Overview of Grid Integration Testing

1st International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains – NWTC, Bolder, CO

June 13, 2013

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Transforming the electrical grid into an energy efficient network requires:

- new technologies that must play a significant role in power system stability.
- the ability to replicate a complex dynamic system like the electrical grid for testing purposes.
- extensive testing of hardware and software to meet safety and quality assurance requirements through ***'fully integrated'*** system testing.
- parallel model verification and validation of physical hardware to ensure higher reliability and stability once deployed on the electrical grid.

Advanced Testing Lowers the Risks and Costs of New Technology Introduction into the Market

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Grid Integration Evaluations

Steady State and Envelope Evaluations
- Power Set Points
- Voltage and Frequency Variations
- Controls Evaluation

Power Quality Evaluations
- Voltage Flicker
- Harmonic Evaluations
- Anti-Islanding (Software)

Ancillary Services
- Frequency Response
- Active Volt-VAR Control
- Active Frequency Regulation

Grid Fault Ride-Through Testing
- Low Voltage Ride-Through (LVRT)
- Unsymmetrical Fault Ride-Through
- High Voltage Ride-Through (HVRT)

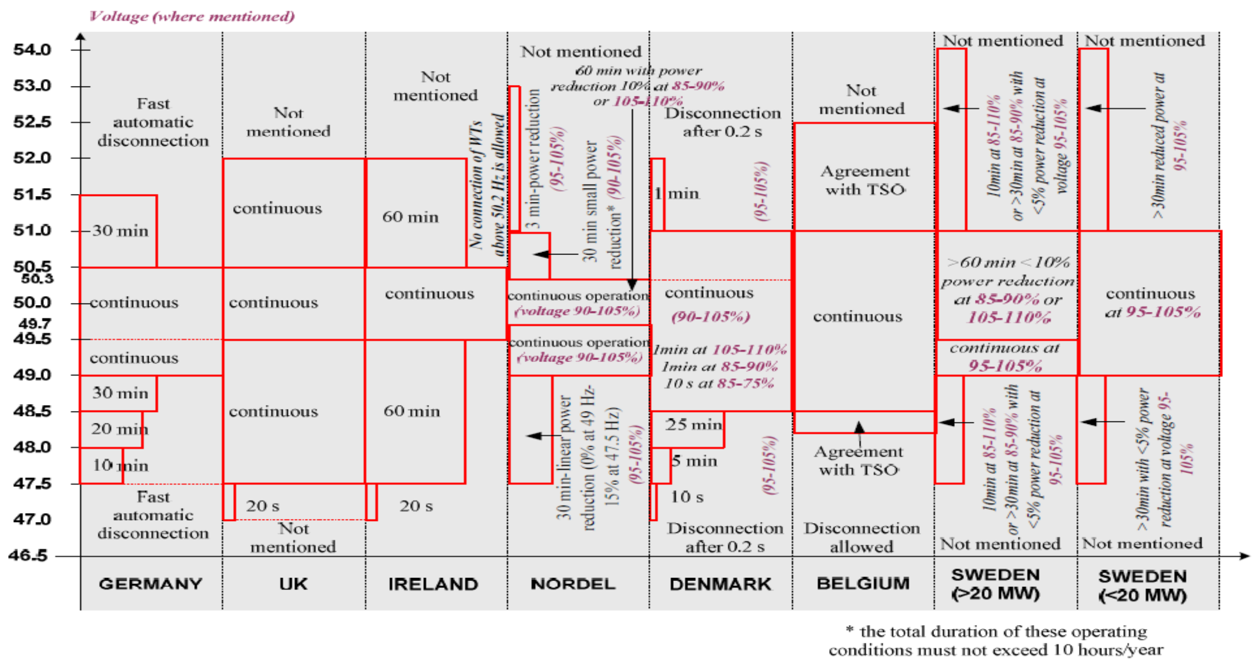
Open Loop Testing
- Recreation of field events with captured waveform data

Hardware-In-the-Loop Testing
- Simulated dynamic behavior and interaction between grid and the device under test

Increasing level of difficulty

Steady State Envelope Testing

- Active and reactive power set points, limits and ramp rates as commanded by operations
- Voltage and frequency trip limits and time to trip
  - IEEE 1547 limits and/or those specified in specific grid codes



Frequency and voltage trip points for various TSO's in Europe

"Grid Code Requirements for Large Wind Farms: A Review of Technical Regulations and Available Wind Turbine Technologies" M. Tsili, Ch. Patsiouras, S. Papathanassiou

Power Quality: Harmonic Evaluations

Power Electronic Grid Simulators must have a low noise floor with respect to harmonic ranges required by standards

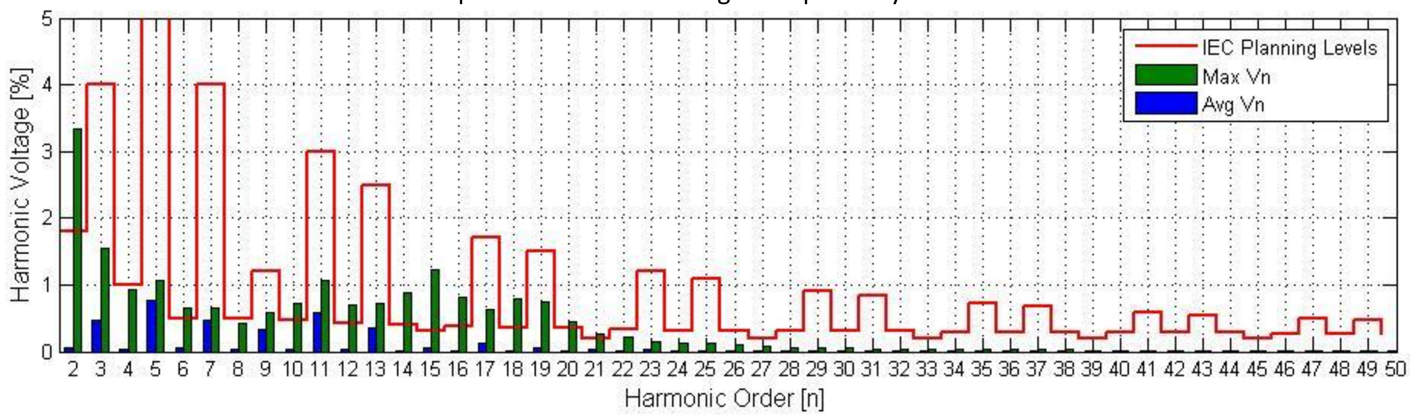
- IEC requires measurement out to the 9 kHz
- Filtering or very fast switching frequencies are desirable to meet this challenge

Harmonic Evaluations:

1. **Injected harmonic current by the DUT**
   - IEEE 519 current limits
2. **Harmonic susceptibility**
   - Background harmonic voltages, DUT susceptibility and trip limits
3. **Programmable system impedance for quasi-stationary harmonic analysis**
   - Harmonic voltage adjusted by the amplifier in order to converge on a specified system and filter impedances

Envisioned harmonic evaluation control schemes are similar to those used in active filtering

Example IEC Harmonic Voltage Compatibility Plot



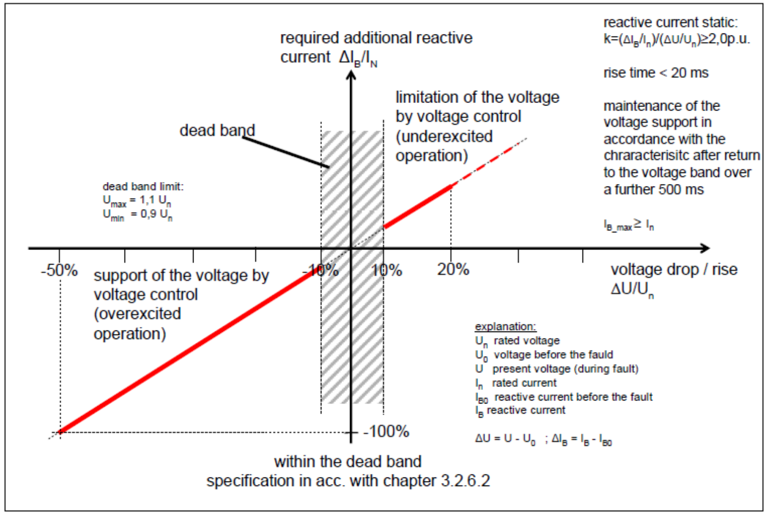
Power Quality: Active Voltage Regulation and Voltage Flicker

Volt/VAR Control:

- Presently limited to extreme circumstances such as fault ride-through events and includes a wide dead band around nominal voltage
- The future standards can involve devices regulate their own voltage through Volt/VAR control (slow acting droop mode control)

Voltage Flicker Susceptibility and Mitigation

- Voltage flicker could be mitigated through fast acting Volt/VAR control
  - May promote voltage instabilities in actual systems
- Voltage flicker testing should include both rectangular and sinusoidal modulation across a wide band of sub-harmonic frequencies



E.ON Netz Grid Code: The principle of voltage support in the event of grid faults

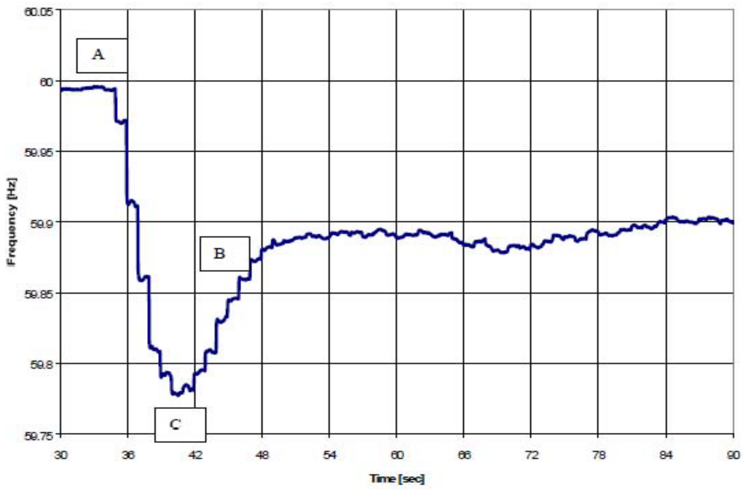
Inertial Frequency Response and Active Frequency Regulation

What role can renewable devices have on inertial frequency response?

- Wind Turbines
- Photovoltaic Converters
- Utility Scale Energy Storage

The need has been recognized to coordinate inertial response testing with drivetrain testing dynamometers

Hub and blade simulation could provide ‘rotor inertia simulation’ for kinetic energy capture during times of emergency frequency response.



FERC Frequency Response Characteristic

A – Frequency of grid before event

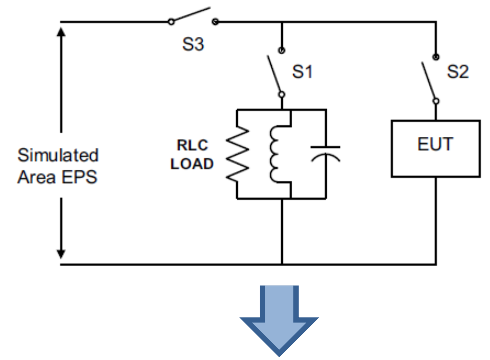
B – Frequency after initial stabilization

C – Frequency Nadir

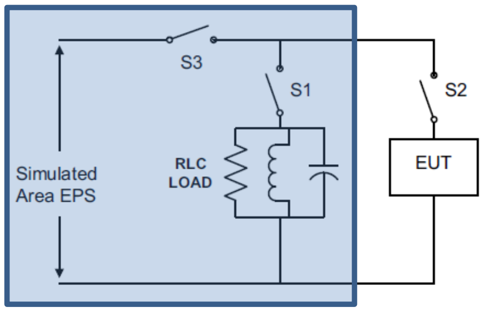
Anti-Islanding (Software)

- What is Anti-Islanding?
  - Unintentional islanding of distributed generation can cause equipment damage, power quality issues and safety hazards.
  - IEEE 1547 “Standards for Interconnecting Distributed Resources to Electric Power Systems”. Established testing protocol for Upper/Lower Voltage and Frequency thresholds used to detect islanding.
- Detection Schemes
  - Primarily voltage and/or frequency variations
- Software Implementation
  - Advantages
    - Lower Power Requirements (no physical components)
    - Flexibility of RLC components
  - Challenges
    - Control Methodology
    - Test Method Validation

Real RLC Load

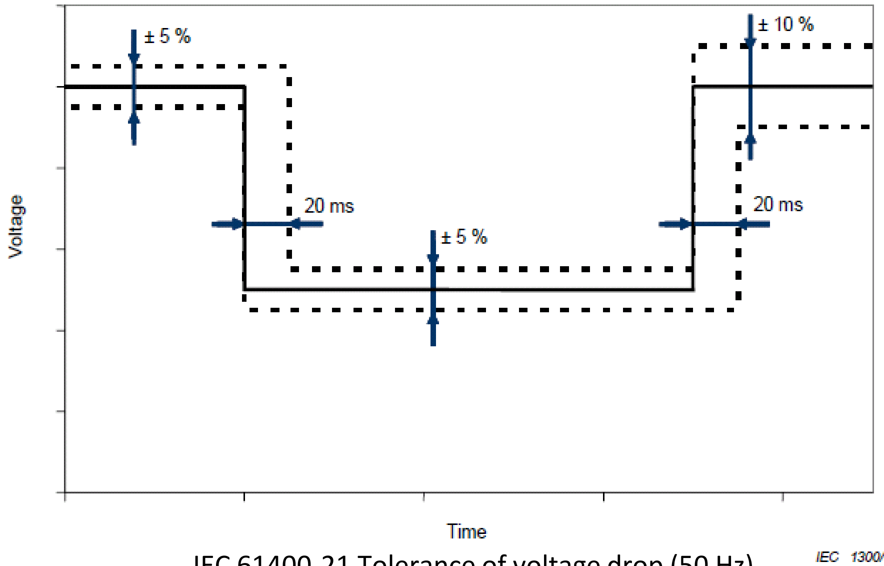


Simulated RLC Load



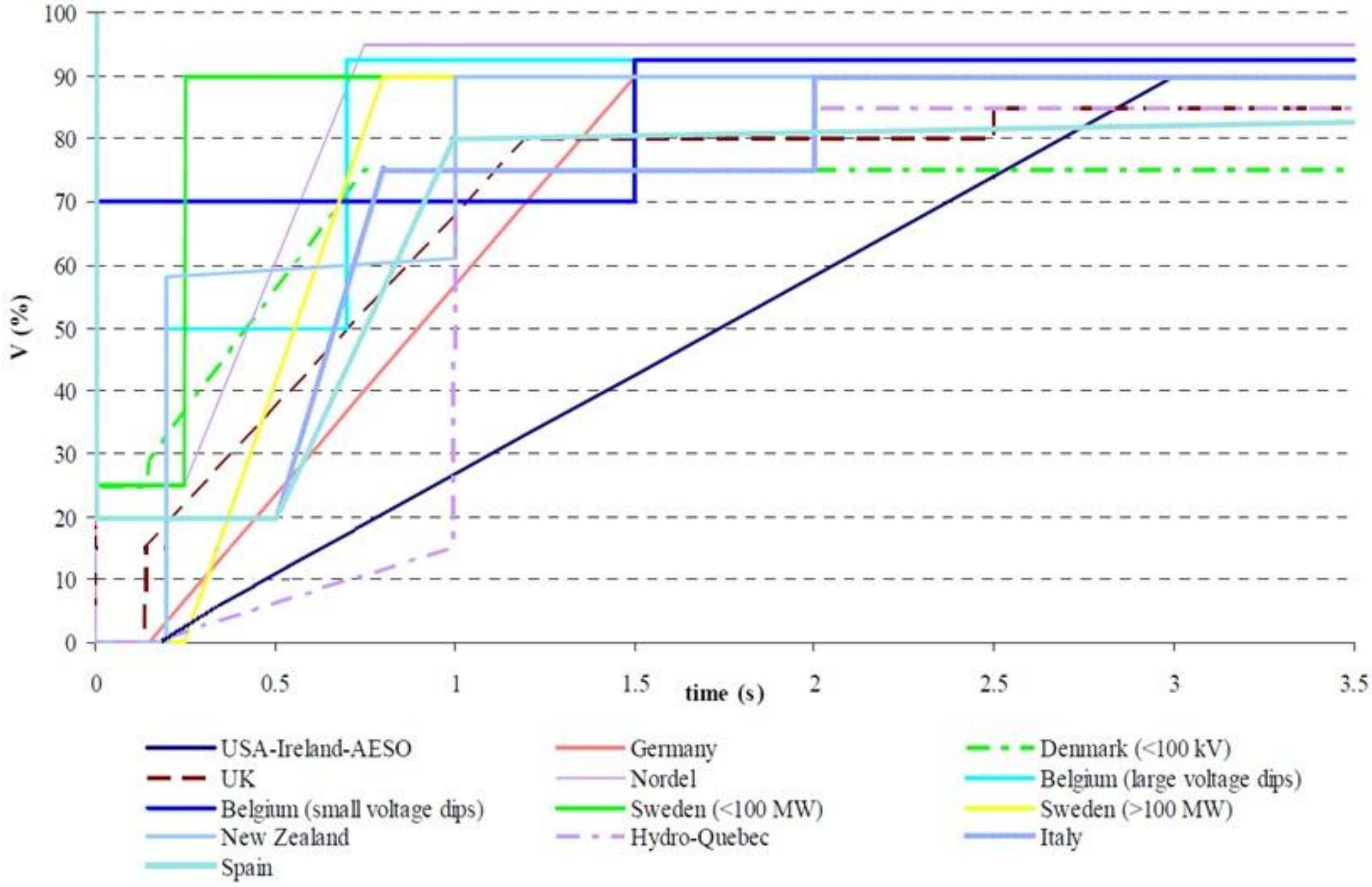
Present Fault Ride-Through Testing Requirements

- The electrical active power (MW) of the generator is reduced by reducing the available voltage
  - Depending on generator design, a drive train torque transient may be established
- Fault Ride-Through Depth
  - IEC 61400-21 levels are 70% and 20% of nominal voltage
  - Designed primarily for DFIGs
  - FERC 661-A : 0% nominal voltage
- Impedance divider is the most common technique and is outlined in the IEC Standard
- Every country and/or regulatory authority has their own LVRT/ZVRT withstanding curves



IEC 61400-21 Tolerance of voltage drop (50 Hz)

Fault Ride-Through (FRT) Withstanding Curves from Around the World



Modified to reflect the present FERC Order 661A standard. From: "Grid Code Requirements for Large Wind Farms: A Review of Technical Regulations and Available Wind Turbine Technologies" M. Tsili, Ch. Patsiouras, S. Papathanassiou

Present State of the Art in Fault Ride-Through (FRT) Testing

FRT Container: FGH Test Systems GmbH

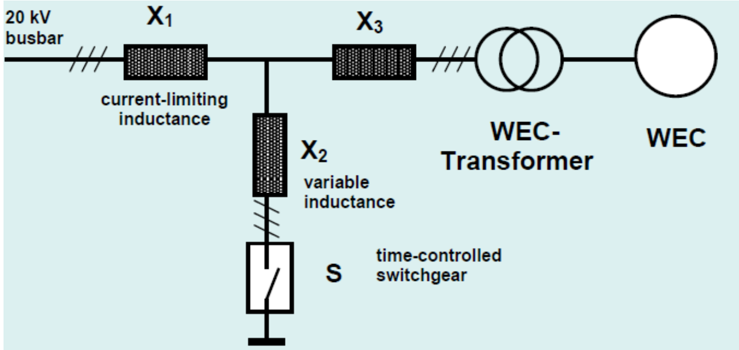
- Commercial containerized solutions for field testing
- High amount of fault duty available due to typical collector bus designs
- Manually tapped reactors used to set the voltage depth
- Fixed source voltage limits realistic slow voltage recoveries

ABB Factory Testing Facility

- Utility connection used for 50 Hz and an 8 MVA synchronous generator for 60 Hz
- Motor driven no load tap changers used on oil filled reactor banks
- Designed to test a 2 MW machine

Vestas and NWTC (Converter Only)

- Converter must handle DUT fault duty
- Converter topologies limit more refined testing scenarios



FGH Test Systems GmbH Web Flyer – Electrical One-line (top) and Reactor container (bottom)

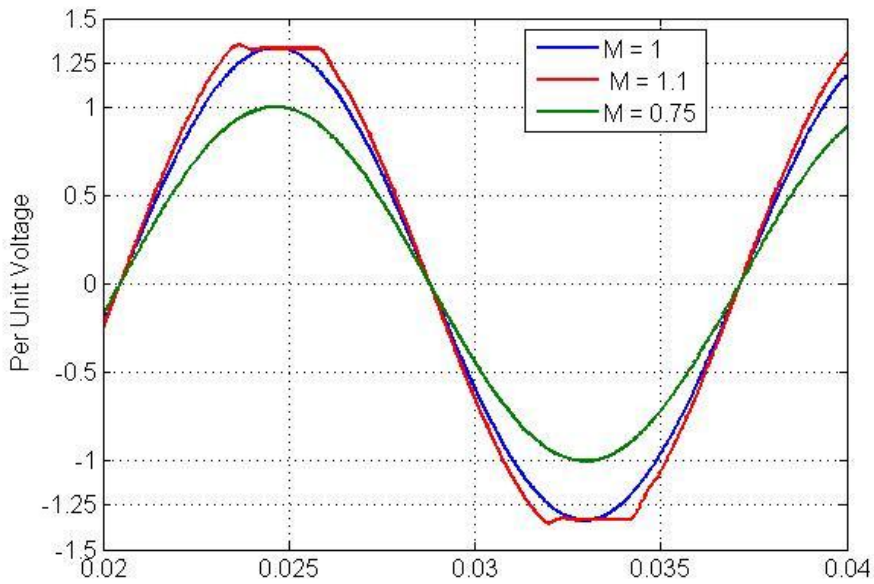
High Voltage Ride Through (HVRT) Requirements

Highest HVRT Limits: Hydro Québec: Supplementary requirements for wind generation – May 2003

1.25 < V < 1.40 p.u.* t_{max} = 0.10 s

V > 1.40 p.u.* t_{max} = 0.03 s

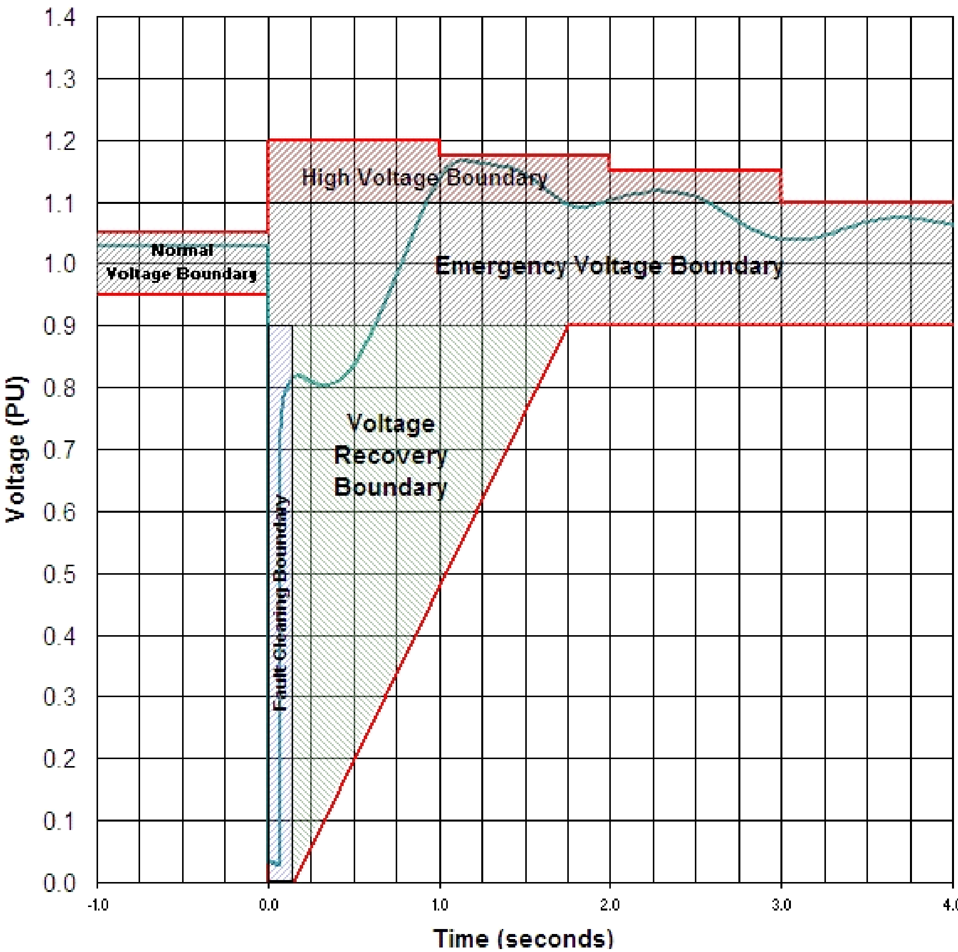
* Power electronics allowed to temporarily block above 1.25 pu.



- High voltage ride-through poses an inefficient use of resources and the utilization of transformer voltage taps may be required.
- Proposed solution includes +10 % high voltage taps on the step-up transformers to achieve 1.45 pu undistorted overvoltage.

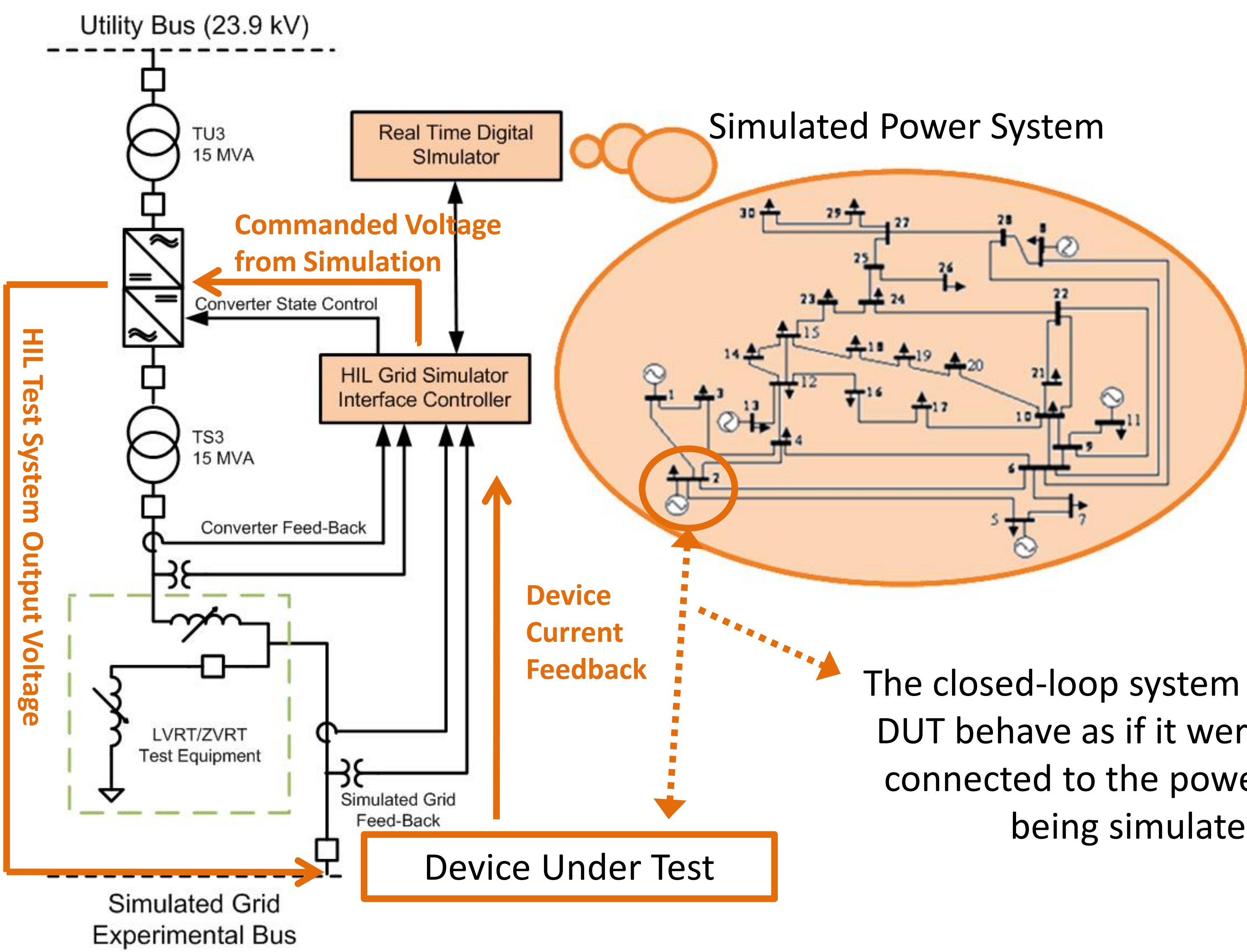
Fault Induced Delayed Voltage Recovery (FIDVR)

- Predominately caused by the stalling and subsequent tripping of a high penetration of line connected induction motors.
- Built in HVRT capabilities makes simulation of this type of event possible



FERC FIDVR Report: WECC FRT Boundaries

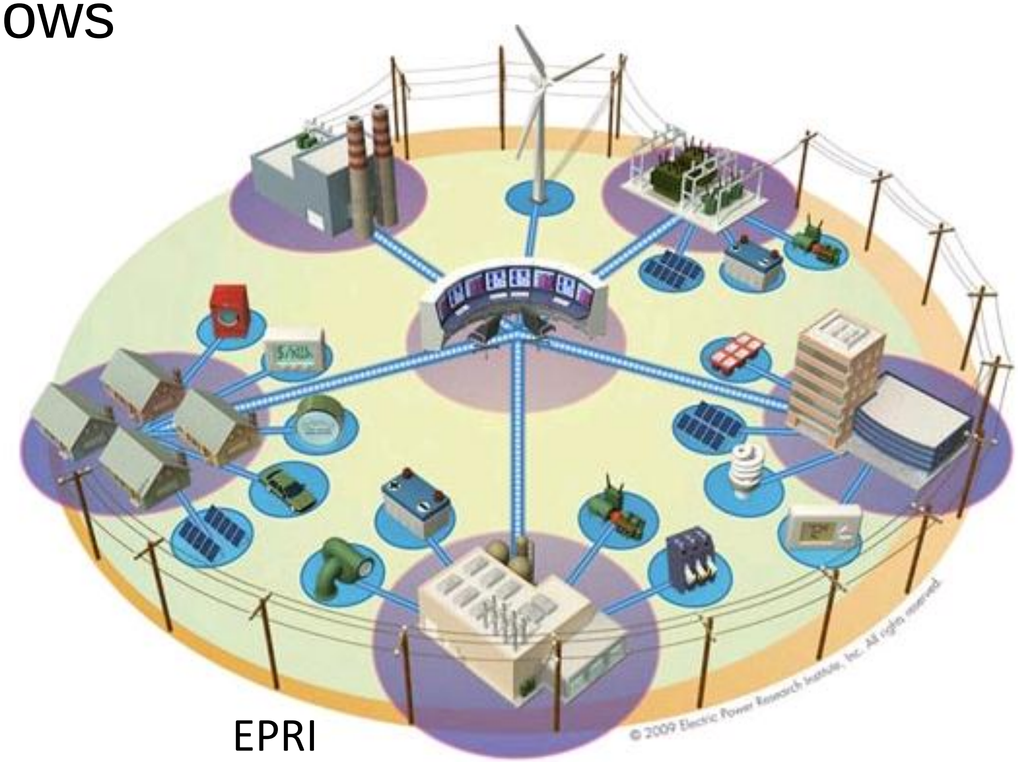
Power Hardware-In-the-Loop (HIL)



The closed-loop system allows the DUT behave as if it were actually connected to the power system being simulated

HIL Testing Capabilities: Microgrid

- Use HIL capabilities to emulate loads, generation, or a combination of the two
- Simulate whole sections of a ‘microgrid’ at once
- The larger capacity allows for testing of several pieces of equipment simultaneously
- Microgrid controllers, DG inverters and controllers, load controllers, etc.



EPRI
Microgrid Graphic