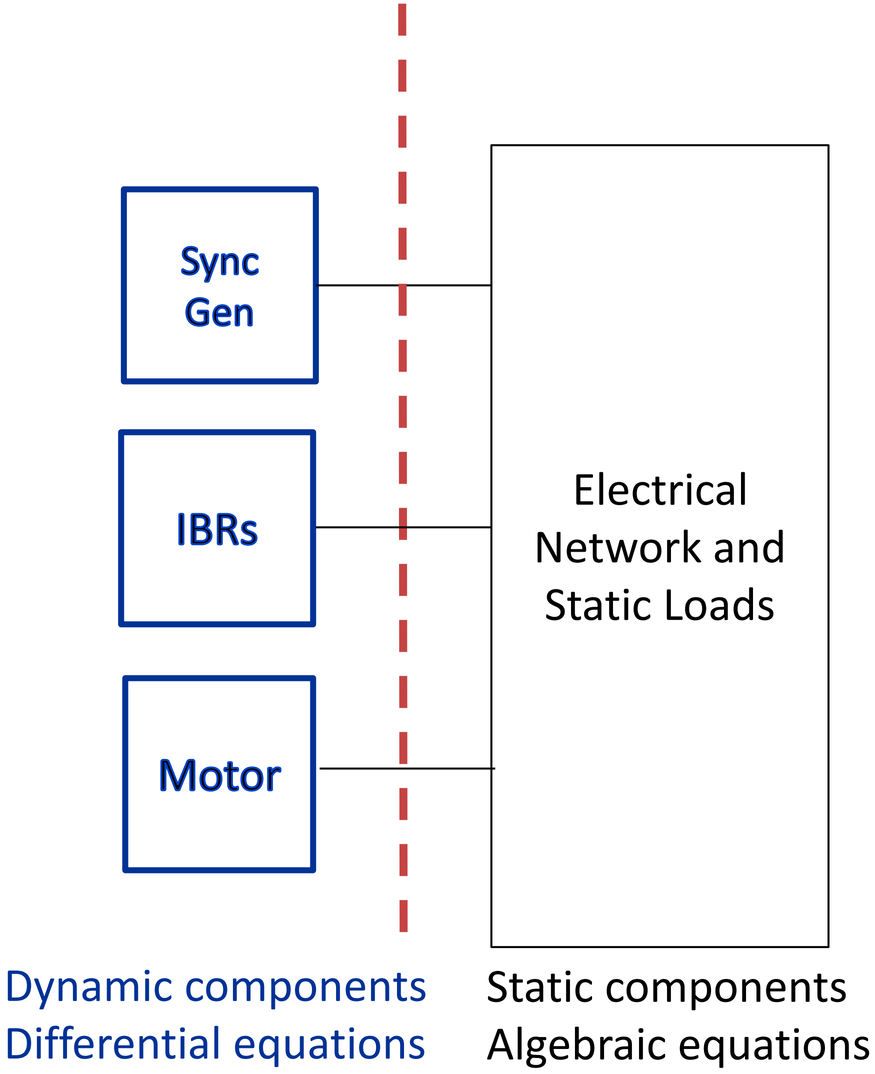
PDT software

- Solves a system of differential – algebraic equations (DAE) in a sequential manner
- Network equations are solved as algebraic equations
- Dynamic device equations are solved as differential equations
- Boundary between differential and algebraic equation solvers is known as network interface



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Process of running dynamic simulation in PDT software

- Solve power flow
- Initialize state variables
- Start time
  - Solve network equation
  - Take updated values of boundary variables as input to differential equation
  - Evaluate update value of differential term
  - Numerically integrate equations
  - Evaluate updated value of injection variables
- End time

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PDT Strengths

Key Strengths	Descriptions
Maturity	PDT methods are well-understood and validated worldwide, sufficiently accurate to study electromechanically phenomena of SG dominated networks.
Computational Efficiency	Model simplifications enable large integration time and fast execution of simulating large networks considering multiple contingency scenarios. This allows applications to run simulations online supporting control room decisions.
Model Availability	Generic PDT models are widely available, vendor-specific models are also normally available and created due to grid code requirements.

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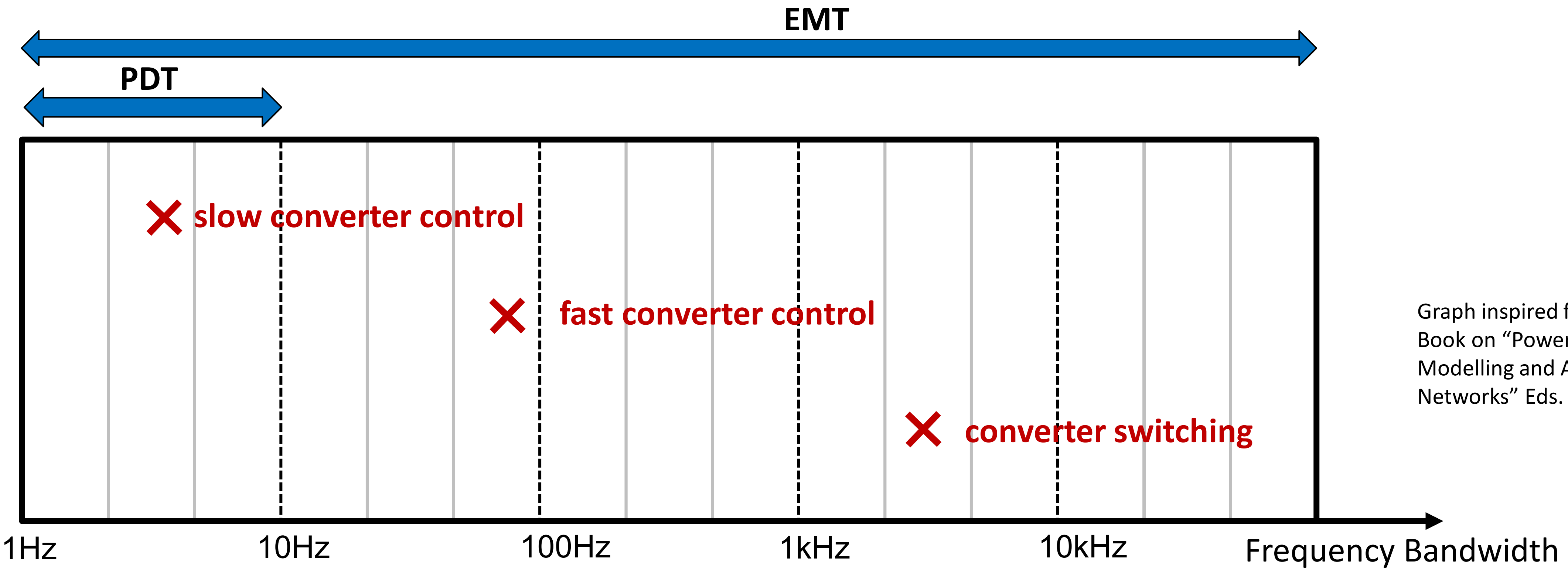
PDT Limitations

Key Limitations	Descriptions
Limited Bandwidth	Up to 10Hz, not suitable for studying SSO
Static Network Representation at $\boldsymbol{\omega_0}$	Any harmonics and dynamics occur at frequencies other than ω_0 are absent



Graph inspired from the CIGRE Green Book on "Power System Dynamic Modelling and Analysis in Evolving Networks" Eds. B. Badrzadeh & Z. Emin

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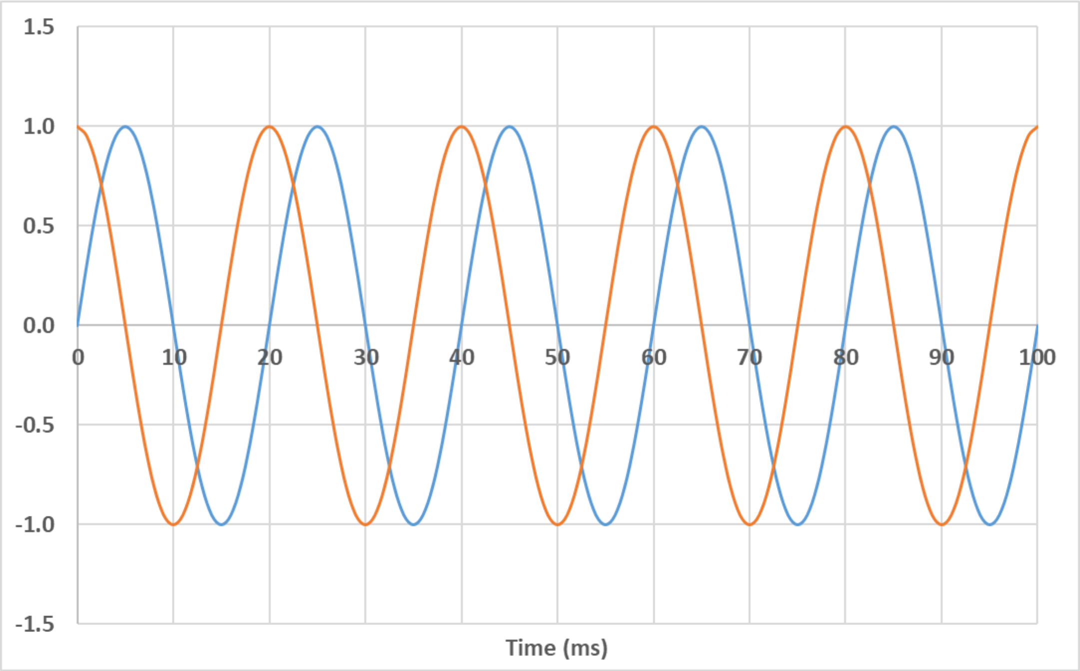
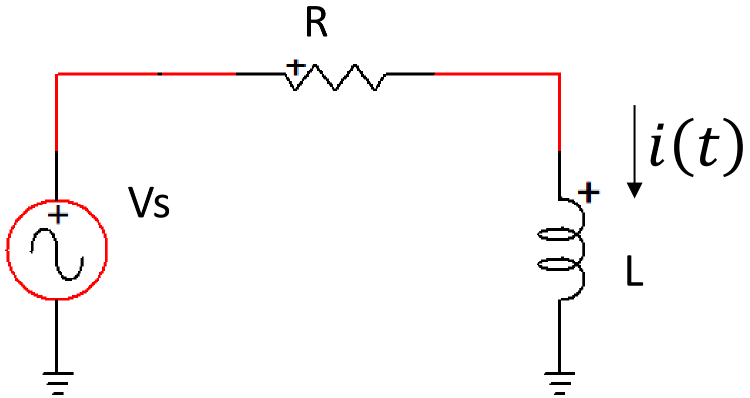
Electromagnetic Transients (EMT)

- Instantaneous values of V and I are explicitly calculated.
- Network elements and control systems are both modelled using differential equations.
- Classical switching and lightning studies are done in EMT due to wide frequency bandwidth.



$$V_s(t) = R\, i(t) + L \frac{di(t)}{dt}$$



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Electromagnetic Transient Software

- EMT software was developed traditionally to study electromagnetic transient phenomena.

- EMT software solves a set of differential equations in time domain which represent both network and control system equations.

- One common simulation method used in EMT software is Nodal analysis based, which is computationally efficient for solution of large-scale grids.

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Nodal Analysis-Based EMT Solver

- Network is represented as Nodal model.

known network time-varying admittance matrix

$$V_N(t) = Y_N^{-1} I_N$$

unknown node voltages

known current injections from Norton equivalent sources

- Control systems are represented at State-space models.

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

x:states

y:outputs

u:inputs

A,B,C,D: state-space matrices

- Concatenated system equations

$$X = \begin{bmatrix} Network & \\ & Control \end{bmatrix}^{-1} Y$$

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Process of running a time domain simulation in EMT software

- Find initial condition at t=0 s
  - Network (branch currents & node voltages)
  - Control (state variables)

- Start time

- Solve differential equations of the nodal model and state-space model.

- End time

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EMT Strengths

Key Strengths	Descriptions
Network Representation	Network elements are frequency-dependent, which allows dynamic interactions due to harmonics and system resonances to be studied.
Bandwidth	Wide bandwidth (up to kHz) which allows IBRs fast controllers to be modelled more accurately.

- Due to the strength of EMT analysis, dynamic stability phenomena influenced by IBRs such as SSO can be studied using EMT software.

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EMT Limitations

Key Limitations	Descriptions
Computational Burden	Detailed modelling and small time-step (μs) may lead to long simulations time, i.e. few seconds of simulation time can take several minutes or even hours to compute.
IBR Model Availability	Generic IBR models are increasingly available, however may not be sufficiently detailed or accurate for some types of studies. Parameterization/tuning of generic models to produce similar response to real device can also be challenging.
Vendor-specific IBR Model Management	Vendor-specific models are also increasingly available but continuous support of these specific models may be an issue. Vendor-specific models may run only on specific integration time-step. They may also be compiled for specific versions of EMT software as they are normally provided in black box format.

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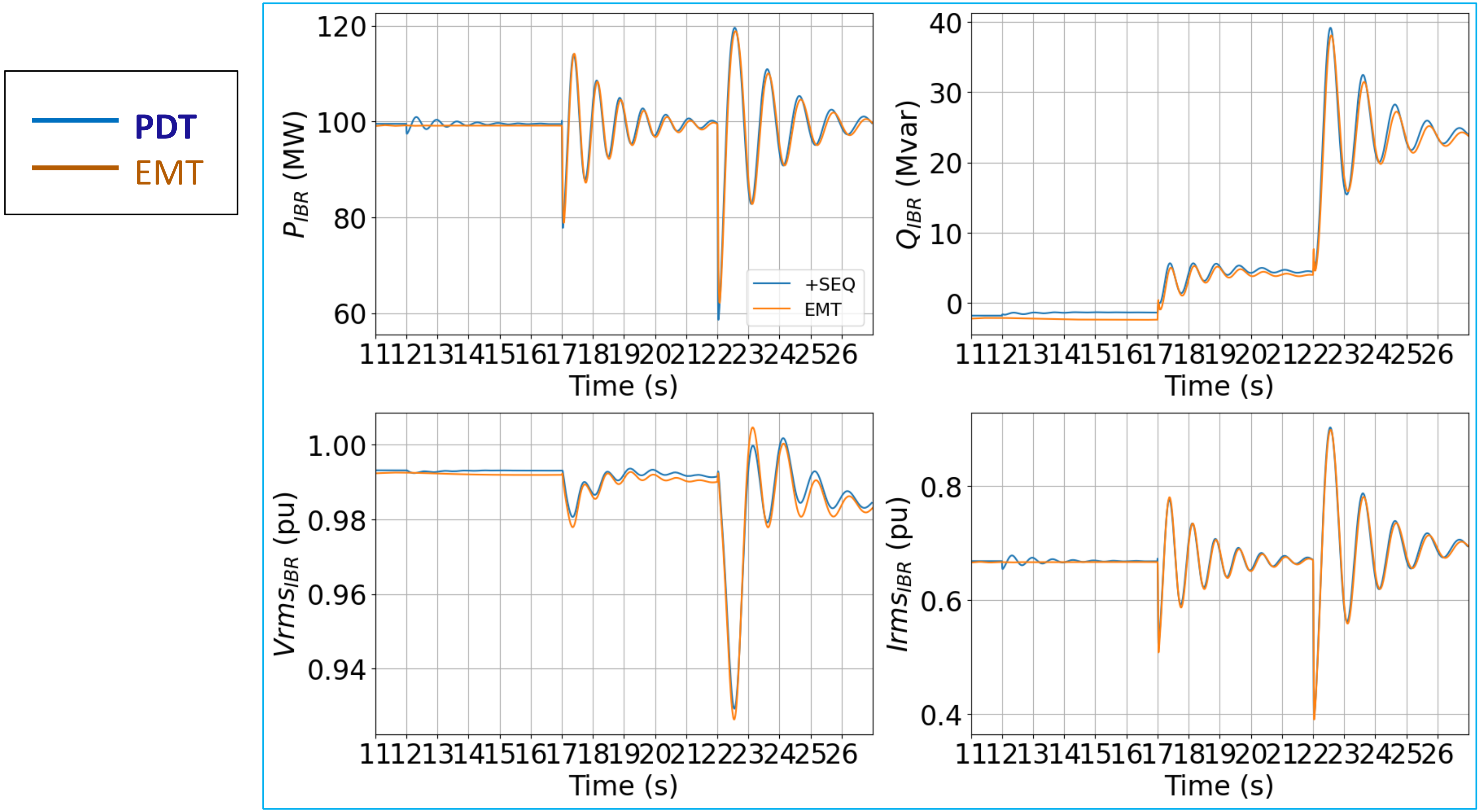
Comparing SG Response between PDT and EMT

- Change in Short Circuit Ratio (SCR) from 3.0 to 2.0 to 1.0 (reducing system strength)



Models of synchronous machine and its excitation and governor system are represented in a similar manner in both domains

The content of this slide is from EPRI "Grid Forming Inverters: EPRI Tutorial", Oct 24, 2025.

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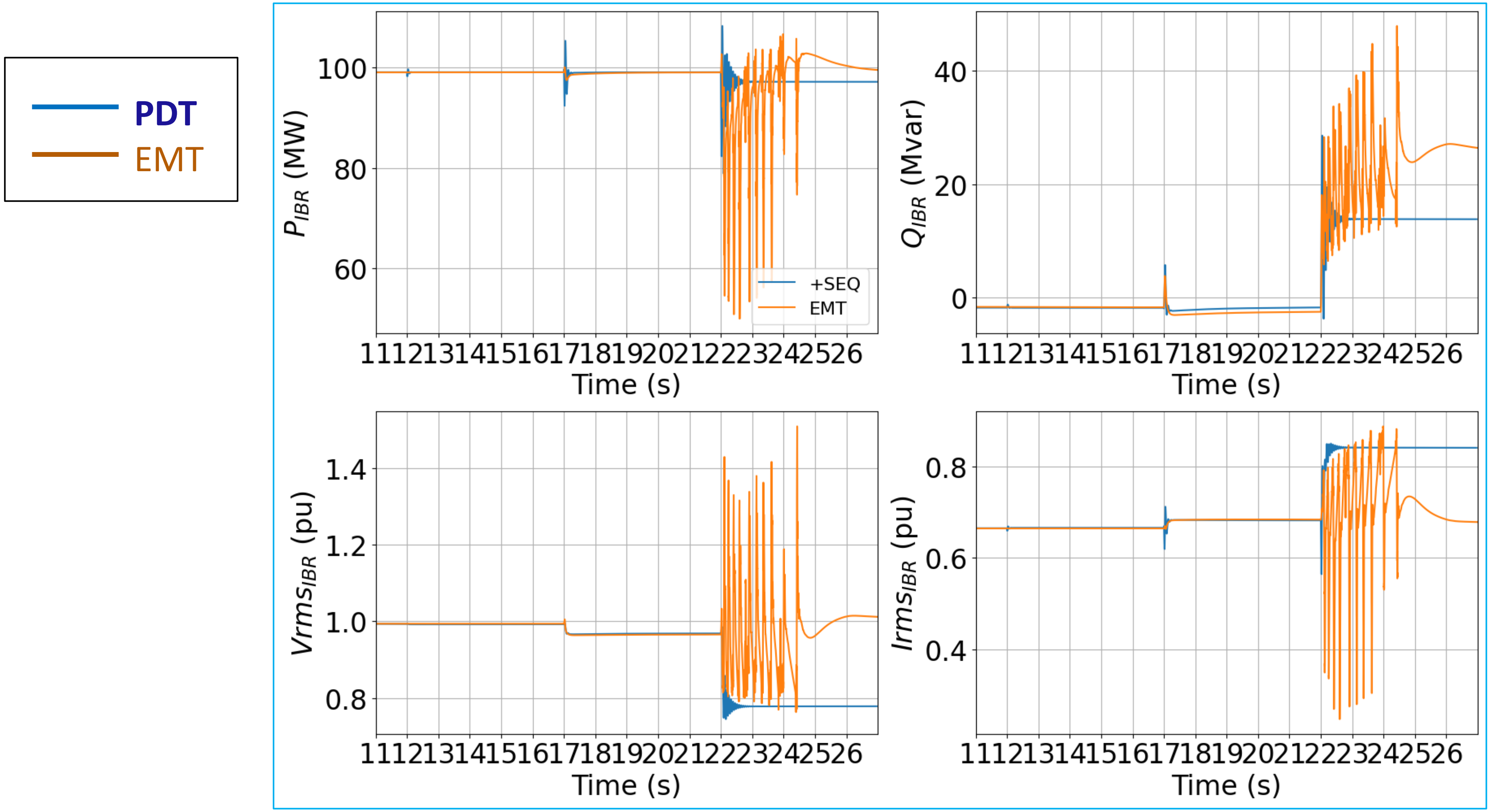
Comparing IBR Response between EMT and PDT

- Change in SCR from 3.0 to 2.0 to 1.0



Models of IBR plant, while represented in a similar manner, have different responses due to speed of control loops, bandwidth of simulation domain, and triggers/thresholds for control changes

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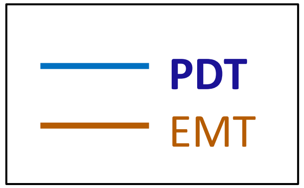
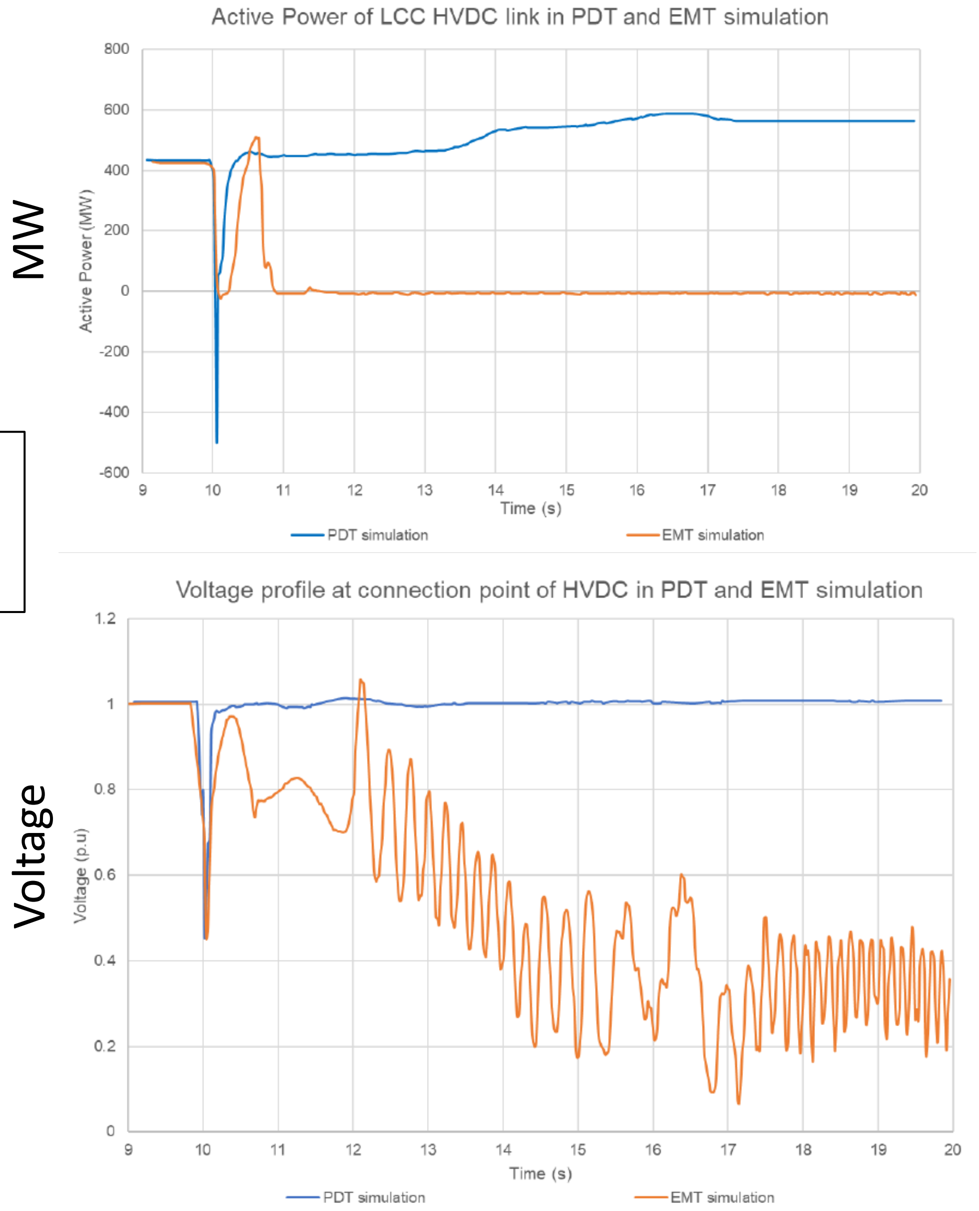
PDT vs EMT Study Result Example – HVDC Response

- Figures compare HVDC response simulated by EMT and PDT software in a fault event.
- In PDT, HVDC had successfully ride-though the fault; however, in EMT, HVDC encountered commutation failure and tripped.
- Failed to identify the HVDC tripping in PDT can lead to system instability in real time and potentially economic and safety consequence.





Graph from the CIGRE Technical Brochure 881 “Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high penetration of inverter-connected generation”.

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WTG Components Modelling Requirements in EMT/PDT

- Table shows components of wind turbine generators (WTG) required to be modelled for different types of studies in PDT and EMT domain.
- Item with asterisk* meaning the component may or may not have a significant impact depending on wind turbine type and make.

Components	Transient Stability	SSO	High-frequency Switching Transients	Harmonics
Aerodynamics	PDT*, EMT*	EMT*	-	EMT*
Pitch controller	PDT*, EMT*	EMT*	-	EMT*
Mechanical drive train	PDT*, EMT*	EMT	-	EMT*
Torsional damping	PDT*, EMT*	EMT	-	EMT*
Electrical generator	PDT, EMT	EMT	EMT	EMT
Dynamic braking resistor/chopper	PDT, EMT	EMT		EMT
DC link	PDT, EMT	EMT	EMT*	EMT
IGBT switches and PWM switching	-	-	EMT	EMT
Unit transformer	PDT, EMT	EMT	EMT	EMT
Internal filter	PDT, EMT	EMT	EMT	EMT
Inner loop converter control	EMT	EMT	EMT*	EMT
Outer loop converter control	PDT, EMT	EMT	EMT*	EMT
Phase locked loop	EMT	EMT	EMT*	EMT
Frequency control	PDT, EMT	EMT		
High voltage ride-through	PDT, EMT	EMT	EMT	
Low voltage right-through	PDT, EMT	EMT		
Protection	PDT, EMT	EMT	EMT	

Table from the CIGRE Technical Brochure 881 “Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high penetration of inverter-connected generation”.

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Building Large Scale EMT Dynamic Study Capability

When to use EMT for dynamic studies

- Due to high computational burden, model availability and complexity, it is not practical to run dynamic simulations using EMT software extensively.

- Some key areas where running simulations in EMT is recommended:
  - wide-area dynamic studies of IBRs interactions followed by critical disturbances or in low system strength conditions.
  - Interconnection/compliance studies, such as fault-ride-though, short-circuit analysis etc., to ensure Grid Code compliance and identify potential issues at early stage before connection.
  - IBRs model validation by comparing simulated response to filed data to ensure its accuracy.

- Since last decade, electricity utilities worldwide have started building knowledge and capabilities of carrying out network modelling and simulations in EMT to tackle challenges brought by IBR connections.

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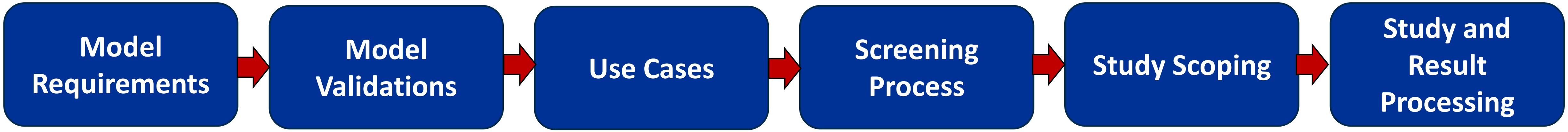
Building Large Scale EMT Study Capability - 1

- Main phases/stages towards building capabilities of large-scale EMT studies:



- **Model requirements**: clear definition of detailed EMT plant models – how they should be and for what applications, i.e. SSO analysis, protection studies etc. For vendor-specific 'black-box' models, it is important to define what variables should be available for the user to change.
- **Model validations**: development of comprehensive model testing process to ensure model quality and accuracy, i.e. they are fit-for-purpose. The test results should be well documented.

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Building Large Scale EMT Study Capability - 2

- **Use Cases:** determine list of cases/events which trigger studies in EMT. A flowchart with study criteria could be used to assist defining use cases.
- **Screening Process:** utilize developed process or tools, such as steady-state frequency scan etc., to identify 'high risk' network areas and scenarios to be studied in EMT. This reduces complexity, computational burden and time required for EMT studies.
- **Study Scoping:** clearly define study objectives, network model boundaries, equipment model detail or equivalencing, number of network operating conditions and contingencies.
- **Study and Result Processing:** EMT studies should be conducted with well-trained study engineers with good knowledge in IBRs and network modelling in EMT, and various types of system dynamic phenomena and how network components could respond and interact.

Model Requirements → Model Validations → Use Cases → Screening Process → Study Scoping → Study and Result Processing

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Conclusions

- IBRs bring new dynamic stability challenges to modern power systems, resulting from interactions between IBRs control systems and other network components and devices.

- PDT analysis domain was traditionally used to simulate dynamic stability of power systems networks dominated by synchronous machines. However, IBRs related dynamic stability phenomena may not be accurately simulated using PDT software due to PDT's limited bandwidth and lack of network resonance modelling capability.

- EMT analysis domain has much wider bandwidth allowing IBR's fast controls and connected networks to be modelled accurately based on differential equations. As a result, many electricity utilities worldwide have started adopting EMT software to study IBR related dynamic stability phenomena.

- However, there are major computational challenges associated with systemwide EMT modelling and analysis and the area is under development continuously.

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References and Further Readings

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What’s Next?

- State-of-the-art in EMT with various TSOs
- EMT modelling requirements (provision, validation, acceptance) considering different applications, such as stability, fault ride through, protection, and power quality.
- Practicalities of EMT analysis (when is it required, what methods are used to move to EMT domain)
- Example of EMT simulation results

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