Modeling and Dynamic Performance of Power Systems Dominated by Converter-Interfaced Resources Including Weak Systems

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Content

- Types of CIG and their Dynamic Performance
- Dynamic performance challenges in a system with high penetration of CIG
- Modeling of CIG
- Summary and Q&A

Types of CIG and their Dynamic Performance

Wind Turbine Generators

Four main types:

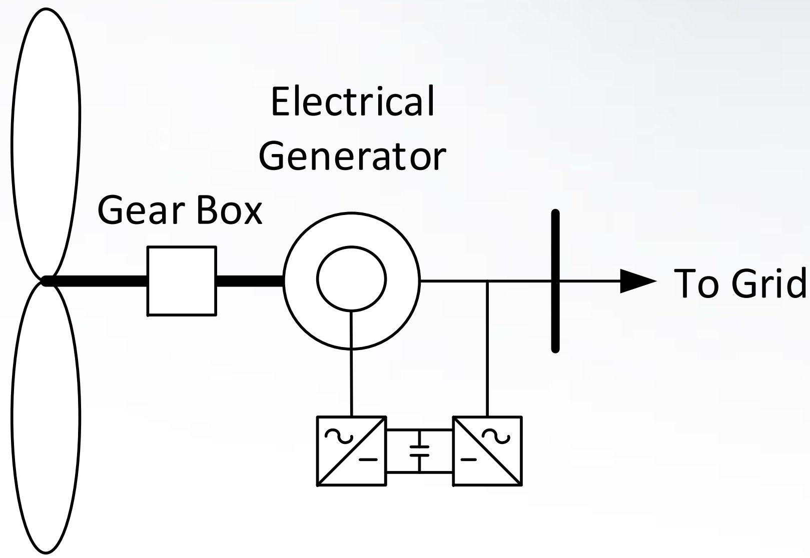
- Type 1
- Type 2
- Type 3
- Type 4

(Type 3 and Type 4:) Converter-Interfaced Generation (CIG)

Wind Turbine Generators

- Type 3 – Doubly-Fed Asynchronous Generator
- Highly controlled
- Variable-Speed
- <u>Electrical Response modeling:</u> generator/converter + electrical controls + mechanical side models

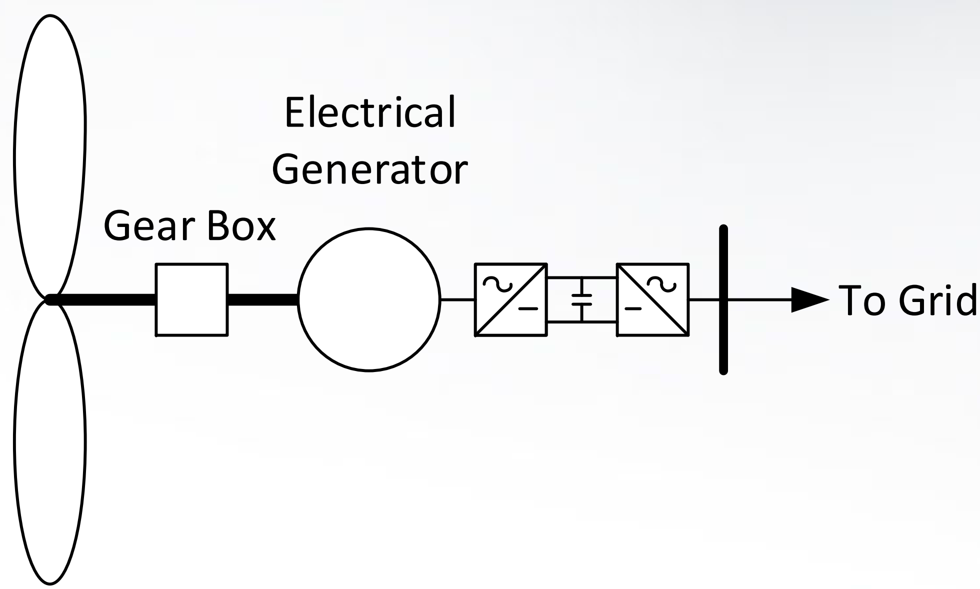
Type 3 WTG – Doubly-Fed Asynchronous-Generator



Wind Turbine Generators

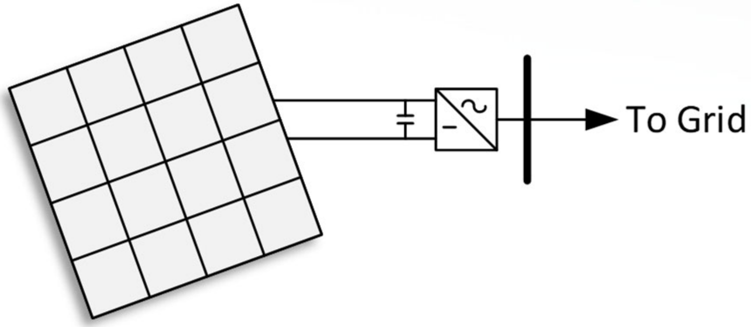
- Type 4 – Full-converter Interface
- Highly controlled
- Variable-Speed
- Electrical Response modeling: generator/converter + electrical controls + mechanical side models

Type 4 WTG – Full-Converter Unit



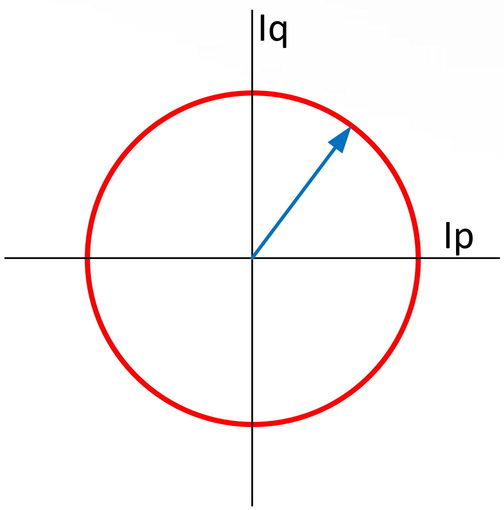
Photovoltaic (PV) Generation

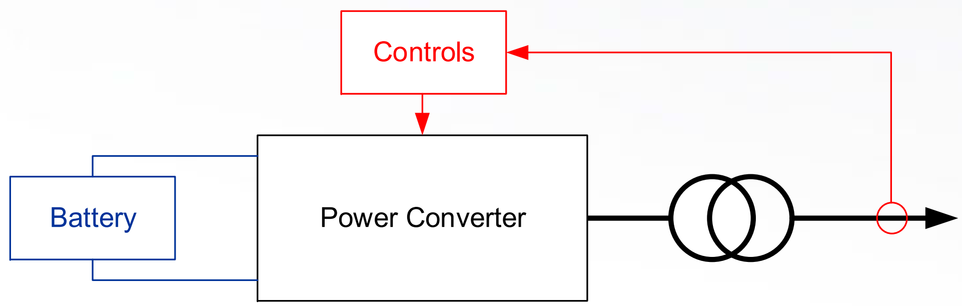
- Solar Panels
- DC side controls
- Inverter (power converter interface between DC to AC side)
- Most systems (e.g. one shown here) have solar tracking systems
- Inverter fully rated for power
- P and Q fully and independently controllable (within current rating of inverter)



Battery Energy Storage

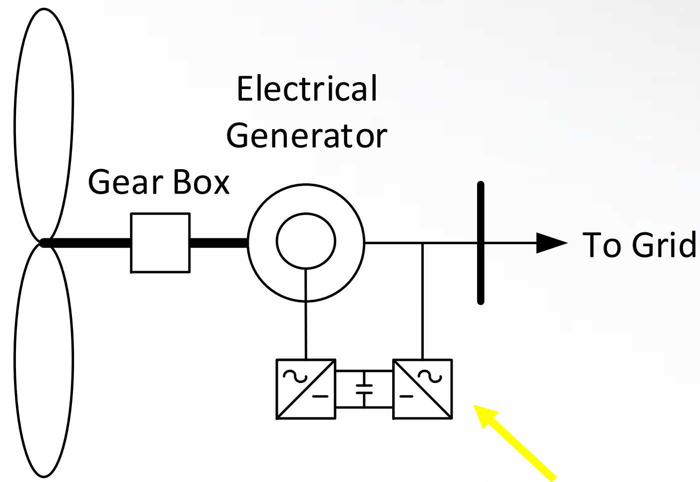
- Similar in electrical behavior to other inverter based generation but power is clearly bi-directional
  - Inverter fully rated for power
  - P and Q fully and independently controllable (within current rating of inverter)



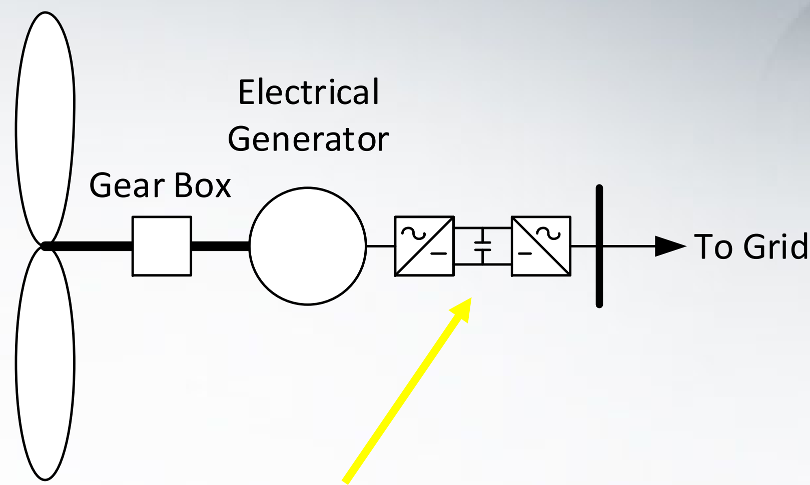


Technology Summary

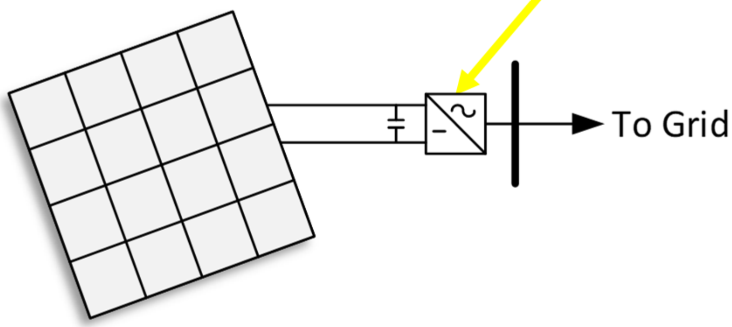
Type 3 WTG – Doubly-Fed Asynchronous-Generator

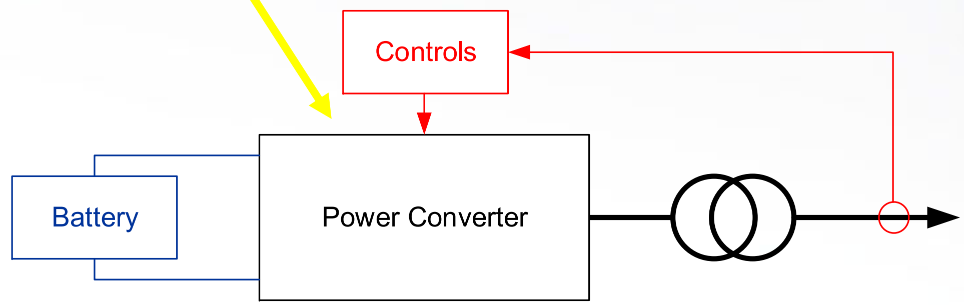


Type 4 WTG – Full-Converter Unit



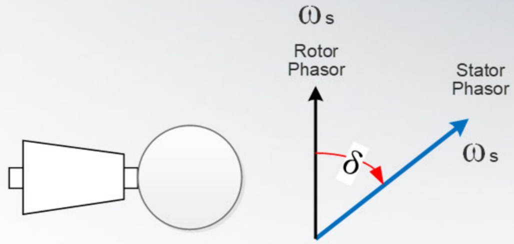
Heart of all these is the power electronic converter





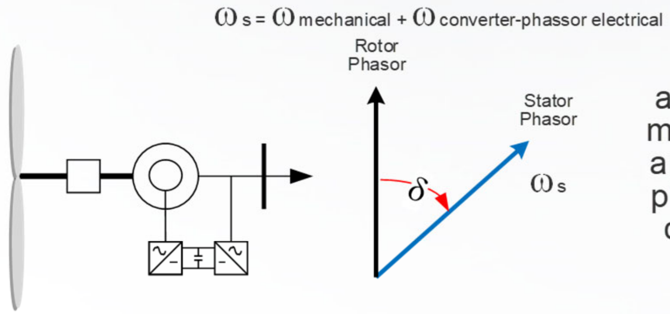
Transient Stability

Synchronous Machine

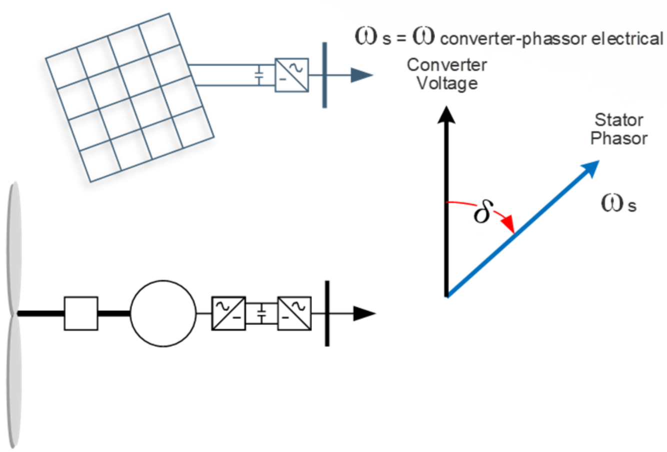


δ is an indicator of stability

Grid fault occurs → Can we keep synchronism?



asynchronous machine; rotor-angle between phasors tightly controlled by converter

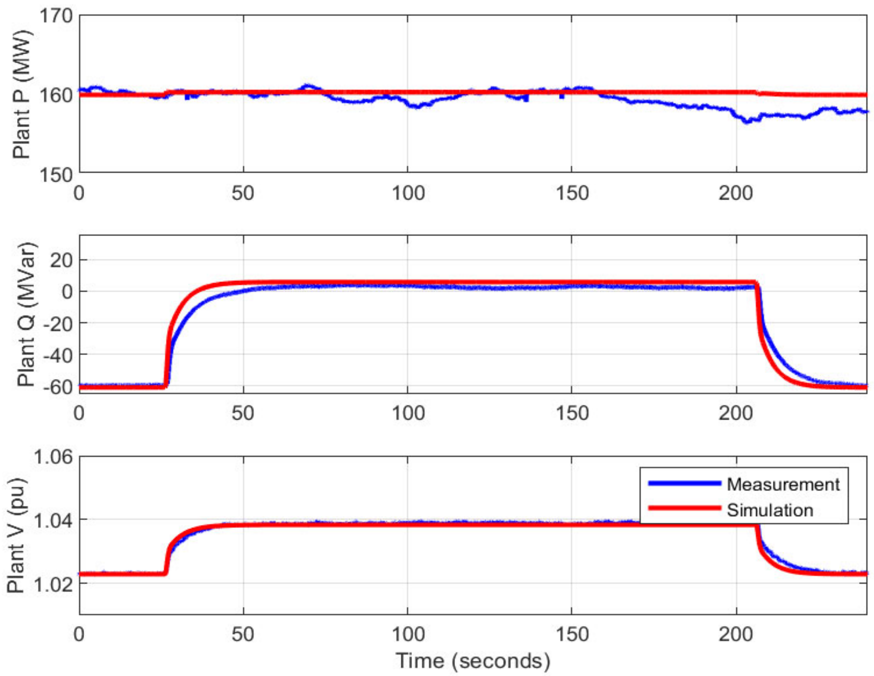


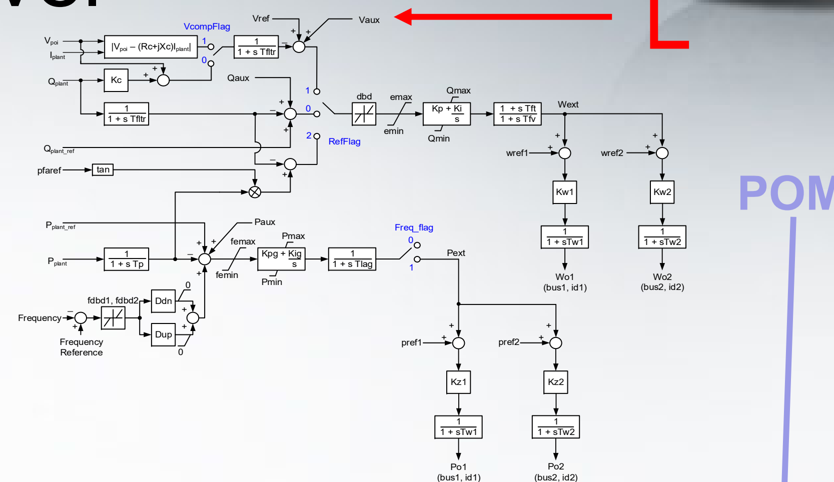
full-converter interface; completely governed by converter controls

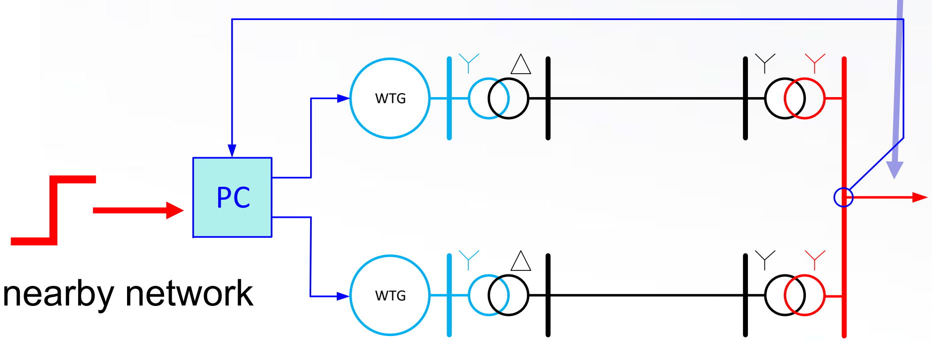
Grid fault occurs → Will it ride-through?

Volt/Var Control

Vref Step test at the plant level





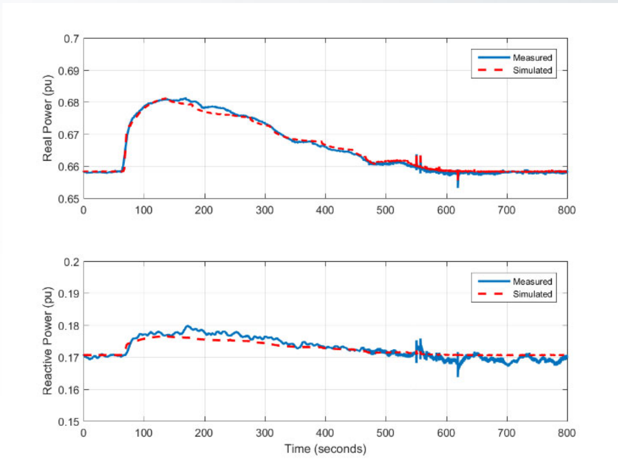


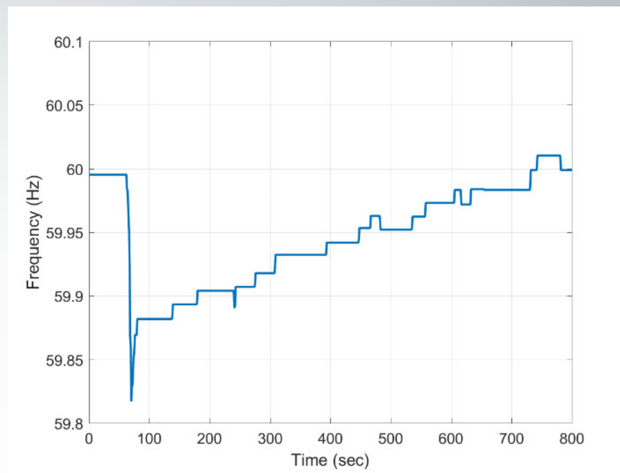
Simulated in GE PSLF™ with full representation of nearby network

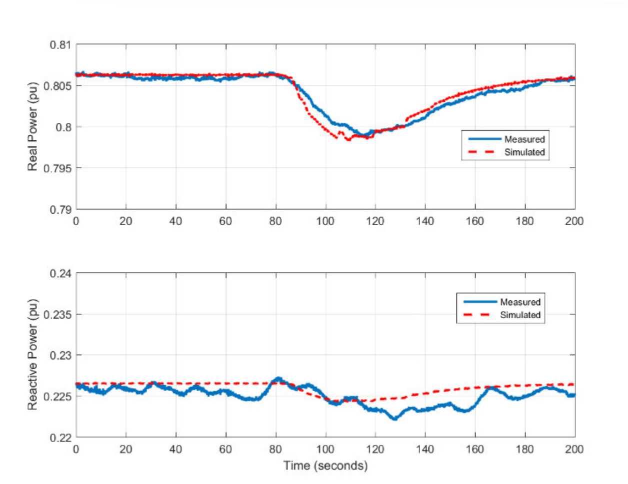
P. Pourbeik, S. Wang and N. Etzel, “Utilizing the REPC_B model for Validation”, 8/26/20
https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/Pourbeik%20-%20Utilizing%20the%20REPC%20Model%20for%20Validation.pdf&action=default&DefaultItemOpen=1

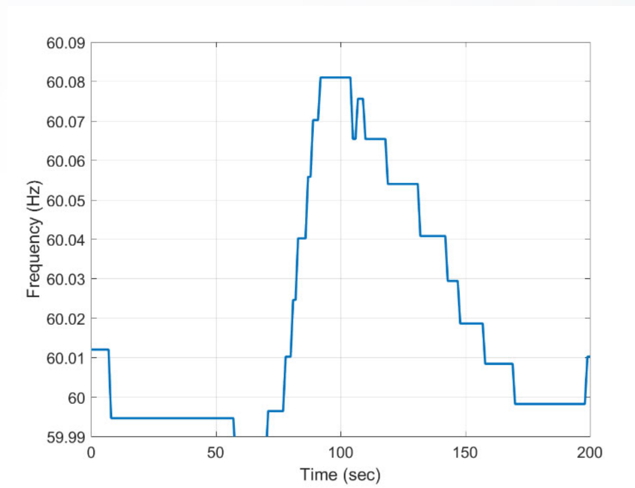
Frequency Control

250 MW PV Plant – Field Test









Frequency Response Summary

Technology	Voltage Control	Primary Frequency Response (sustained)	Oportunity Cost for PFR?	Fast Frequency Response (FFR)	Is FFR Sustained or Inertia Based?	Oportunity Cost for FFR?
Type 3 WTG	Yes - fast	Yes - deliver full amount in seconds	Yes	Yes	Inertia Based	No
Type 4 WTG	Yes - fast	Yes - deliver full amount in seconds	Yes	Yes	Inertia Based	No
PV	Yes - fast	Yes - deliver full amount quite fast	Yes	Yes	Sustained	Yes
Battery	Yes - fast	Yes - deliver full amount very fast	No	Yes	Sustained	No

<u>One could go Hybrid to get all functionality:</u>

- Wind + BESS
- PV + BESS
- Wind + PV + BESS

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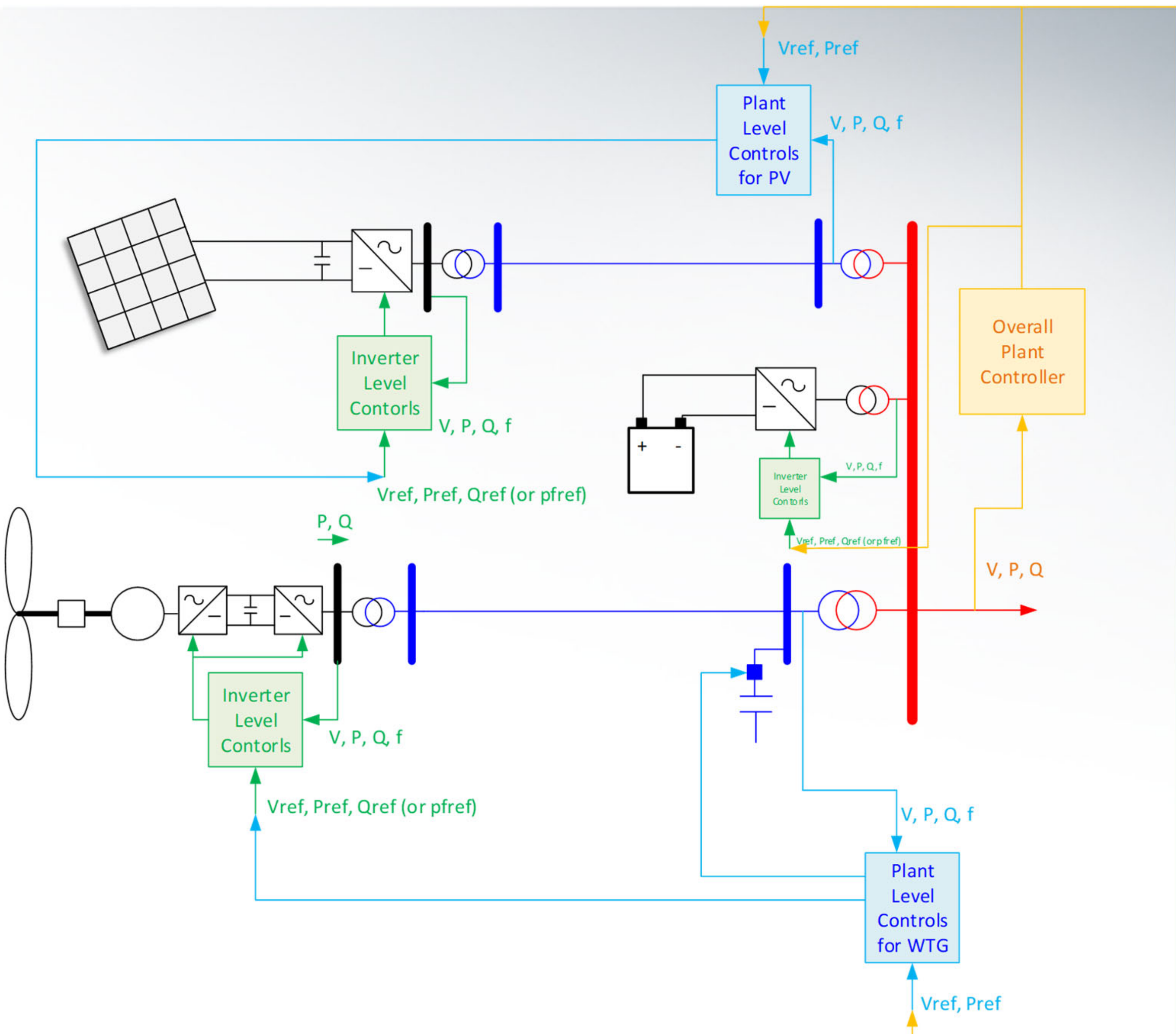
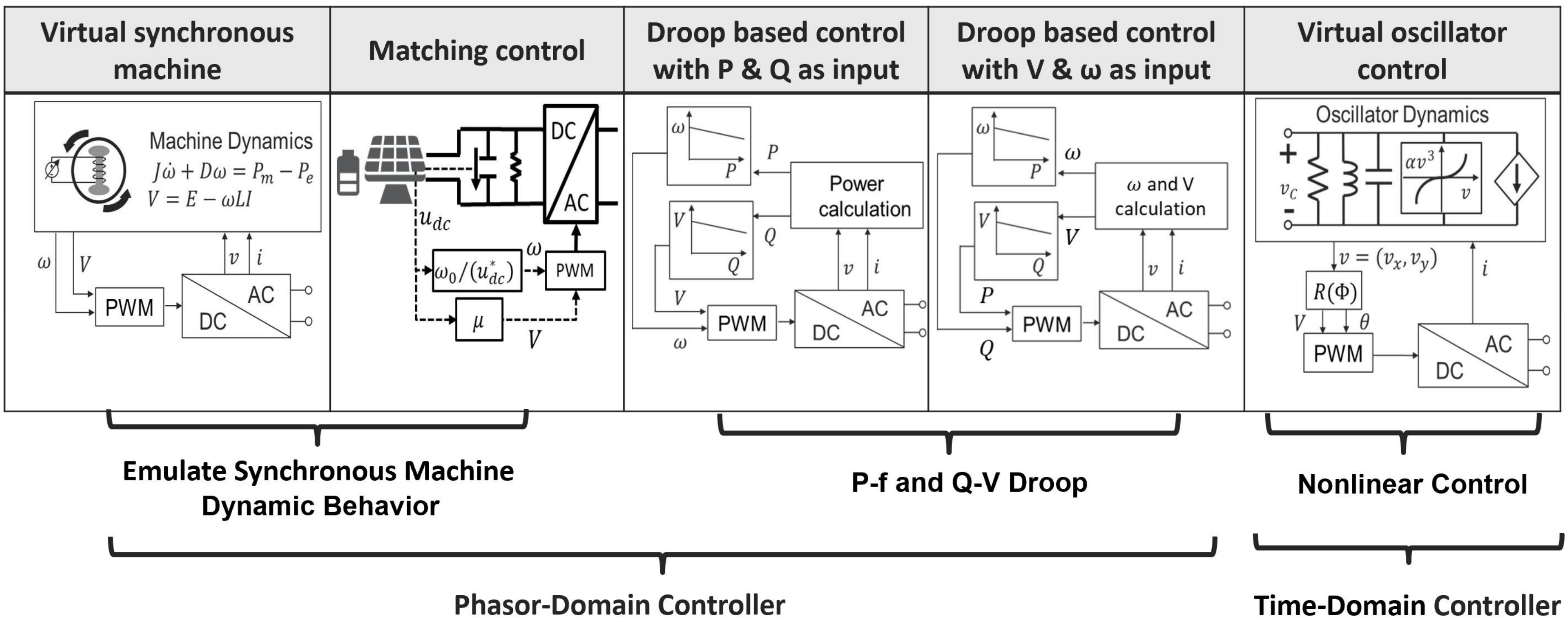
Hybrid-Plants



Grid-Forming



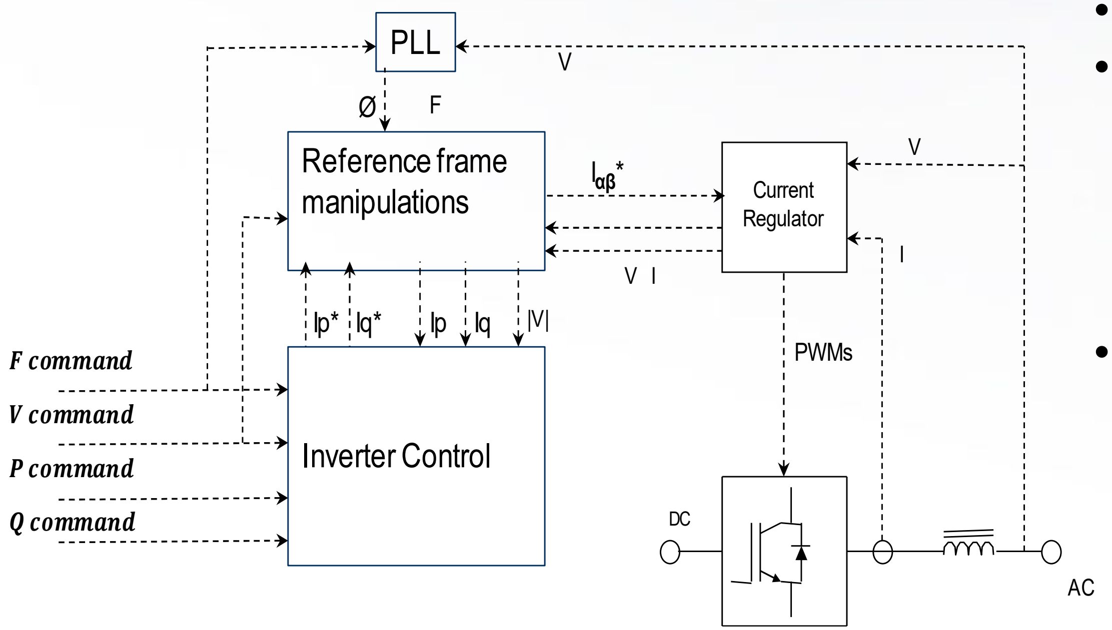
This figure is reproduced with permission from EPRI.

Source: *Grid Forming Inverters: EPRI Tutorial*, EPRI Palo Alto, CA: 2020, 3002018676 (https://www.epri.com/research/products/000000003002018676)

Another Reference is: D. Ramasubramanian, P. Pourbeik, E. Farantatos and A. Gaikwad, "Simulation of 100% Inverter-Based Resource Grids With Positive Sequence Modeling", IEEE Electrification Magazine, June, 2021. https://ieeexplore.ieee.org/document/9447546

Grid-Forming Versus Grid-Following

- <u>Grid-Following:</u>

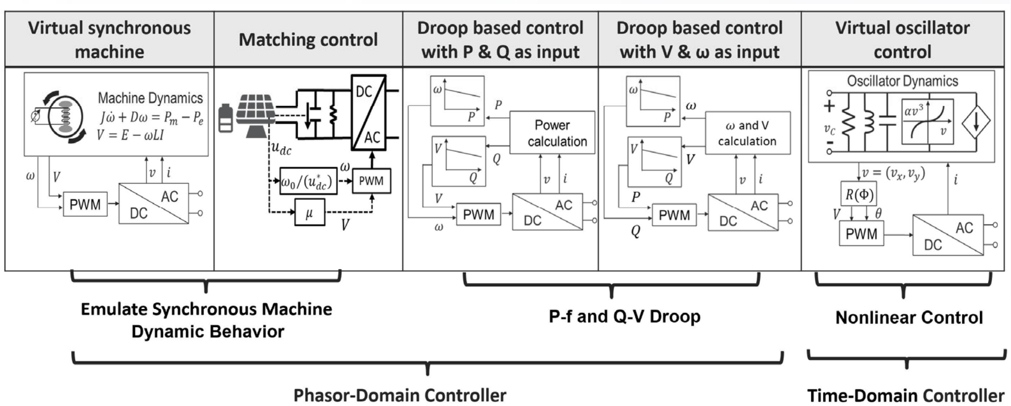


- PLL used to lock into grid phasor
- Current very tightly regulated
- <u>Weak Grid:</u>
  - Small ΔI causes large ΔV
  - System frequency changes very fast (low-inertia) and oscillates more
- Thus, may need to significantly reduce PLL and inner-current control loop gains to avoid instability

Diagram from © CIGRE 2017, P. Pourbeik and J. K. Petter, "Modeling and validation of battery energy storage systems using simple generic models for power system stability studies", CIGRE Science and Engineering, October 2017, pp. 63-72.

Grid-Forming Versus Grid-Following

- <u>Grid-Forming:</u>



- No PLL used to lock into grid phasor
- Plant synchronized, thereafter voltage phasor magnitude (V) and angle (δ) controlled to keep in synch with the system and inject P and Q
- Voltage phasor V and δ controlled to inject P and Q; current only controlled if we hit the current limit
- <u>Weak Grid:</u>
  - Small ΔI causes large ΔV
  - System frequency changes very fast (low-inertia) and oscillates more
- However, in this case smooth and fast control of P (MW) and Q (Mvar) and so better stability control, since fast control of internal V and δ

Important Note

- A system can have conventional generation + grid-following + grid-forming and operator
- One should not draw a general conclusion on one type of control should be pushed versus another
- The key is proper modelling, analysis and tuning to ensure stability

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Dynamic Performance Challenges in a System with High Penetration of CIG

Power System Stability

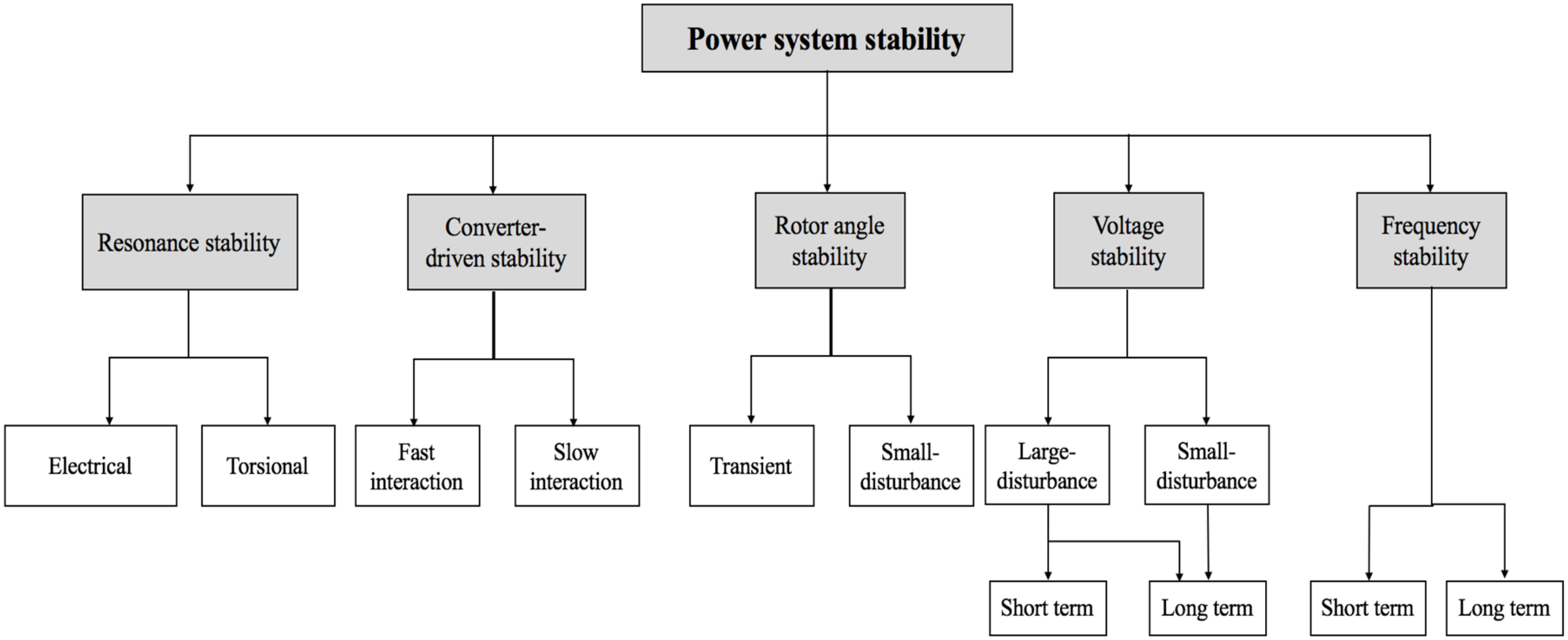
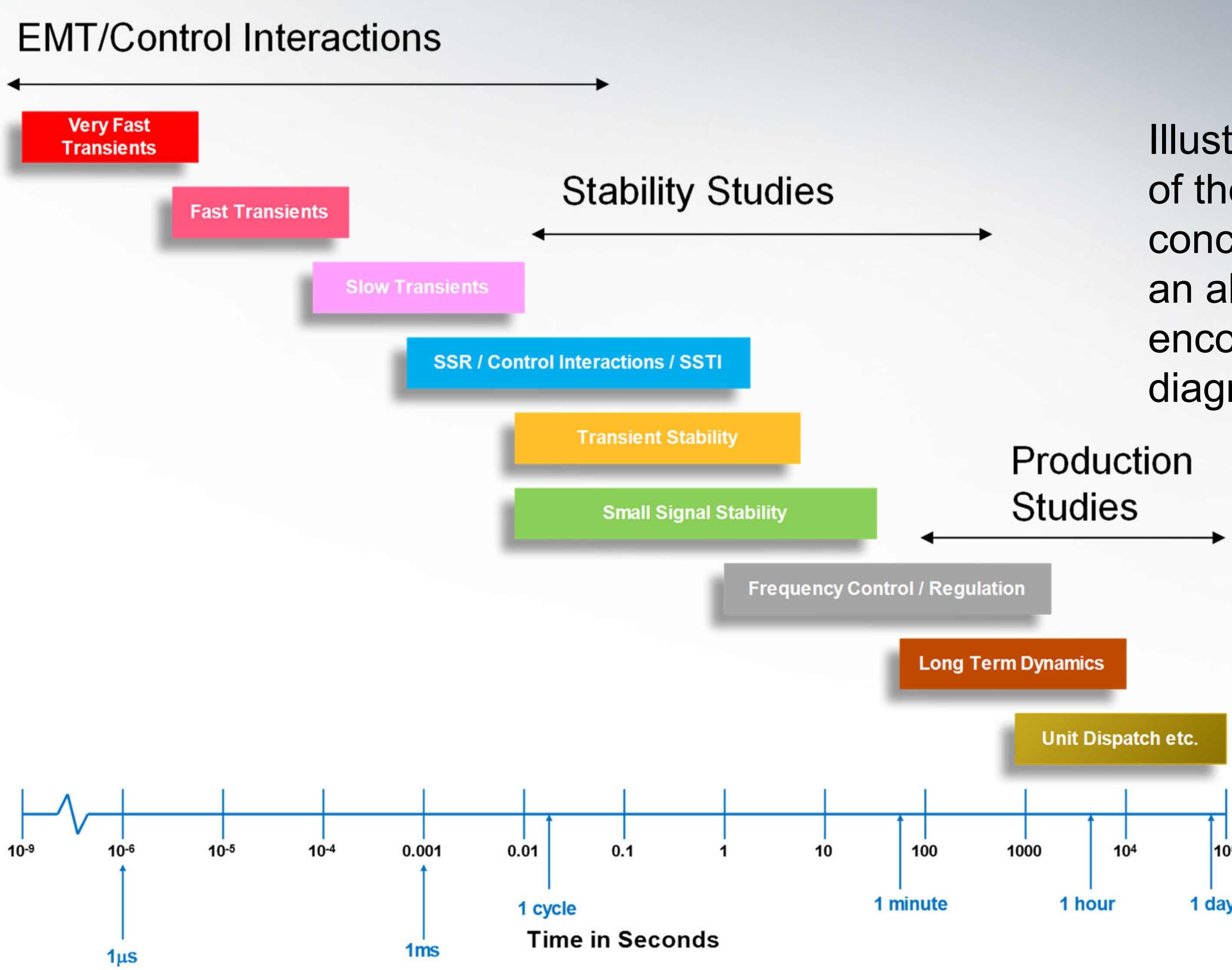


Figure extracted from: IEEE TF Paper ***Definition and Classification of Power System Stability – Revisited & Extended, IEEE Transactions on Power Systems (Volume: 36, Issue: 4, July 2021)***
Available for free download here: https://ieeexplore.ieee.org/document/9286772

Bandwidth of Analysis



Illustrative of the concepts; not an all encompassing diagram

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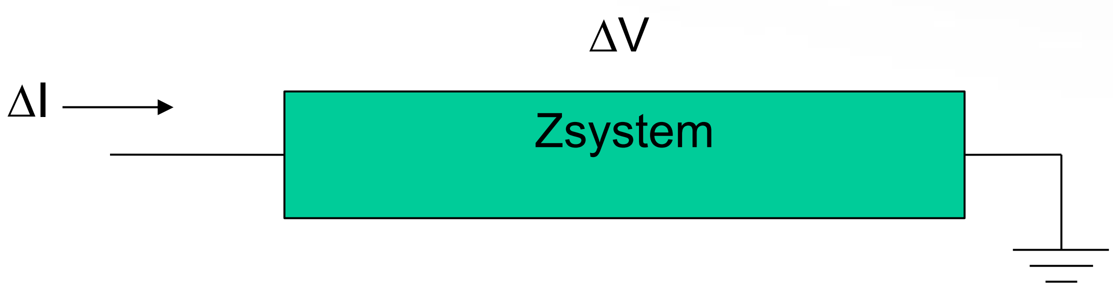
Challenges in a Weak Grid

- Weak grid means high apparent impedance looking into the grid
- Large Z → small ΔI will cause large ΔV
  - closed-loop controls will have reduced gain margins
  - Tuning of controls becomes much more important
  - Gains should be lower



Challenges and Solutions

- Decreasing short-circuit levels
  - Challenges for protection
    - https://www.youtube.com/watch?v=MIYIbd05OLo
    - IEEE TF Report: https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TR_7-18_0068.html
- Challenges for converter interface stability associated with PLL and inner-current control loop recovery after faults:
  - Add synchronous condensers (SC) to increase short-circuit levels (there are limitations here too → stability concerns with SC)
  - Retune PLL/Inner Current Control loops for low SCR
  - Move towards grid-forming inverter technology
  - Some combination of ALL three above

Needed CIG Functionality

- Volt/Var control
- Primary Frequency Response
- Potential need for Fast Frequency Response (FFR)
- Low/High Voltage/Frequency Ride Through
- Reactive Capability

- IEEE P2800 Standard (currently under development) is addressing the minimum requirements for all this, and more, thorough a broad industry effort

Modeling of CIG

Types of Models

- Hardware in the Loop (HIL) + system model
  - Proprietary, actual controls connected to a system model
  - Used for design and commissioning tests
- 3-phase reduced order vendor specific models (EMT – Black box)
  - Proprietary, shared under NDA
  - Use for detailed analysis of grid interactions
- Positive sequence vendor specific models (Black Box)
  - Again, often shared under NDA
  - Typically, benchmarked against second level model above
  - Used for gird interconnection studies
- Generic positive sequence models
  - Open and public
  - Can be parameterized to be quite useful for bulk grid stability analysis

Emerging Method: DLL-based on same compiled code

What Model(s) to Use?

- The model to be used depends on the task
- Understand the task to understand the model needed; proper parameterization is key
- Communication and transparency is key between the equipment vendor, plant owner/operator and transmission owner/operator (model user) to understand the proper model usage and proper model for the task

What Model(s) to Use?

- Detailed vendor specific models will always be needed for certain studies
- Particularly for specialized studies, e.g.
  - SSR → vendor specific EMT model
  - Harmonic → vendor specific EMT model
  - Insulation Coordination → vendor specific EMT model
  - Detailed site specific controls tuning → vendor specific positive-sequence models
- However, standard (generic) models may be quite adequate in many cases, particularly for large system studies and looking at futuristic scenarios where actual equipment still is undetermined

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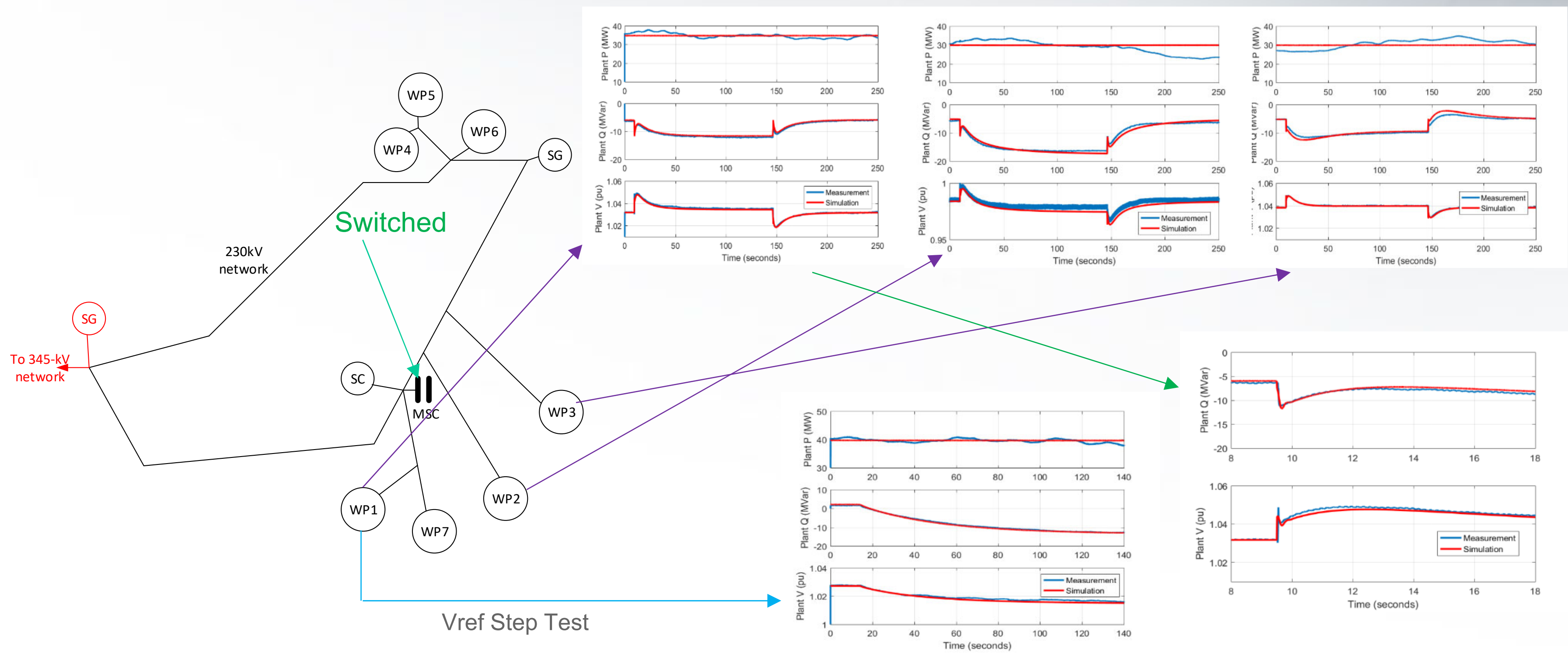
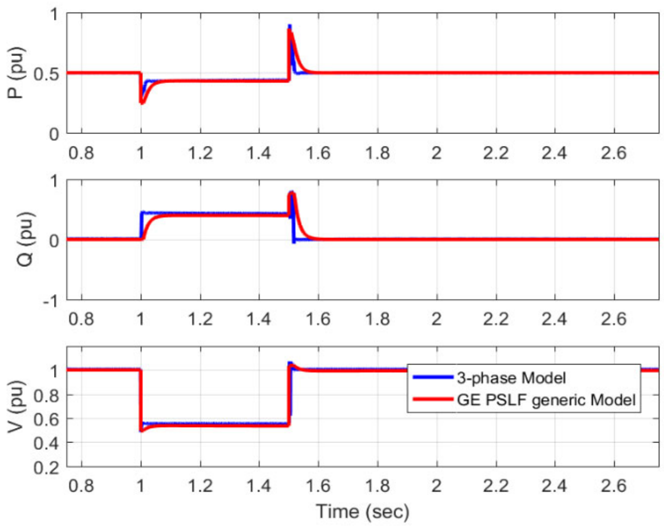
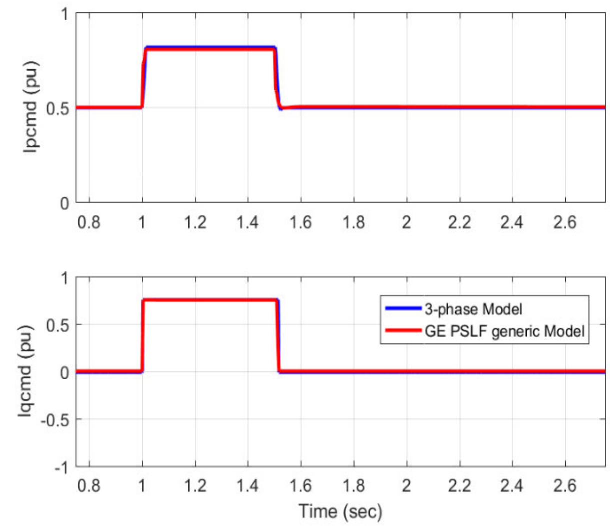
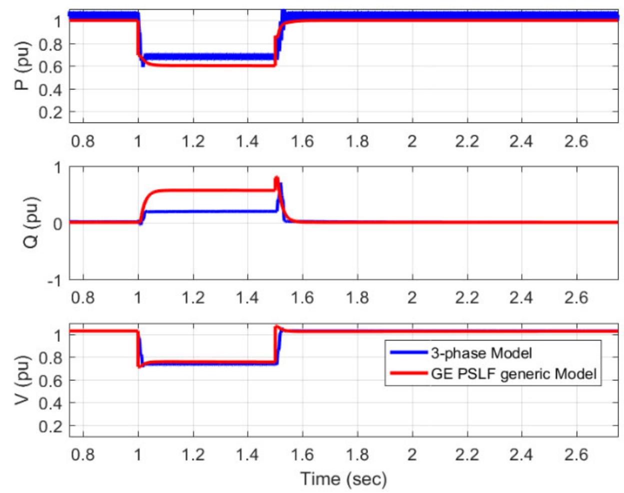
Example System Dominated by CIG



Example Large Signal Response







Figures from © CIGRE 2017, P. Pourbeik and J. K. Petter, “Modeling and validation of battery energy storage systems using simple generic models for power system stability studies”, CIGRE Science and Engineering, October 2017, pp. 63-72.

Summary

- The are new challenges in systems with high penetration of converter interfaced generation
- The challenges can be technically solved
- Models do exist at all levels
- The key is always to understand clearly the objectives and how to use the appropriate model for the appropriate task
- Communication is critical among all stakeholders: vendor, plant owner and system planners