CFES
Center for Future Energy Systems

Stability of Converter-Based Power Systems

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Outline

- Power Electronics in Power Systems
- Characteristics of Machines vs. Converters
- Converter-Based Power System Stability
- Small-Signal Sequence Impedance Theory and Applications
- Summary and Future Development

Power Electronics in Power Systems

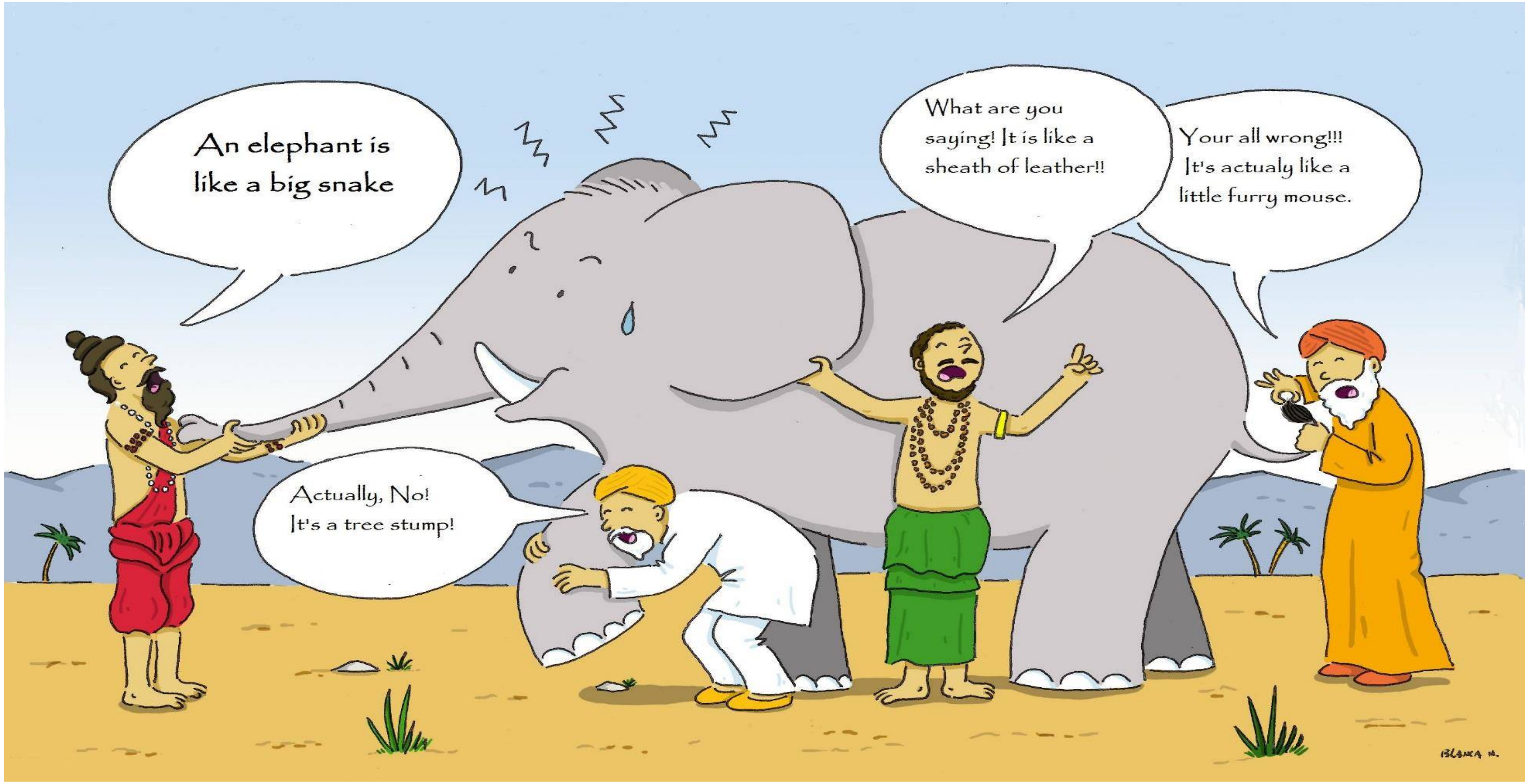
Generation | Transmission | Distribution | Consumption

Power Electronics in Power Systems

Generation → Transmission → Distribution → Consumption

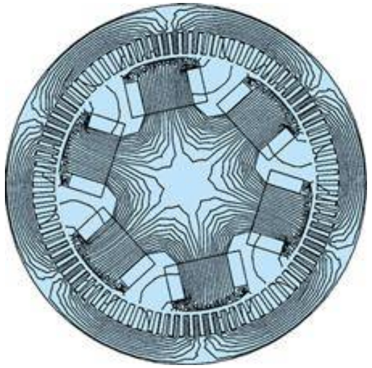
- Power Electronics is the Key to These New Developments
- 100% Renewable → >100% Converter-Based Power System

Converter-Based Power System

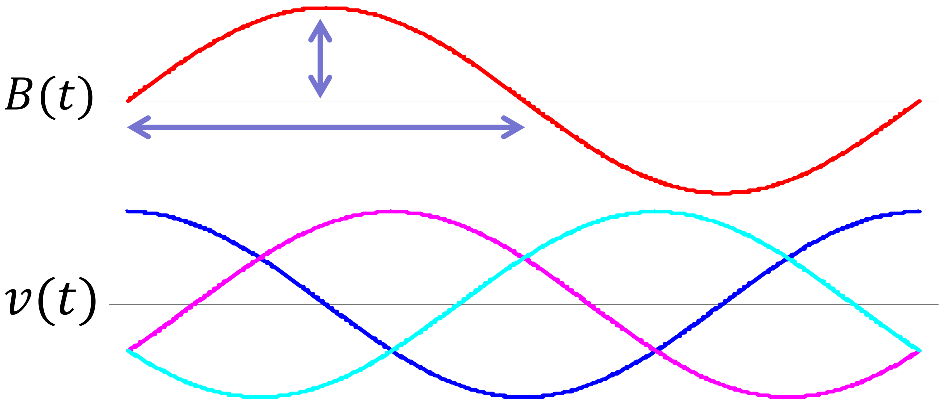


Machines (& Transformers) vs. Converters

- Slow or No Control

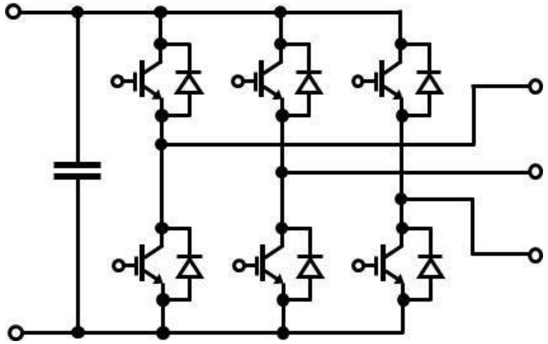


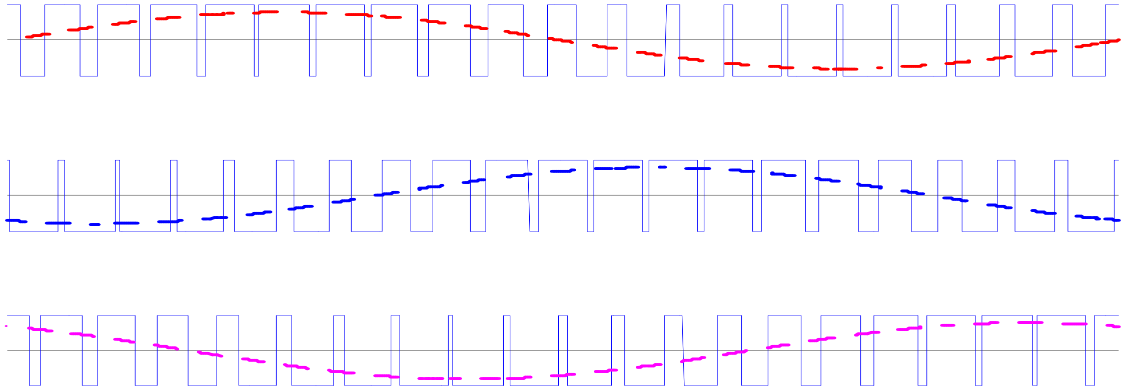
$f_c < 0.1 f_1$



- Fast Control is Essential

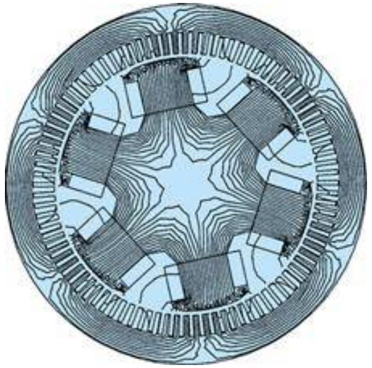
$f_c > 10 f_1$



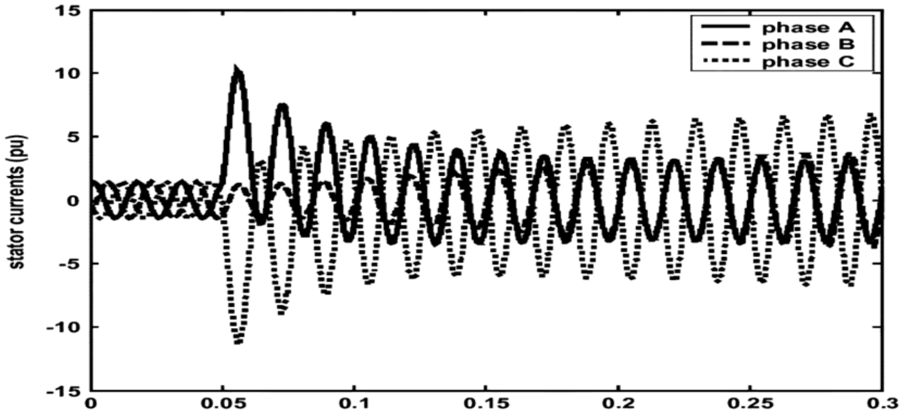


Machines (& Transformers) vs. Converters

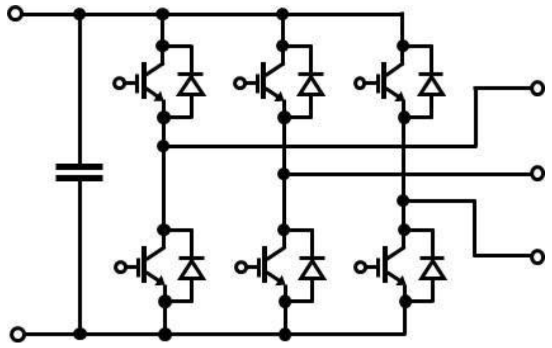
- Overloading Comes Free
- Overloading at High Cost

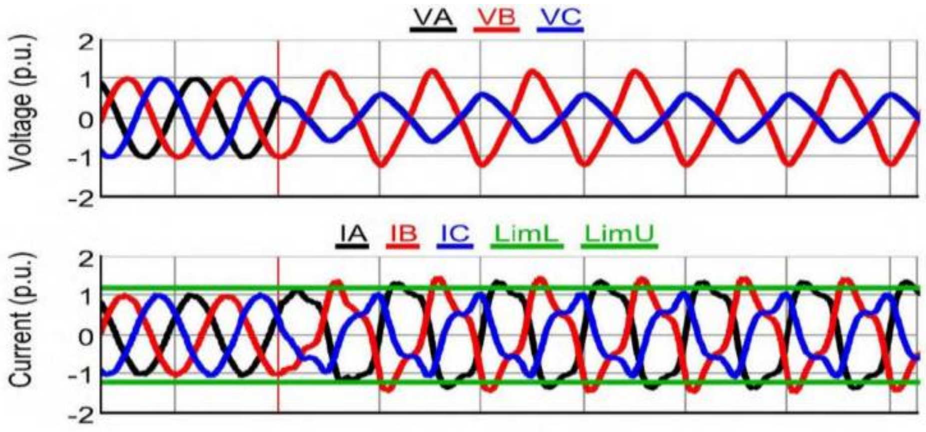


$I_{\max}$: $5\sim10I_N$

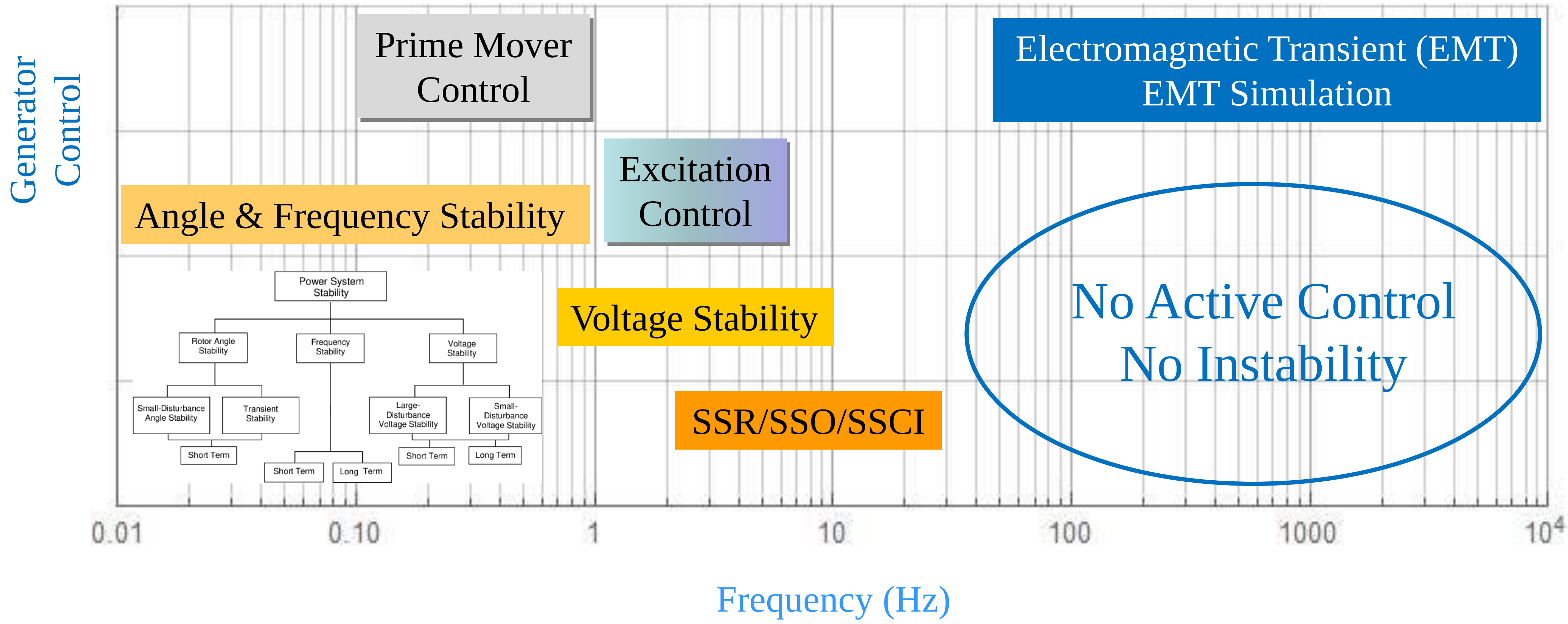


$I_{\max}$: $1.2\sim1.5I_N$

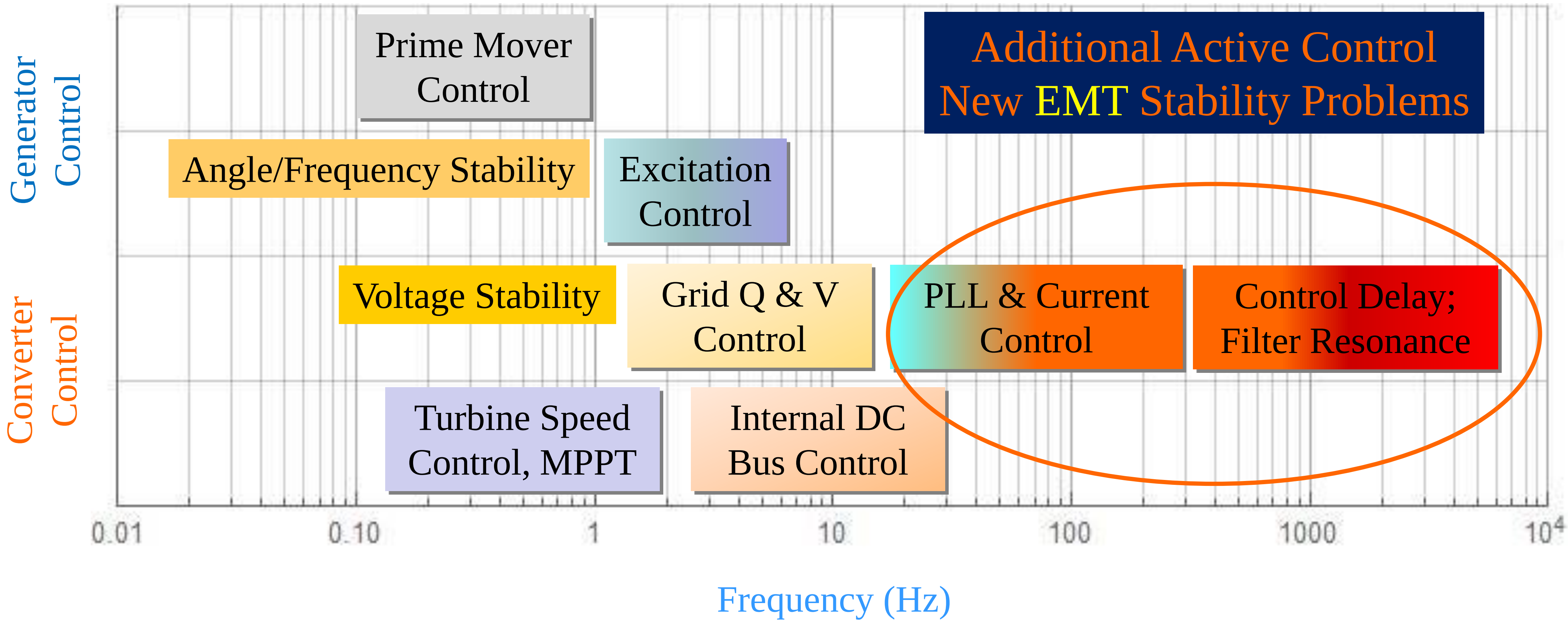




Power System Stability



Converter-Based Power System Stability



EMT Stability

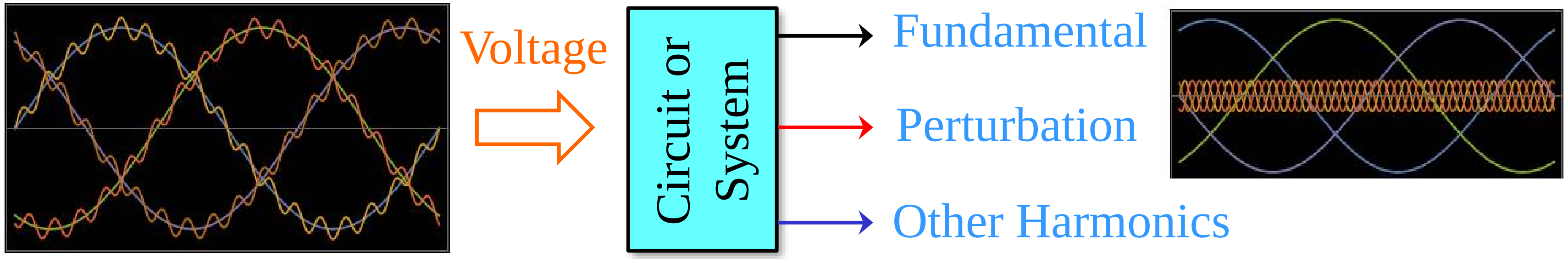
- Study of System Stability in the EMT Frequency Range Requires EMT Models
  - Fundamental-Frequency Models cannot Describe Fast Control & Dynamics
- EMT Simulation is a Useful Tool but Simulation is not Enough
- Analytical and Small-Signal Methods are Required for General Stability Study and System Design → Small-Signal EMT Models
- Direct Linearization of EMT Models Leads to Linear Time Periodic Models That cannot be Handled by Practical Control Methods

$$[x(t)+\Delta x][y(t)+\Delta y] = x(t)y(t) + x(t)\cdot\Delta y + y(t)\cdot\Delta x$$

Harmonic Linearization

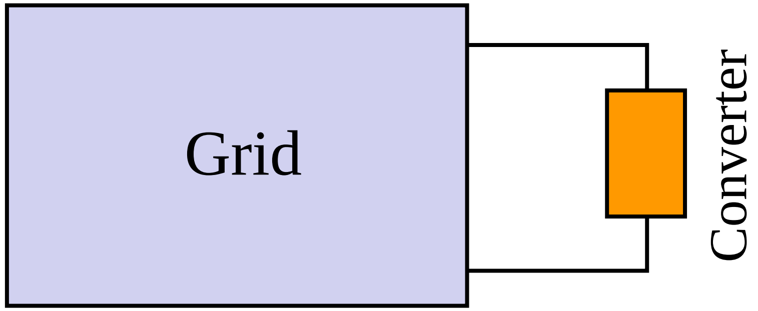
- Linearization Along a Periodic Operation Trajectory (Harmonic)
- Frequency-Domain Models – Small-Signal Sequence Impedances

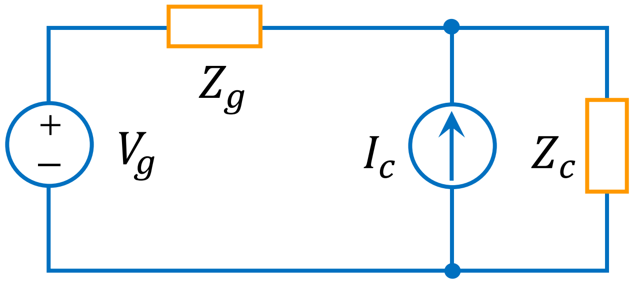
Perturbation Method	Domain	Perturbation
Amplitude (& Phase) Modulation	Time	$[V_r + \Delta v_r(t)]\cos\omega_1 t - [V_i + \Delta v_i(t)]\sin\omega_1 t$
	Frequency	$\left[V_r + \Delta V_r\cos\left(\omega_p t + \varphi_r\right)\right]\cos\omega_1 t - \left[V_i + \Delta V_i\cos\left(\omega_p t + \varphi_i\right)\right]\sin\omega_1 t$
Superimposed Harmonic	Time	$V_1\cos(\omega_1 t + \varphi_1) + \Delta v(t)$
	Frequency	$V_1\cos(\omega_1 t + \varphi_1) + \Delta V_p\cos\left(\omega_p t + \varphi_p\right)$

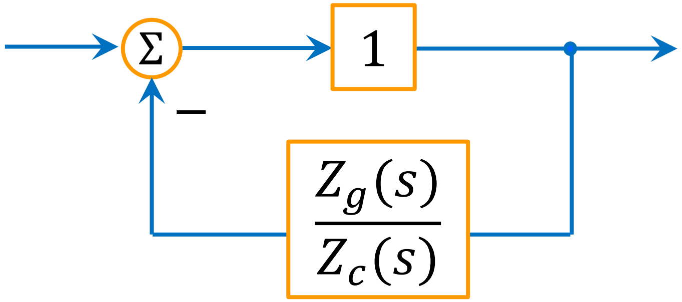


Same Principle for
Analytical Modeling,
Measurement,
Simulation

Impedance-Based System Stability Theory



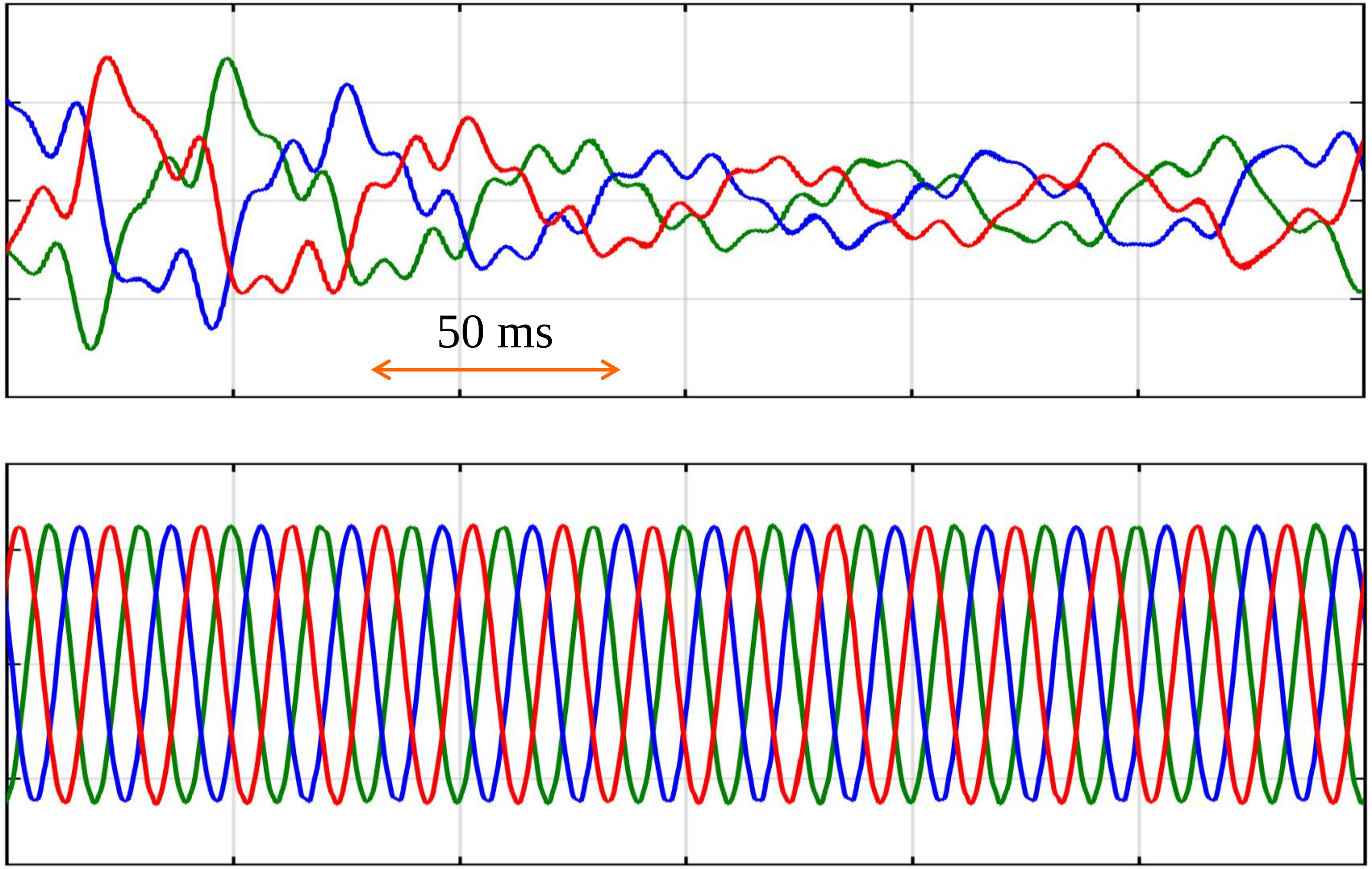


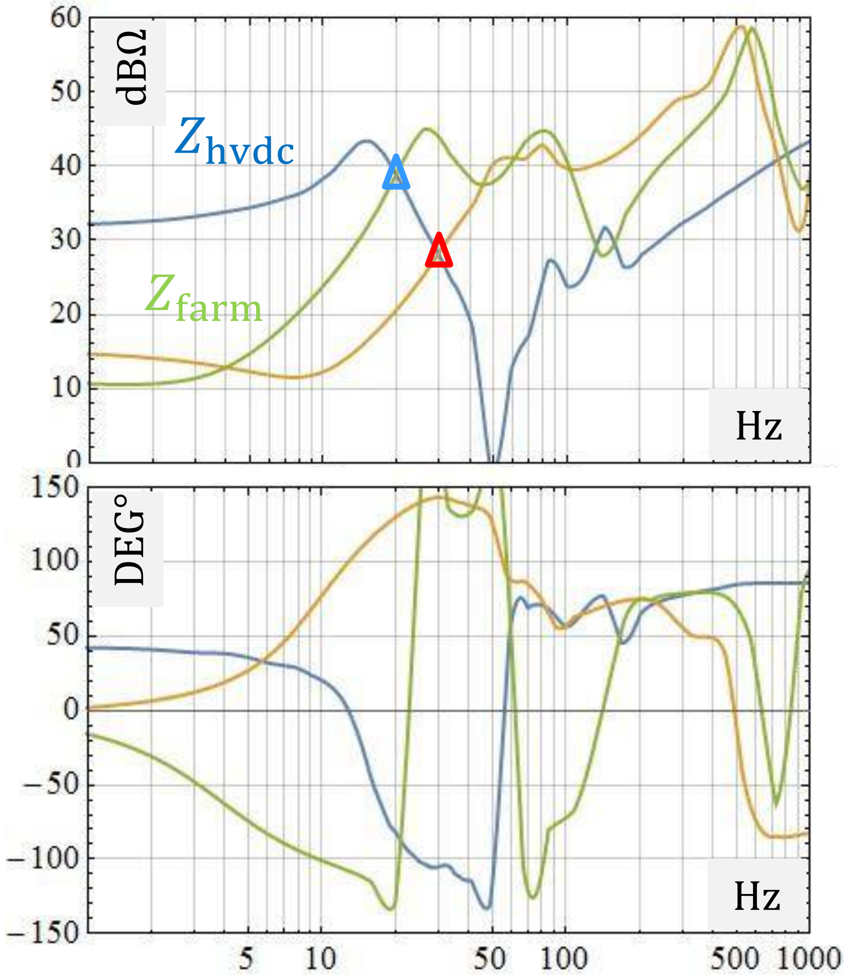


$$I_g(s) = \frac{I_c(s)/Z_g(s)}{\frac{1}{Z_c(s)} + \frac{1}{Z_g(s)}} - \frac{V_g(s)}{Z_c(s) + Z_g(s)} = \left[I_c(s) - \frac{V_g(s)}{Z_c(s)} \right] \cdot \frac{1}{1 + \frac{Z_g(s)}{Z_c(s)}}$$

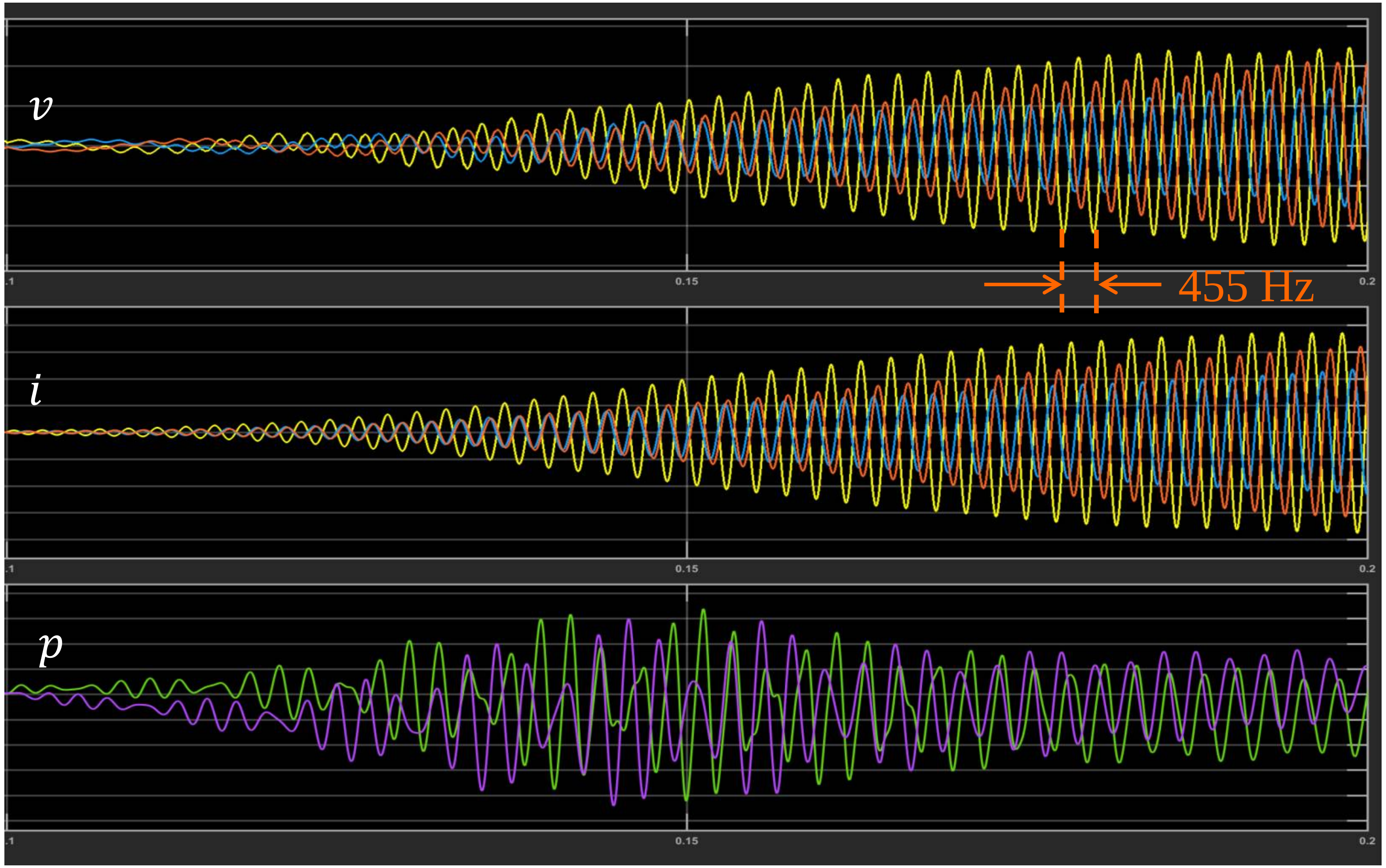
- System Modeling Based on Impedance
- Converter-Grid Forms a Feedback Loop by Virtue of Impedance
- Stability Requires the Resulting Effective Loop Gain to Satisfy Nyquist Criterion
- System is Stable if both Positive and Negative Sequence Subsystems are Stable

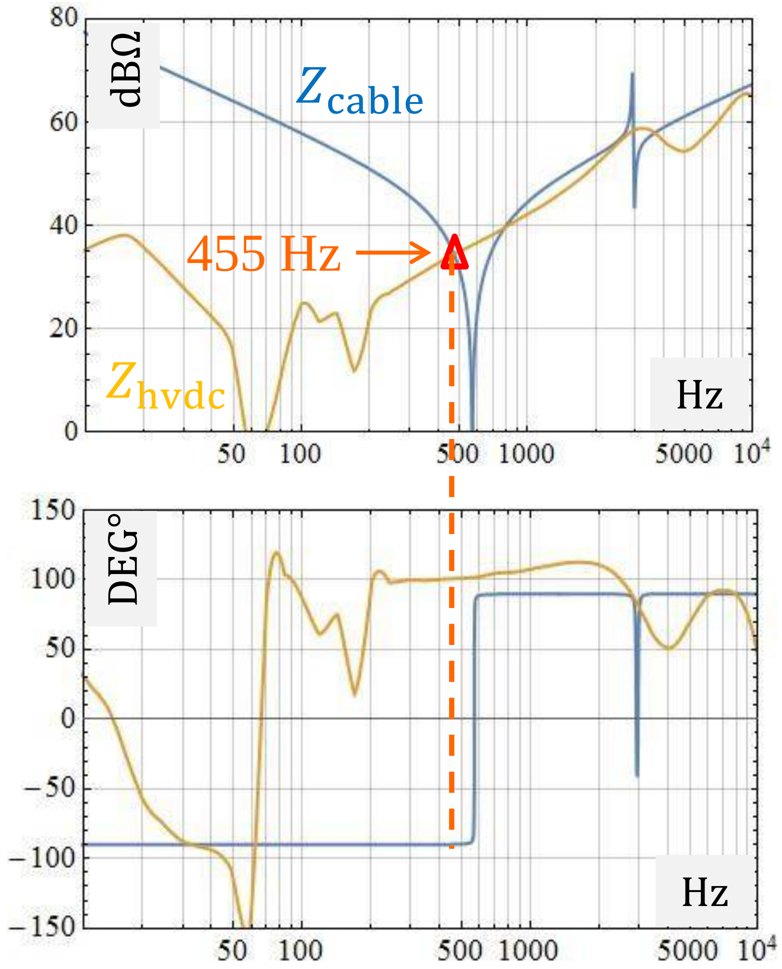
Type-III Turbine with HVDC Converter



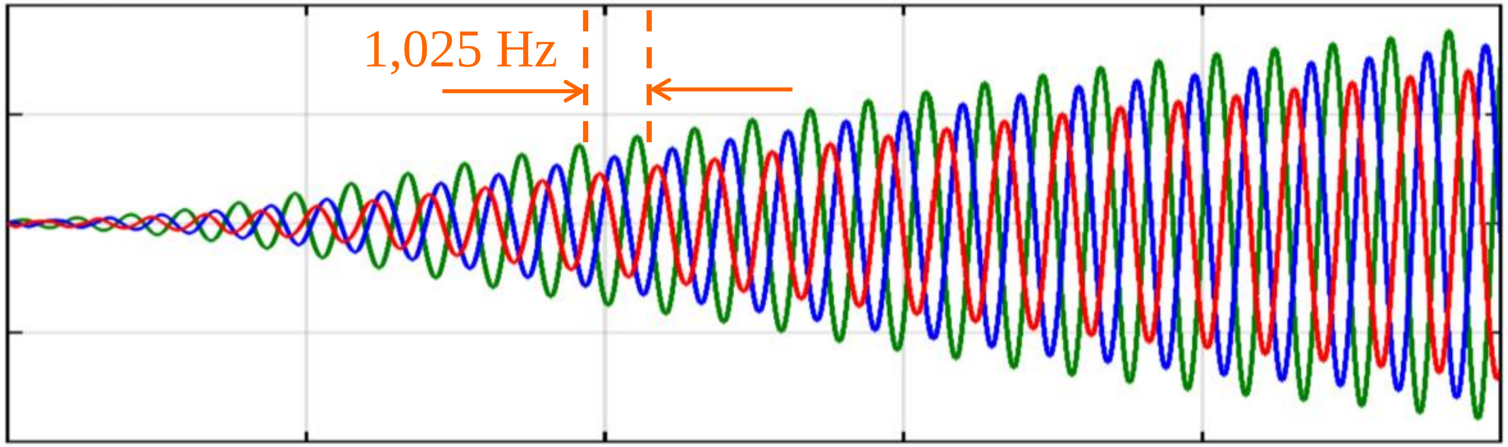


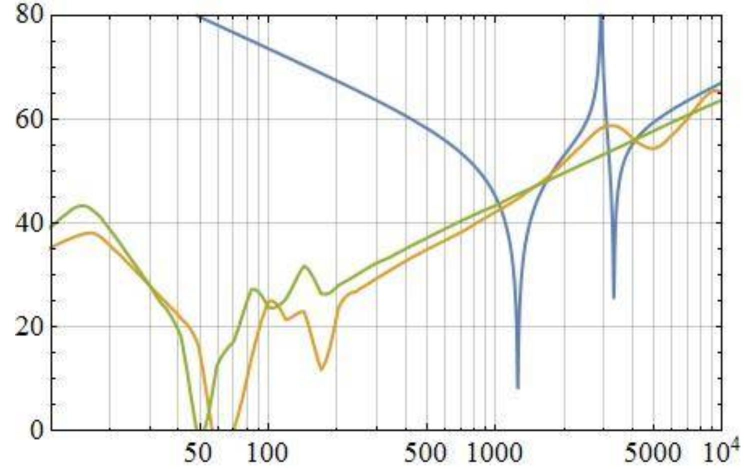
Offshore HVDC Converter & Cable Network



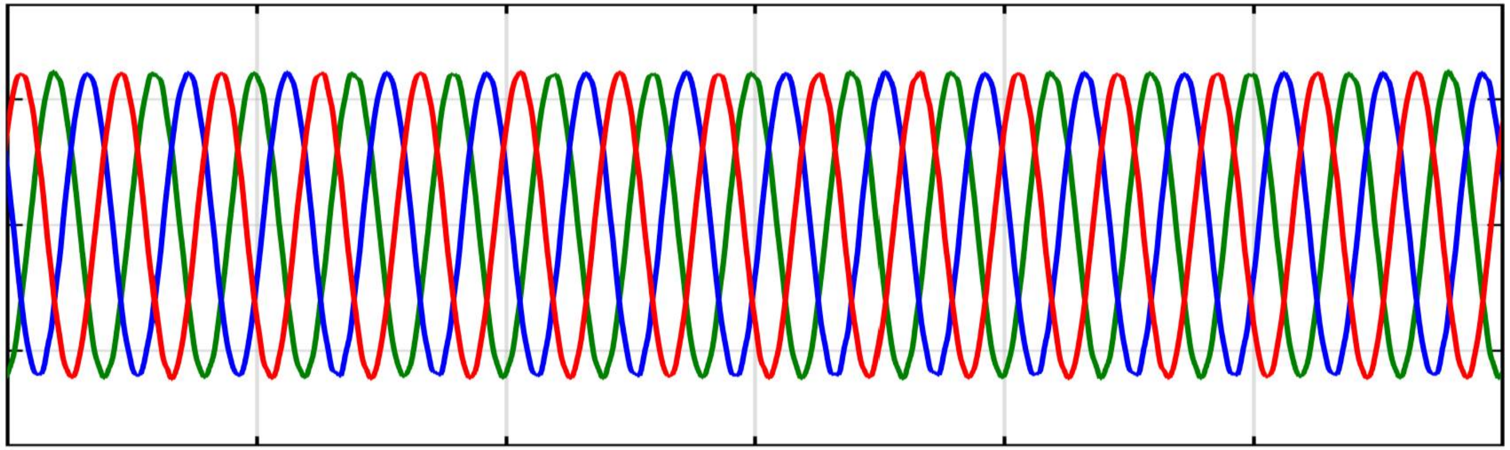


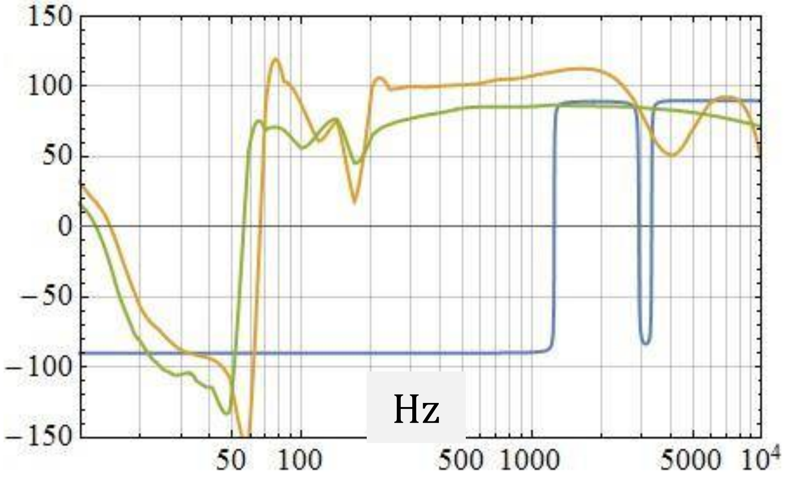
HVDC Converter Resonance with Grid





Active Damping Through MMC Control

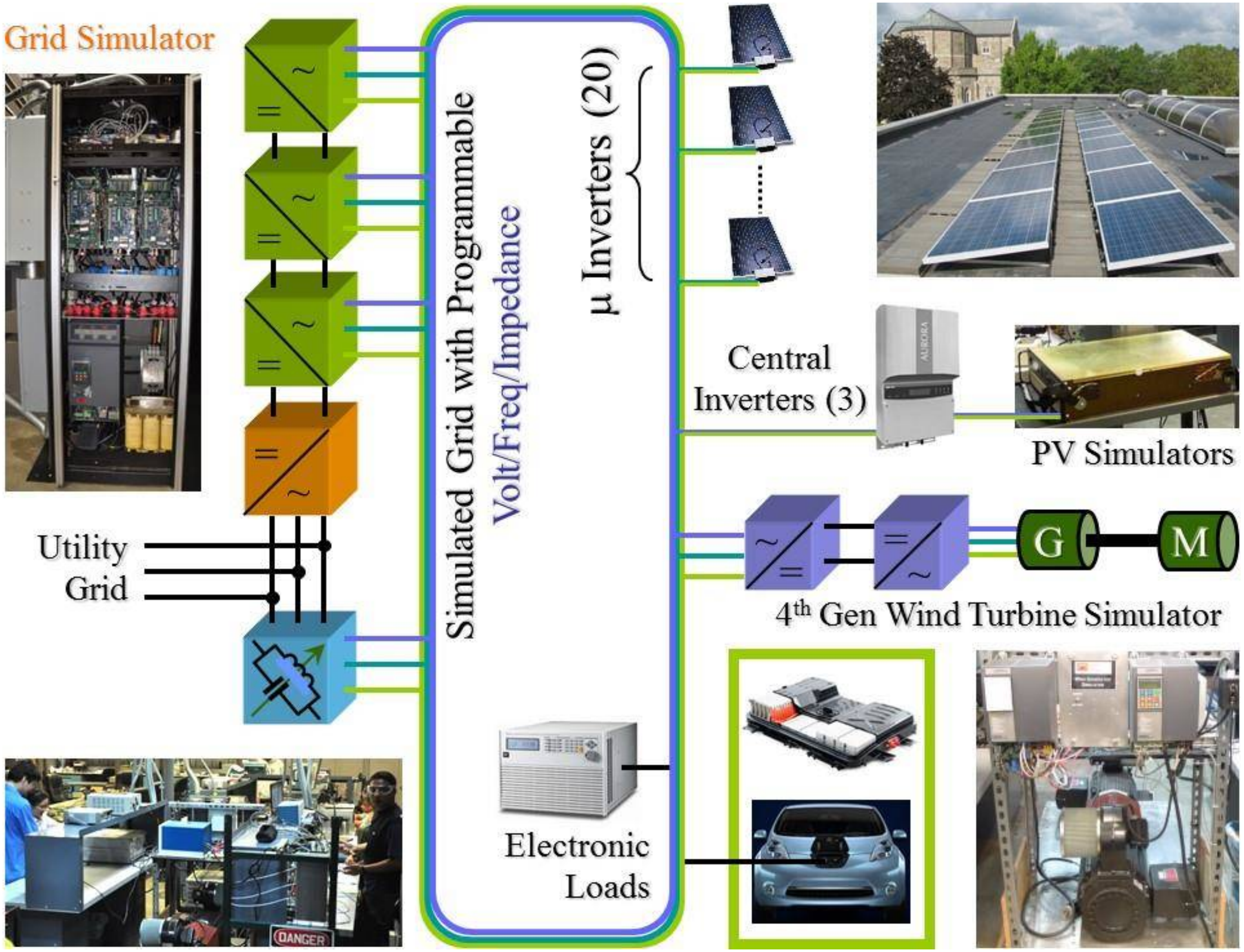


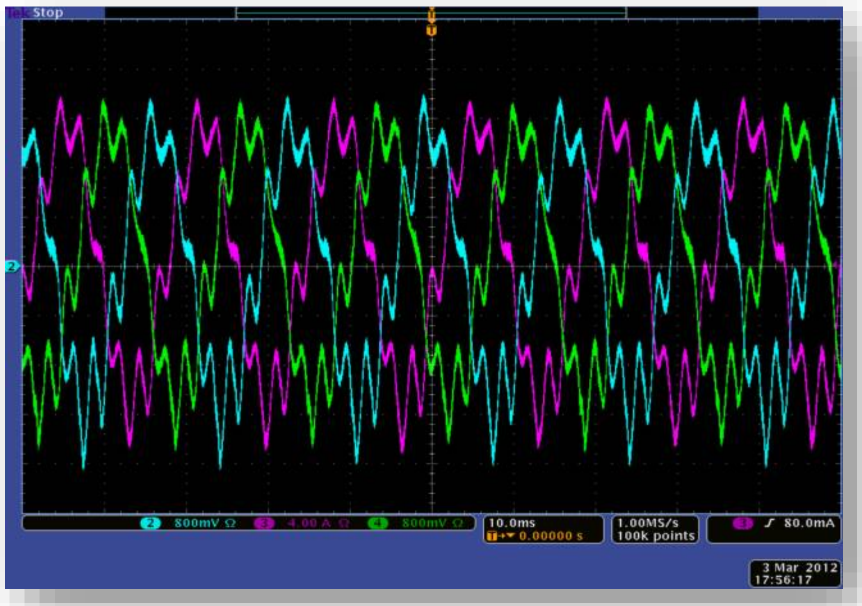


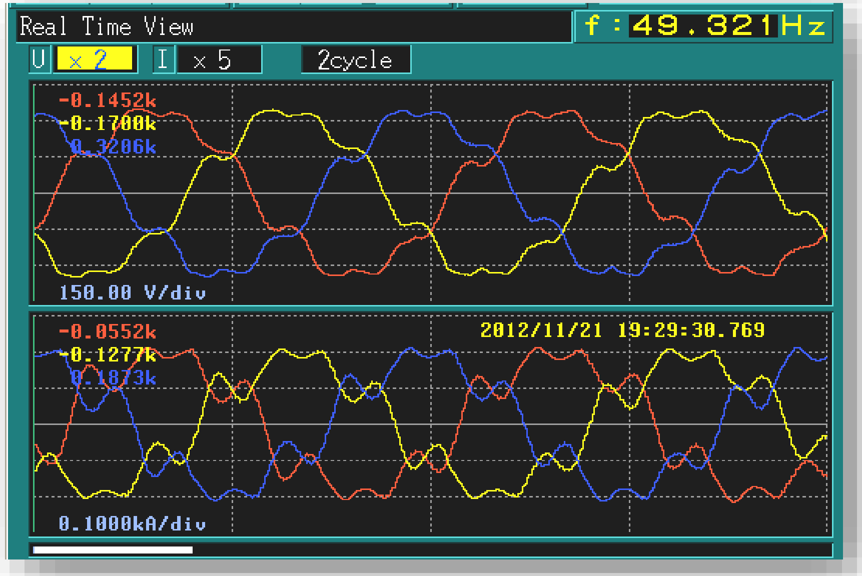
Research Summary

- Development of Analytical Impedance Models
  - PV Inverters; Type III & Type IV Turbines
  - Classical HVDC, MMC-Based HVDC & FACTS
- Impedance-Based System Stability Studies
  - PV Inverters and Wind Turbines Connected to Weak Grids
  - Offshore Wind Farms with HVDC Transmission
  - HVDC Converters for Bulk Power Transmission
  - Multi-Terminal HVDC
- Damping of Resonance and System Stabilization

Converter-Based Power System Testbed







Applications and Practical Development

- Root Cause Analysis & Solutions to System Resonances
  - German (TenneT) North Sea Wind Farms with HVDC – 2014-2015
  - Hami (China State Grid) Renewable Development Zone – 2015-2016
  - Facebook Data Center Power Systems – 2017-2018

Generation → Transmission → Distribution → Consumption

TenneT
Taking power further

国家电网有限公司
STATE GRID
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Applications and Practical Development

- Root Cause Analysis & Solutions to System Resonances
  - German North Sea Wind Farms with HVDC – 2014-2015
  - Hami (China State Grid) Renewable Development Zone – 2015-2016
  - Facebook Data Center Power Systems – 2017-2018
- New Grid Codes for Renewable Energy and HVDC Development
- Impedance-Based Specifications; Measurement and Verification

WG C4.49; WG C4.56

Summary and Future Development

- Converters are Very Different from Machines
- Converter-Based Power Systems Face New Stability Challenges
  - Require New Modeling and System Analysis Methods
- Frequency-Domain Methods Based on Small-Signal Sequence Impedances
- Large-Signal and Transient Stability; Fault and Protection

Characteristics	Small-Signal Stability	Large-Signal Stability
Fast Control		
Overload Capacity		

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