Microgrid Fundamentals and Control

Jian Sun, Professor and Director
New York State Center for Future Energy Systems
jsun@rpi.edu; (518) 276-8297

Microgrid is not New

- Early Power Systems Developed by Thomas Edison and Nikola Tesla were all “Microgrids”
- Large Power Grids Emerged Because of Improved Reliability, Better Generation-Load Balance, and More Stable Voltage & Frequency
- AC Took Over DC due to Easy Conversion

Why Microgrids Again

- New Drivers
  - Utilization of Distributed Generation
    - Renewable Energy, CHP, Energy Storage
    - Reduce Transmission and Distribution Cost & Losses
  - Improve Grid Resiliency and Power Quality
  - Expansion of Electrification
- New Enabling Technologies
  - Power Electronics, Communication, Control
  - Cost-Effective and Efficient Energy Storage

Microgrid Technology

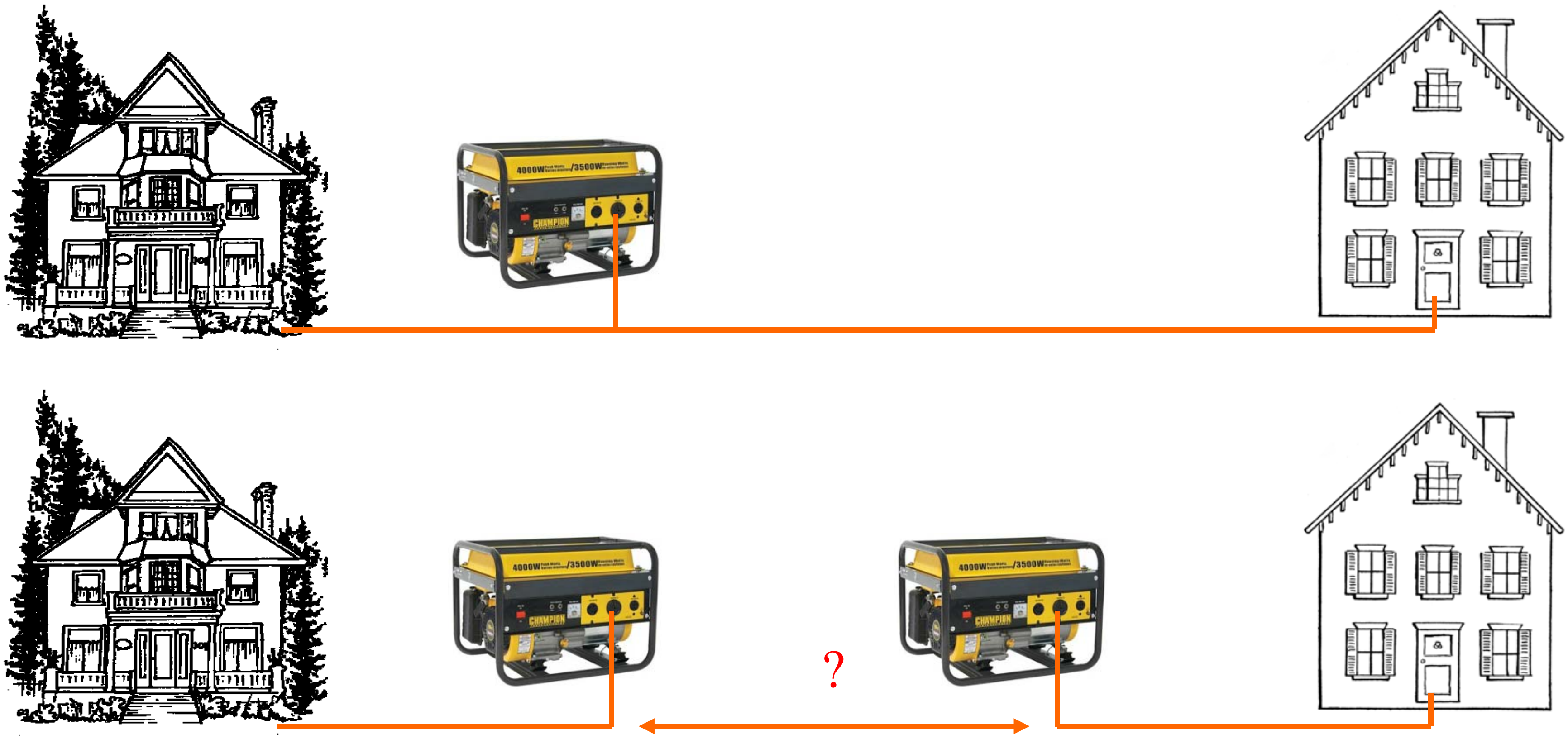
- Many Conferences, Workshops & Seminars about Microgrid Deployment, Benefits & Market
- Technical Materials have been Limited to Specific Techniques for “Specialists”
- Lack of Basic Understanding Often Leads to Hypes, False Claims/Expectations, and Mysteries
- Functionality is Easy; Performance is the Key
  - Promise Performance, Deliver Functionality

This Webinar

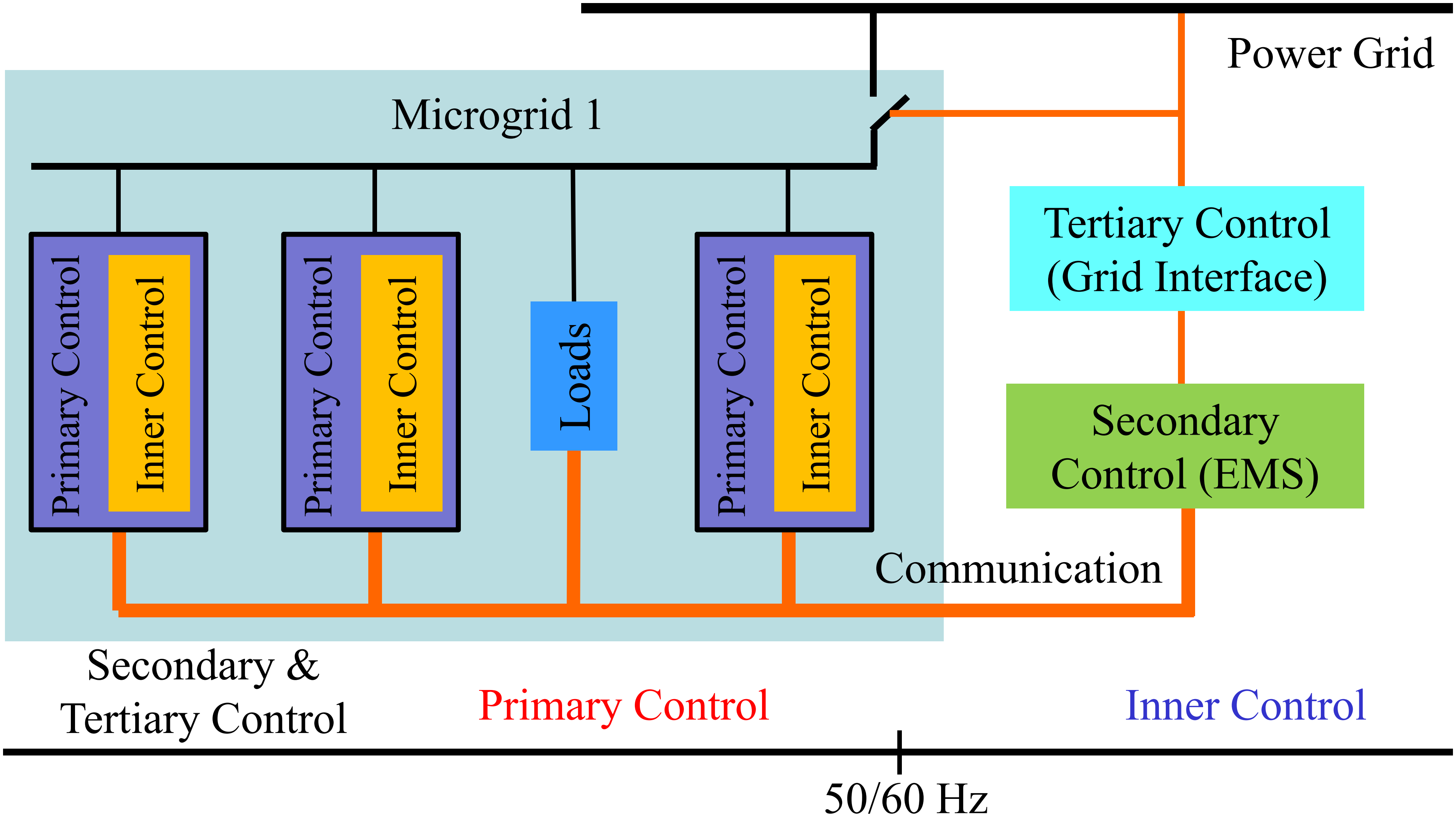
- Covers the Fundamentals of Microgrid
  - Technology, with a Focus on Control
  - Performance, with a Focus on Power Quality
- Targets Audience with General EE Background
- Goals
  - Users: Ask the Right Questions
  - Design Engineers: Know Where to Start
  - Research Engineers: Understand Technical Challenges and Opportunities for Innovation

Power Sharing

- Microgrid Control is about Sharing Power Among Multiple Sources While Maintaining Stability



Control Hierarchies



General Considerations

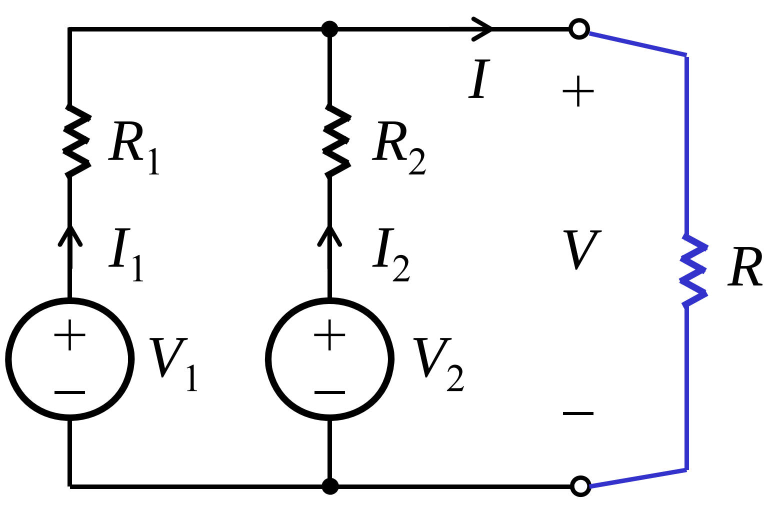
- Inner and Primary Control are Local
- Secondary and Tertiary Control are Central
  - Require Communications
  - Add Complexity and Cost
  - Limit Flexibility
- Plug-and-Play is Desirable for Microgrid
  - Autonomous Inner and Primary Control
  - No/Minimal Secondary and Tertiary Control

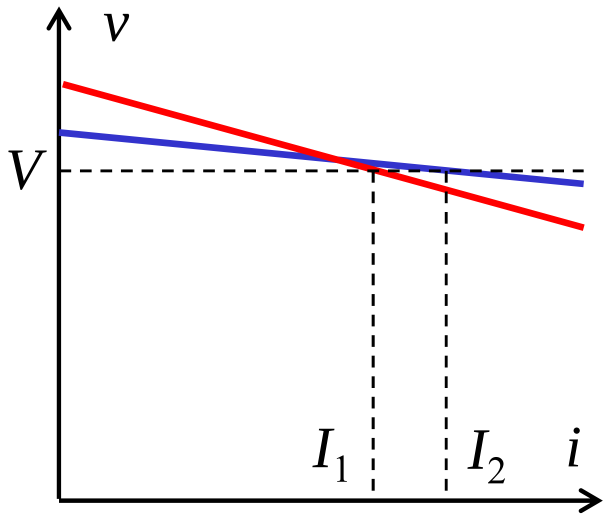
Outline

- DC Microgrid Control
- AC Microgrid Control
- Stability, Power Quality, and Control Development

Interconnecting DC Sources

- Voltage Sources can be Connected in Series but not Directly in Parallel
  - Current Sources can be Paralleled but not in Series
- Resistors Required to Limit Circulating Currents
  - Minimal Resistance Required to Avoid Back Feeding
  - Power Losses; not Feasible in Practice





If $V_1 > V_2$

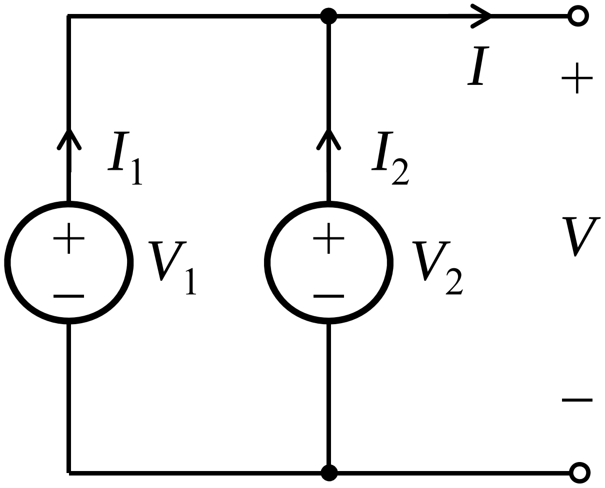
$$R_1 > R\left(\frac{V_1}{V_2}-1\right)$$

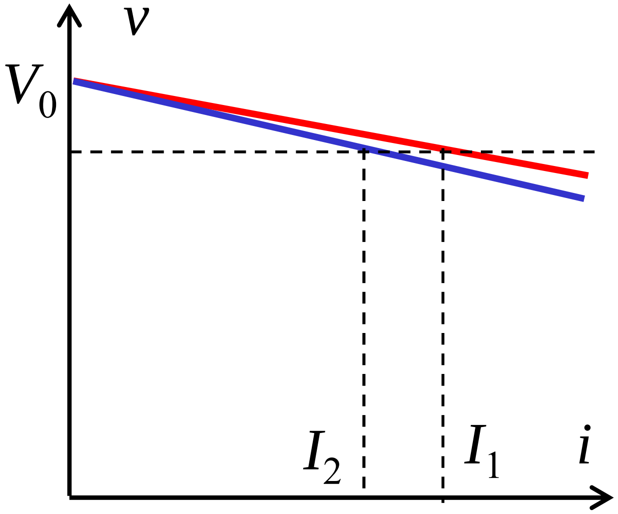
If $V_2 > V_1$

$$R_2 > R\left(1-\frac{V_2}{V_1}\right)$$

Droop Control

- Current-Dependent Voltage Sources
  - “Virtual” Series Resistors Avoid Power Losses
  - Open-Circuit Voltages can be Matched
  - Select Droop Coefficients Based on Current Sharing Goals
  - Made Possible by Power Electronics
- Applicable to Multiple Voltage Sources





$$V_1 = V_0 - R_1 I_1$$

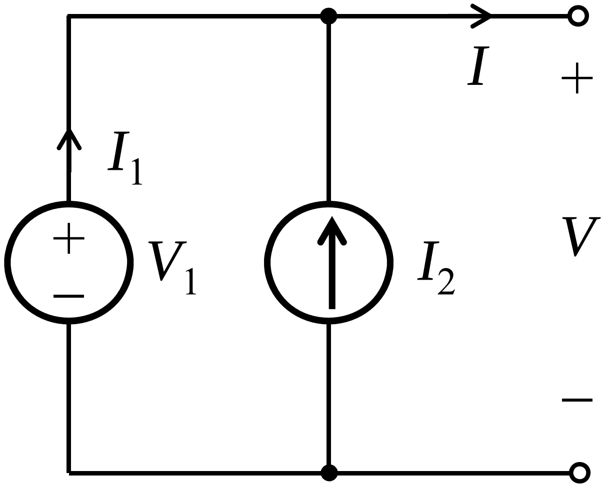
$$V_2 = V_0 - R_2 I_2$$

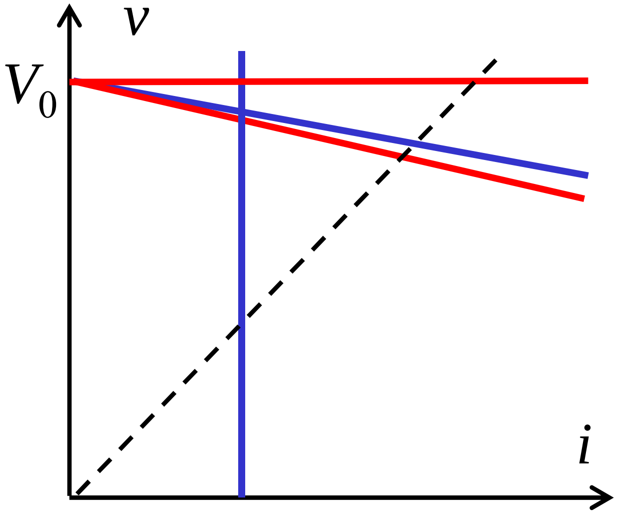
$$\frac{I_1}{I_2} = \frac{R_2}{R_1}$$

Effects of Parasitic Resistance Ignored (Output, Line)

Master-Slave Control

- One Source Sets the Voltage (Master)
- Other Sources Inject Currents (Slaves)
- Power Sharing not Directly Controlled
- Master and Slave Units are Pre-designated
  - Whole System is Down when the Master is Down
- Similar to Residential Solar Integration into the Grid





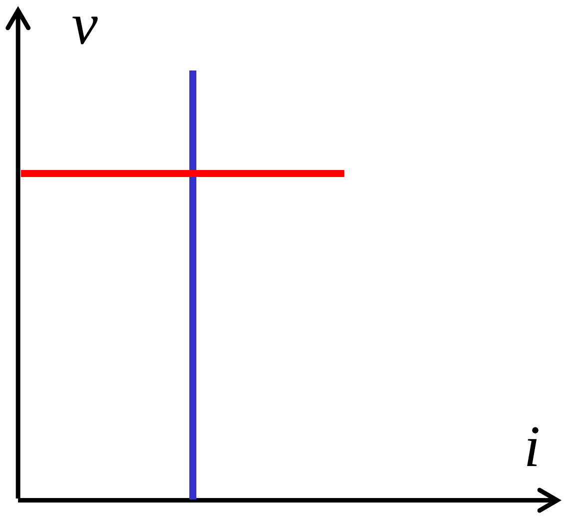
$$R_1 = 0$$

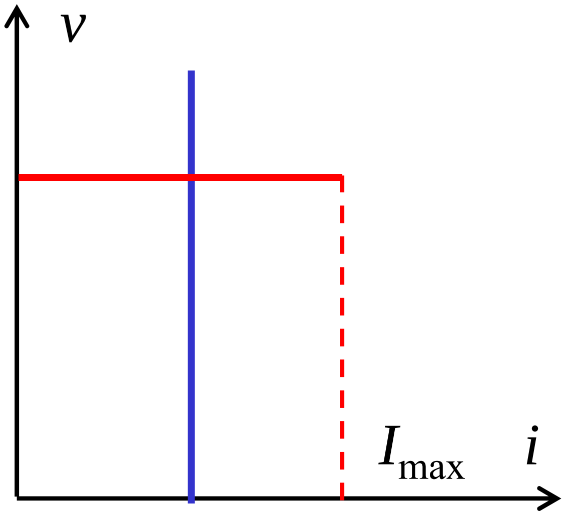
$$R_1 = \infty$$

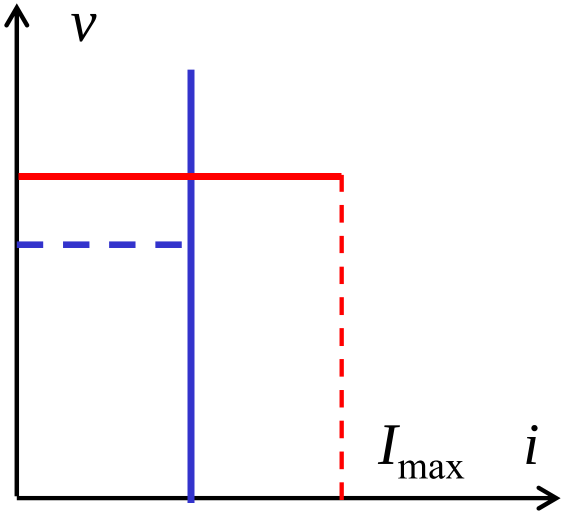
$$I_1 = \frac{V_1}{R} - I_2$$

Other Variations

- Master May Enter Current Limiting Mode
- Master May Relinquish Voltage Regulation Responsibility by Reducing the Voltage
  - Slave Enters Voltage Regulation Mode When Voltage Drops to Certain Level (Voltage Margin Control)
- HVDC System Control Provides Good Source of Reference

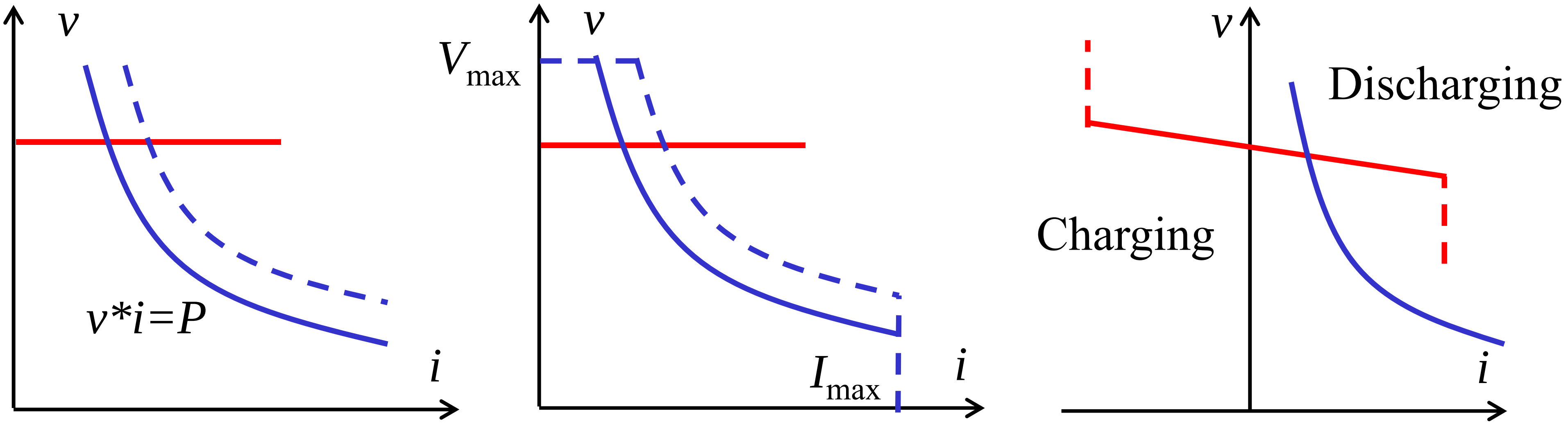






Other Variations – Cont’d

- Renewable Sources can be Treated as Constant-P Sources
  - With Max Voltage and Current Limit
- Battery or Other Controllable Units May be Used as Master
  - Parallel with Supercapacitors to Lower Impedance
  - Automatic Switching between Charging and Discharging Mode by Introducing a Voltage Droop

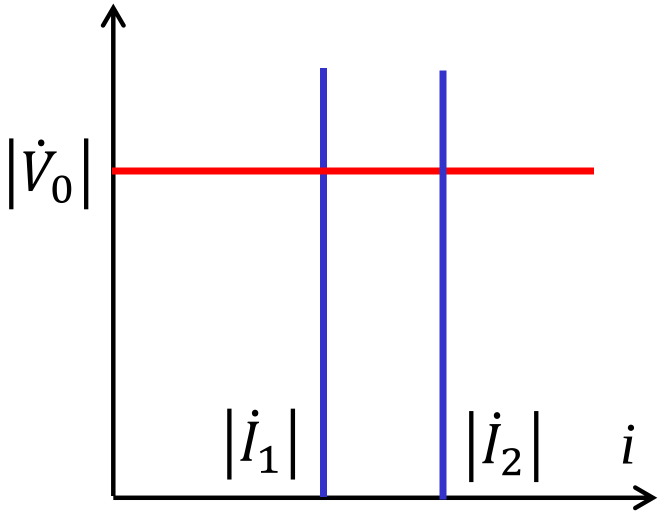


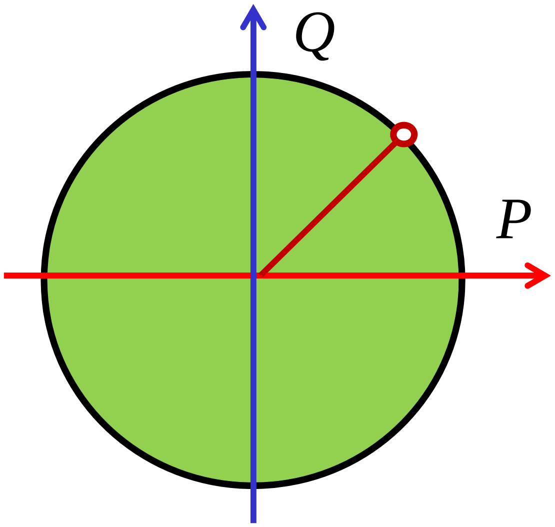
Outline

- DC Microgrid Control
- AC Microgrid Control
- Stability, Power Quality, and Control Development

Master-Slave Control

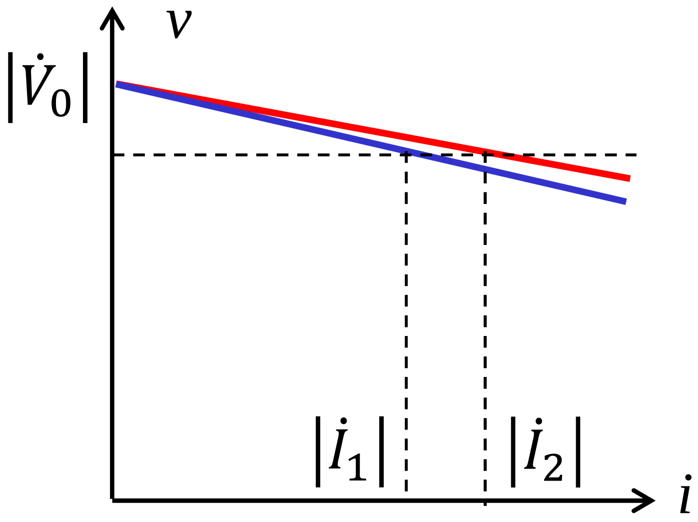
- Similar to Use in DC Microgrid
- Slaves May Inject Both Active and Reactive Currents
  - – Synchronization to Grid Voltage Angle is Required
  - – Reactive Current Causes Small Active Power Loss
    - Also Limited by Total Capacity of Interface (Inverter)
  - – Reactive Power Control can be Central or Distributed





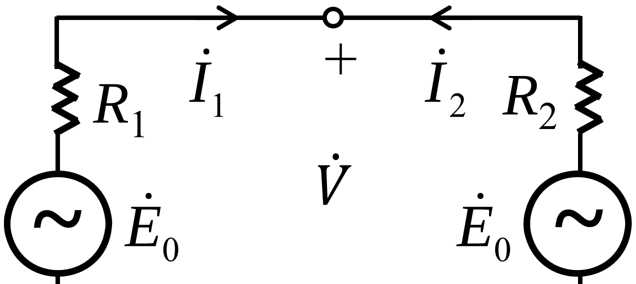
Droop Control

- Easy to Implement Voltage Magnitude Droop
  - Based on Current Magnitude
  - Unable to Control Active/Reactive Power Sharing
- Matching/Coordinating Phase Angles Requires Central Control



Droop Control Operation

- Power is Shared Based by Droop if
  - No Line Impedance is Present
  - Both Open-Circuit Voltages and Phases are Matched
- Complex Droop Coefficients can be Used to Provide Different Sharing of Active and Reactive Power



$$\dot{I}_1 / \dot{I}_2 = R_2 / R_1$$

$$\dot{I}_1 = \frac{\dot{E}_0 - \dot{V}}{R_1} = \frac{E_0 \cos\delta_0 - V}{R_1} + j\frac{E_0 \sin\delta_0}{R_1}$$

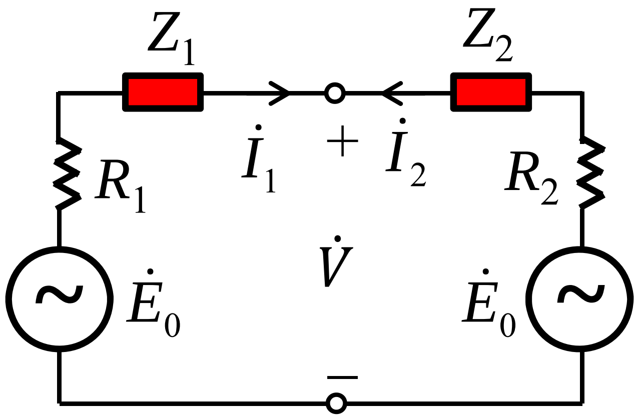
$$\dot{I}_2 = \frac{\dot{E}_0 - \dot{V}}{R_2} = \frac{E_0 \cos\delta_0 - V}{R_2} + j\frac{E_0 \sin\delta_0}{R_2}$$

Rensselaer

Jian Sun 10-17-2014

Effects of Line Impedance

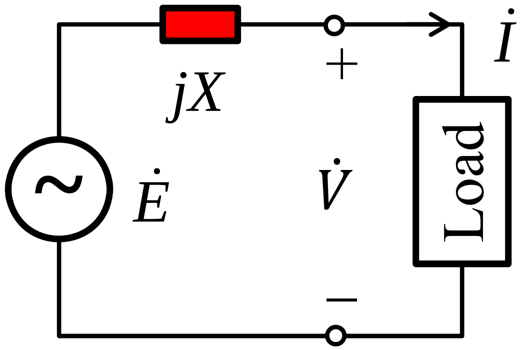
- Line Impedance Affects Current Sharing
- Impossible to Cancel this Effect Through Droop Design
  - More Complicated in Large Network with Multiple Sources
  - Also Remember the Difficulty of Matching the Voltages
- Possible to Reduce the Effects by Using Large Droop, but will Result in Very Soft (Weak Grid) Behavior



$$\dot{I}_1 = \frac{\dot{E}_0 - \dot{V}}{R_1 + Z_1} = \frac{E_0 \cos\delta_0 - V}{R_1 + Z_1} + j\frac{E_0 \sin\delta_0}{R_1 + Z_1}$$

$$\dot{I}_2 = \frac{\dot{E}_0 - \dot{V}}{R_2} = \frac{E_0 \cos\delta_0 - V}{R_2 + Z_2} + j\frac{E_0 \sin\delta_0}{R_2 + Z_2}$$

Pure Inductive Network



$$\dot{I}=\frac{E\cos\delta-V}{jX}+j\frac{E\sin\delta}{jX}=\frac{E\sin\delta}{X}-j\frac{E\cos\delta-V}{X}$$

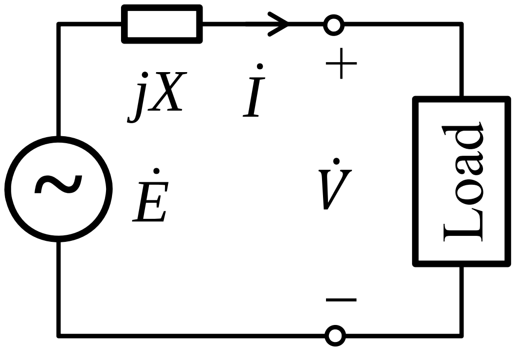
$$P=\frac{EV\sin\delta}{X},\quad Q=\frac{V(V-E\cos\delta)}{X}$$

- With a Small Phase Angle δ: $P\approx\frac{EV}{X}\cdot\delta,\quad Q\approx\frac{V}{X}\cdot(V-E)$
  - Active Power can be Controlled by Varying the Phase (δ)
  - Reactive Power can be Controlled by Varying Voltage (*E*)
- Phase Angle Relative to the Load cannot be Measured
- Frequency can be Measured Locally and $\delta=\int_0^t\Delta\omega(\tau)d\tau$

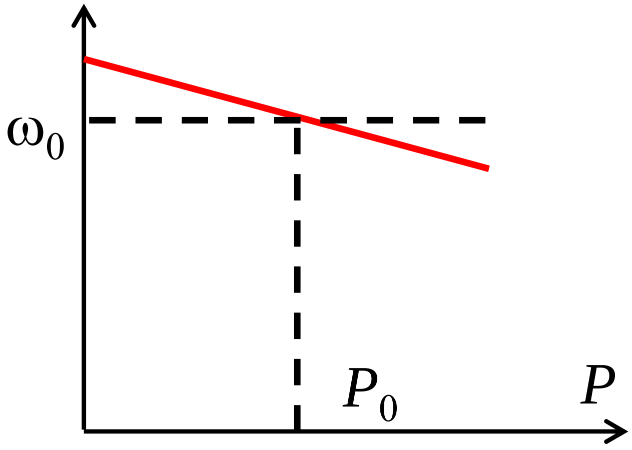
Frequency and Voltage Droop

- Frequency Droop to Control Active Power Sharing
- Voltage Droop to Control Reactive Power Sharing
- Droop Characteristic Emulates a Reactance
  - Should be High Compared to Actual Line Reactance
- Cross Coupling Affects Transient Responses
- Integration Introduces Dynamics – Stability Considerations

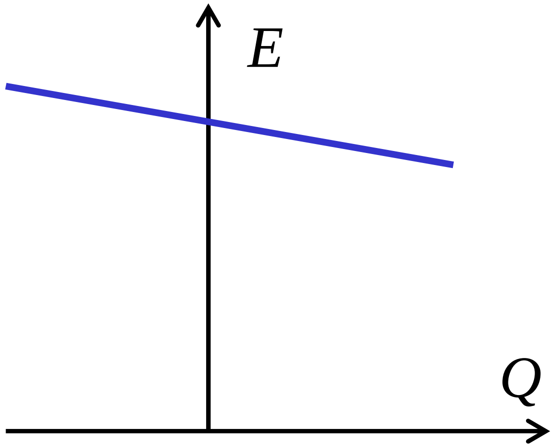
$$\delta = \int_0^t \Delta\omega(\tau)d\tau$$



$$\omega_i = \omega_0 - m_i(P_0 - P_{0i})$$

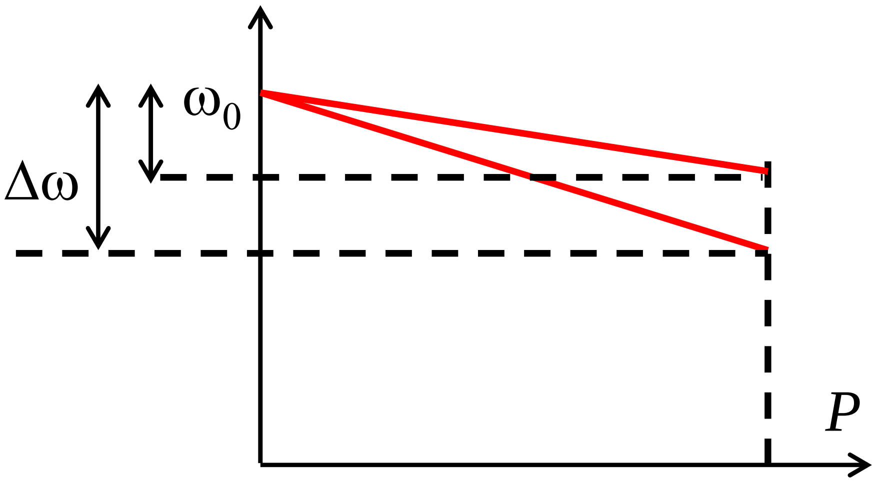


$$E_i = E_0 - n_i(Q_i - Q_{0i})$$



Frequency Deviation

- Large P Droop Improves Active Power Sharing Control
  - But Results in Large Δf – Undesirable for Certain Loads
  - Also Increases Coupling with Reactive Power Control
- Secondary Control can be Used to Restore Nominal Frequency after Transient by Adjusting ω_0



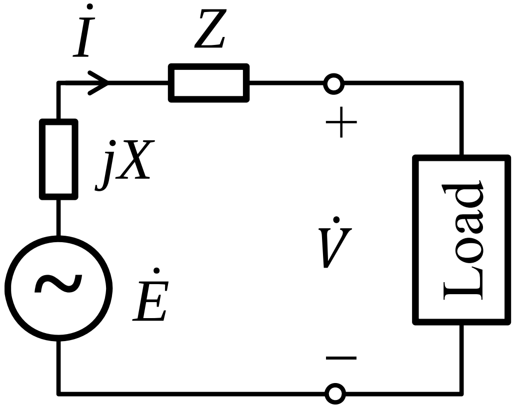
$$\omega_i = \omega_0 - m_i(P_0 - P_{0i})$$

$$P = \frac{EV\sin\delta}{X}, \quad Q = \frac{V(V - E\cos\delta)}{X}$$

$$\delta = \int_0^t \Delta\omega(\tau)d\tau$$

Effects of Line Impedance

- Actual Line Impedance Depends on Distance
  - More Significant for Large Microgrids
- Reactance of the Line Consumes Reactive Power
  - *Q* in *Q*-*E* Droop Curve is Meant for System Reactive Power Sharing but is Measured at the Terminal of Each Unit
- R/X Ratio, Highly Resistive for Distribution Lines
- All of These May Reduce Effectiveness of Droop Control



$$\dot{I} = \frac{E\cos\delta - V}{jX + Z} + j\frac{E\sin\delta}{jX + Z}$$

Z: Line Impedance

X: Emulated Reactance

Various Methods can be Used to Mitigate These Problems but are Usually Sensitive to Actual Line Parameters.

Droop with Dynamics

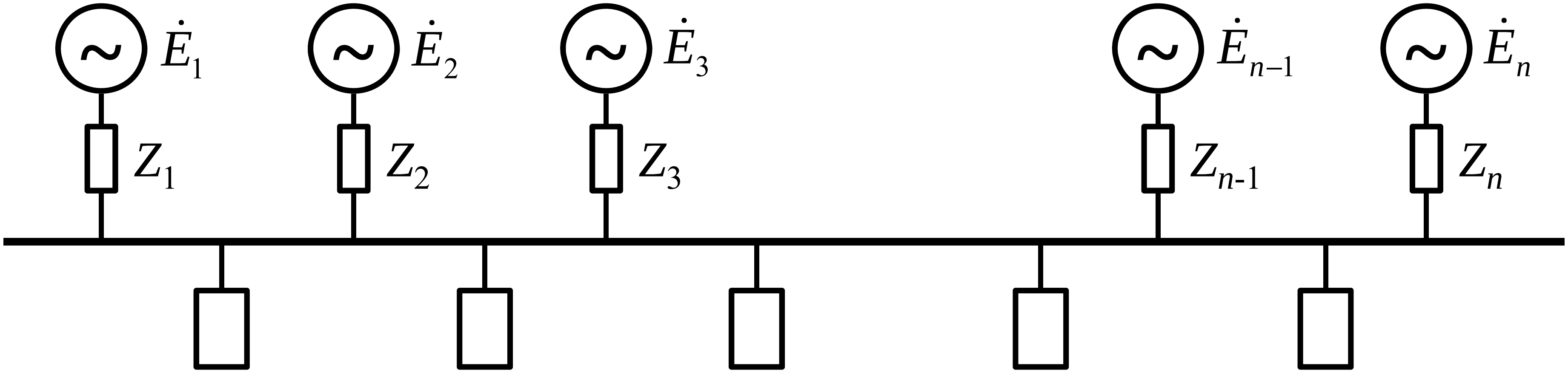
- Integral Relationship from ω to δ Introduces Dynamics
- Additional Dynamics due to Power Control Loops
- These May Lead to Poor Transients, Oscillatory Responses
- Possible Improvement by Introducing Dynamics into Droop Characteristics
  - Emulate PID Control
- Need Proper System Models for Design
  - Nonlinear Effects of Angle and Voltage; Linearization Required

$$\delta = -m_p P - m_d \frac{dP}{dt} - m_i \int P d\tau \quad \Rightarrow \quad \omega = \omega_0 - m_i P_i - m_p \frac{dP}{dt} - m_d \frac{d^2 P}{dt^2}$$

$$E = E_0 - n_p Q - n_d \frac{dQ}{dt}$$

Virtual Impedance Method

- Instead of P & Q Droop, Each Unit can be Controlled to have Fixed Output Impedance
  - Output P and Q are Controlled by Varying $\dot{E}$
  - System Frequency can be Kept Constant
  - Limits Current at Initial Connection, Hot Swap Capability
  - Resistive Output Impedance May Improve System Damping
- No Direct Control of System P & Q Balance



Droop vs. Master-Slave Control

- Droop Control Works Well with Defined Power Sharing Objectives
  - Generators, Power Supplies, Parallel Modules
- Master-Slave Control Works for Renewable Sources
  - Slaves Work to Maximize Their Power Output
  - Master has to have Enough Capacity and Speed in Addition to Being Reliable/Controllable
- Various Combinations are Possible
  - Droop Control of Multiple Maters
  - Democratic Mater-Slave Control

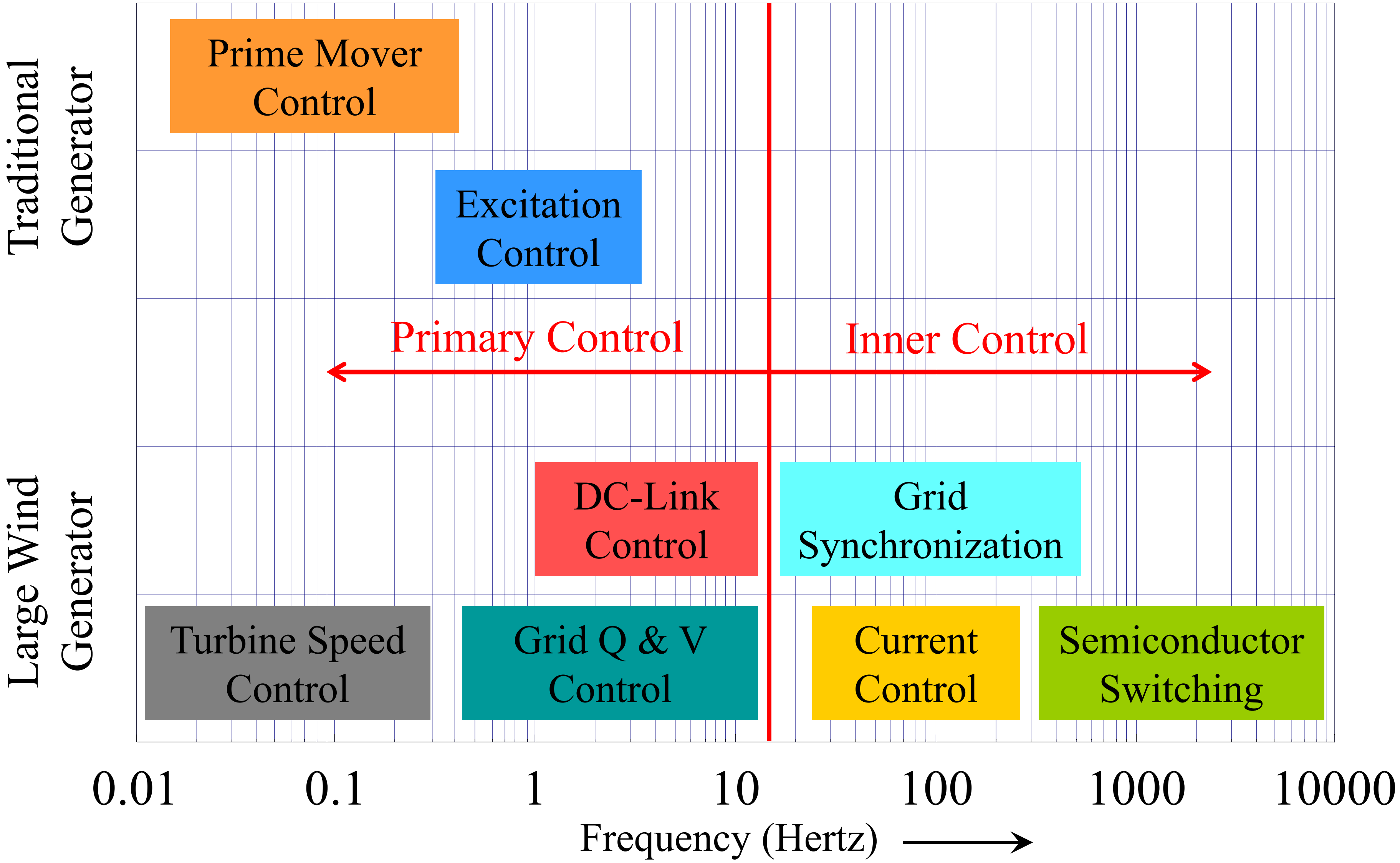
Outline

- DC Microgrid Control
- AC Microgrid Control
- Stability, Power Quality, and Control Development

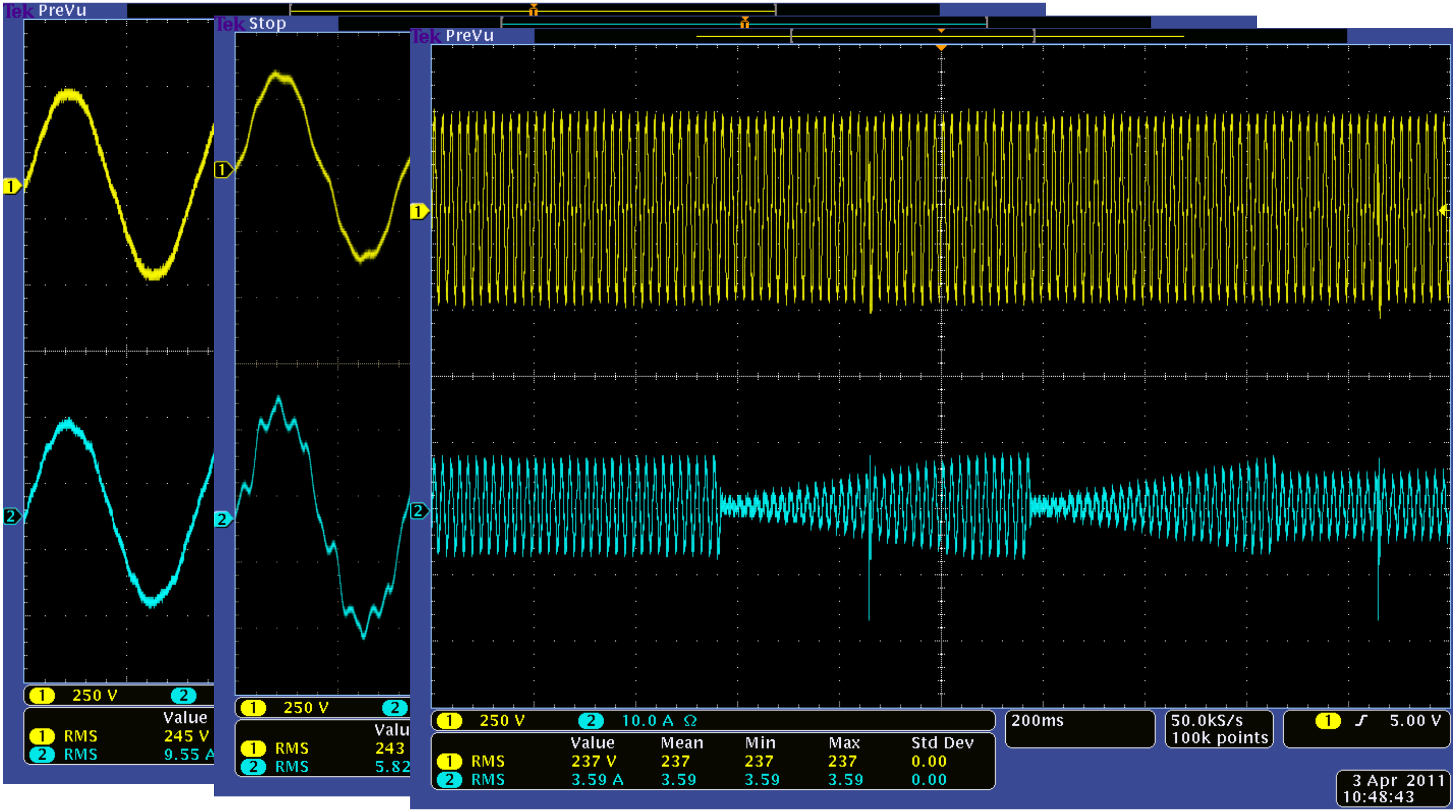
Microgrid Stability

- Microgrid is a Weak Grid by Definition
  - Much Easier to Become Unstable than the Large Grid
  - May Actually Degrade Reliability and Power Quality
- Inner Control Designed to be Stable for Assumed (Often Ideal) External Conditions
  - May Become Unstable in an Actual System
- Droop and Master/Slave Control are Meant for Steady-State Power Sharing and Don’t Guarantee Transient Stability

Control and Stability



Weak-Grid Problem

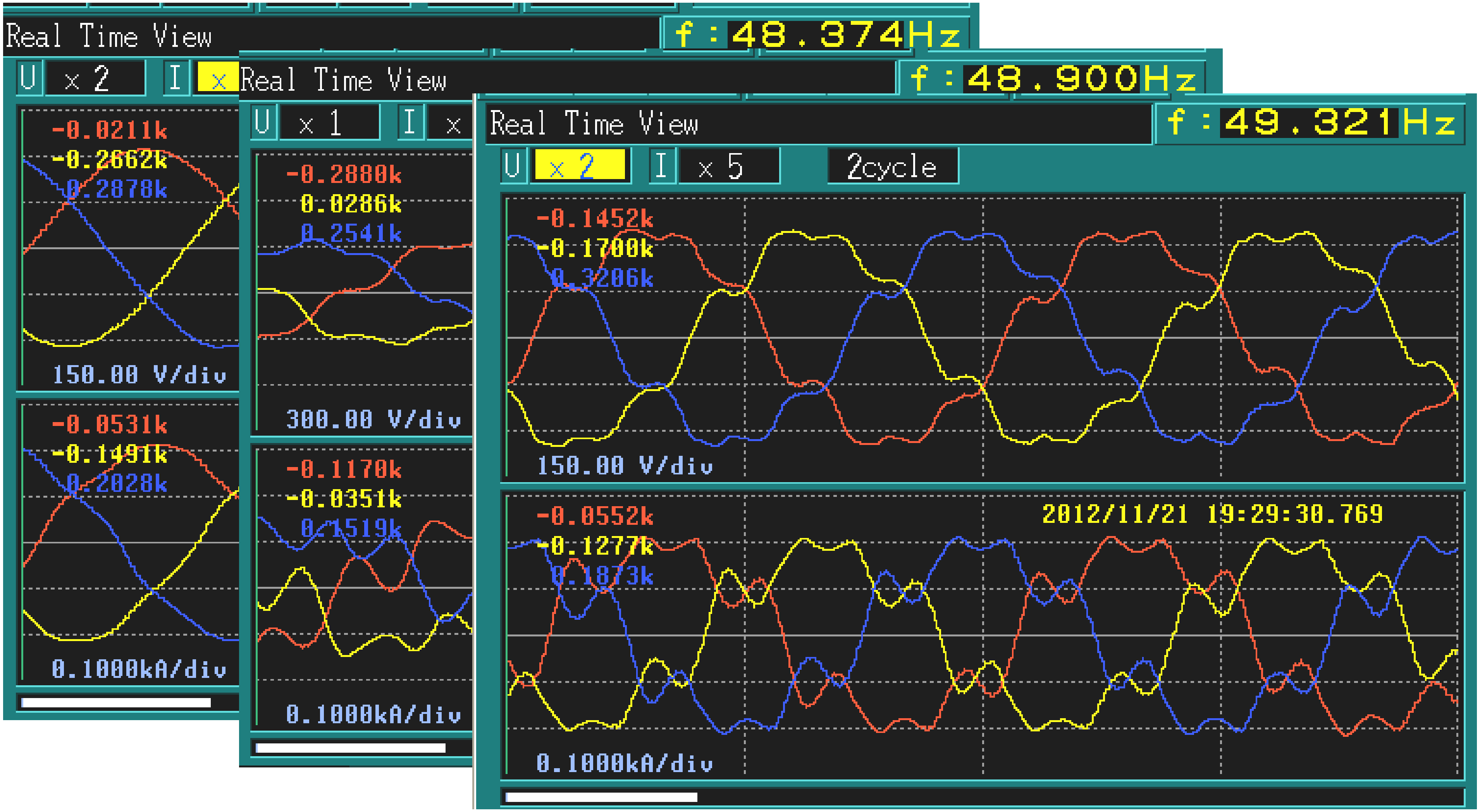


	Value
1 RMS	245 V
2 RMS	9.55 A

	Valu
1 RMS	243
2 RMS	5.82

	Value	Mean	Min	Max	Std Dev
1 RMS	237 V	237	237	237	0.00
2 RMS	3.59 A	3.59	3.59	3.59	0.00

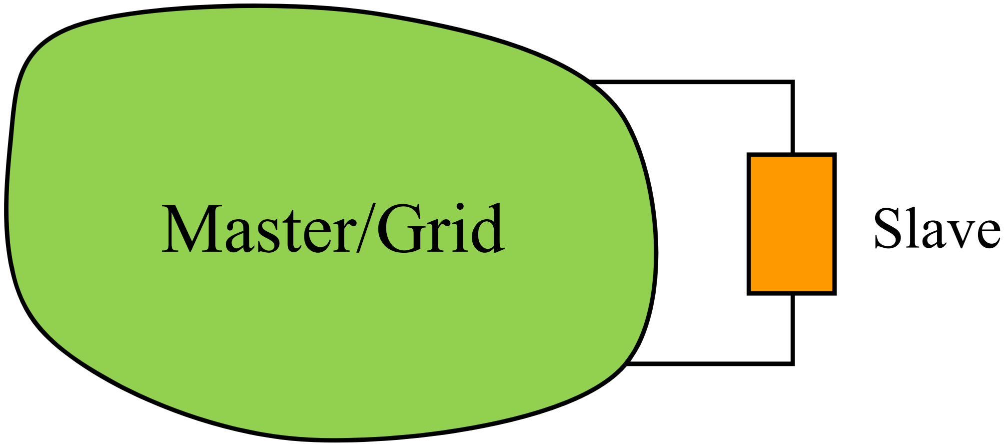
Solar Farm


Real Time View
f : 48.374Hz
U
x 2
I
x
-0.0211k
-0.2662k
0.2878k
150.00 V/div
-0.0531k
-0.1491k
0.2028k
0.1000kA/div
Real Time View
f : 48.900Hz
U
x 1
I
x
-0.2880k
0.0286k
0.2541k
300.00 V/div
-0.1170k
-0.0351k
0.1519k
0.1000kA/div
Real Time View
f : 49.321Hz
U
x 2
I
x 5
2cycle
-0.1452k
-0.1700k
0.3206k
150.00 V/div
-0.0552k
-0.1277k
0.1873k
2012/11/21 19:29:30.769
0.1000kA/div

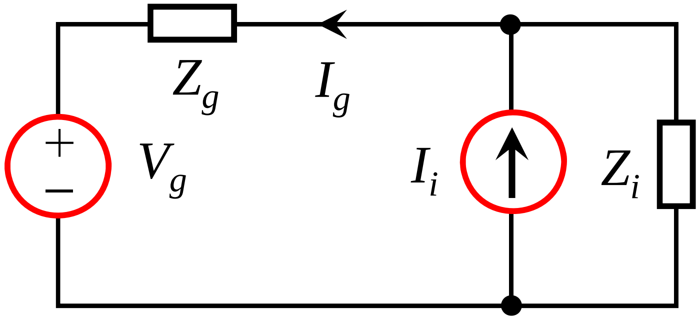
Impedance-Based Analysis

- Each Device is Modeled by an Impedance Element for Small-Signal Analysis
  - Dynamic, Over Entire Frequency Range of Interest
- System Stability is Determined Based on the an Impedance Network
  - State-Space Analysis – Overall System Analysis
  - Input-Output Analysis – Individual Unit Stability under the Influence of the System

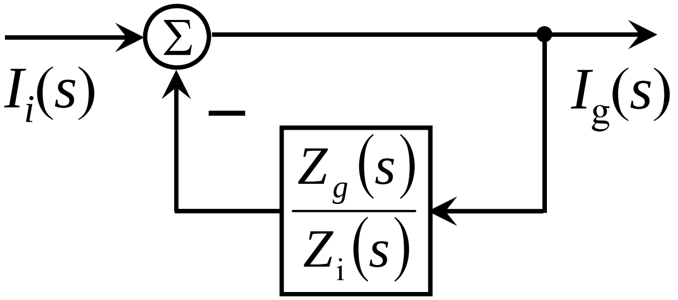
Master-Slave Control Stability



Small-Signal Model



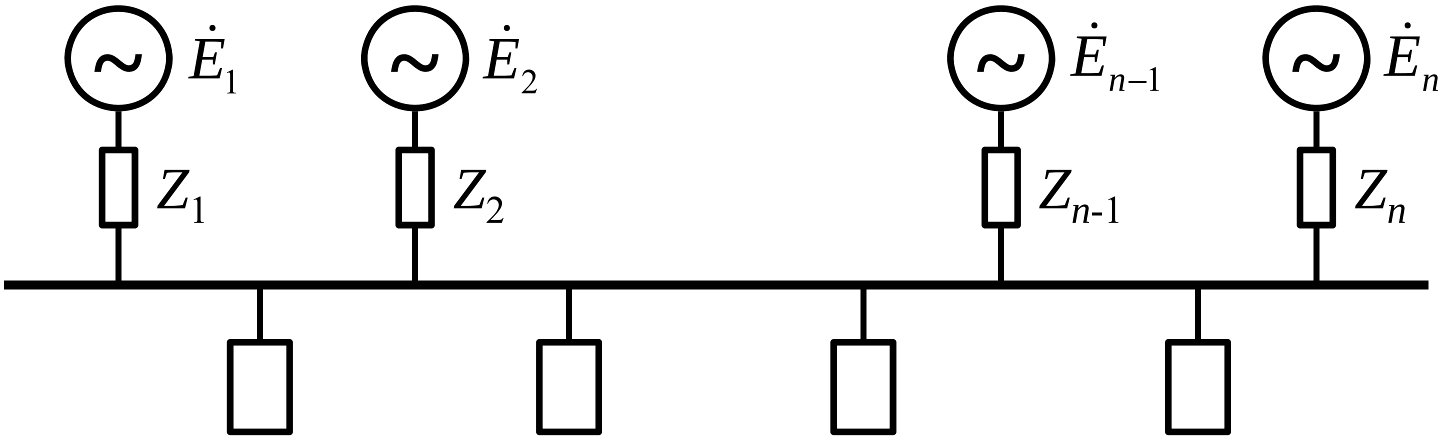
- Master is Modeled by an Ideal Voltage Source Behind Impedance
- Each Slave is Modeled by an Ideal Current Source in Parallel with an Output Impedance; Individual or Combined

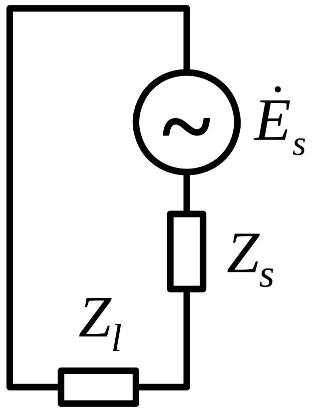


$$\frac{I_g(s)}{I_i(s)} = \frac{Z_i(s)}{Z_i(s)+Z_g(s)} = \frac{1}{1+\frac{Z_g(s)}{Z_i(s)}}$$

Droop Control Stability

- Lumped into a Single Source-Load Model
  - Overall System Stability and Source-Load Interactions
  - Effects of Changes in Sources or Loads on Stability
- System Impedance Network – Matrix Description
- Extension to Other Primary Control Methods

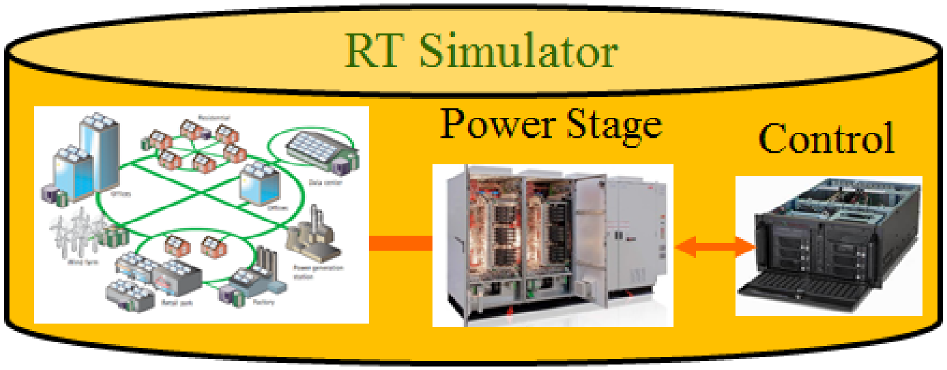


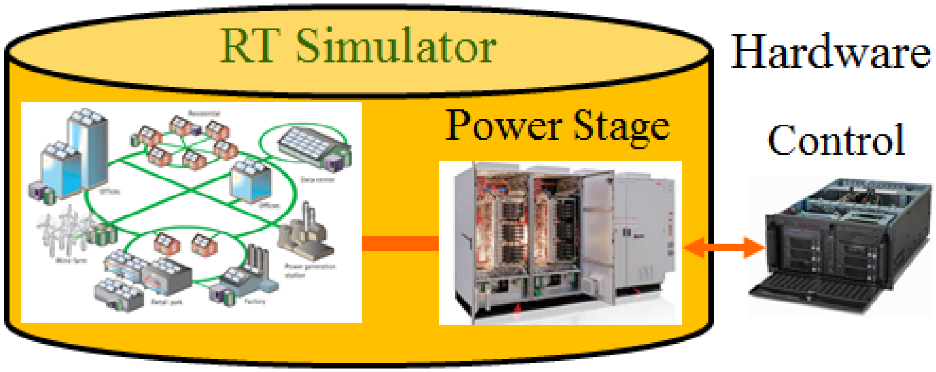


Simulation

- Limitations of Small-Signal Analysis
  - Startup; Shutdown; Operation Mode Transition
  - Abnormal Operation; Interaction with Protections
  - Nonlinear and Time-Varying Behavior
- Detailed Circuit and Control Simulation Complements Small-Signal Analysis
  - Possible due to Relatively Small System Size

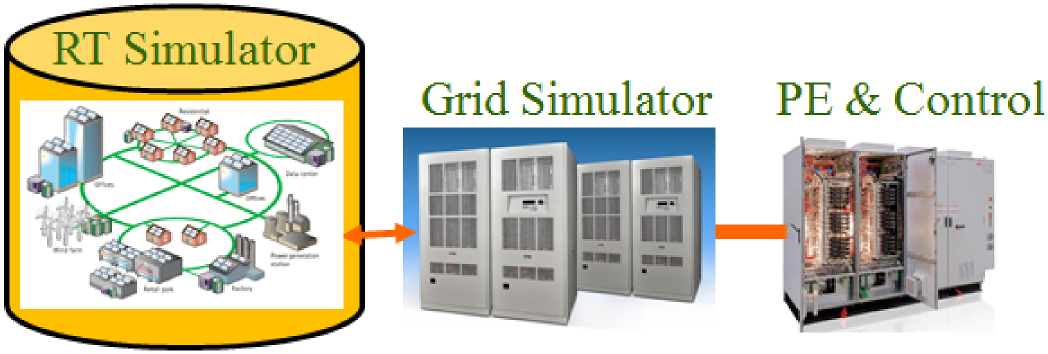
Real-Time (RT) Simulation





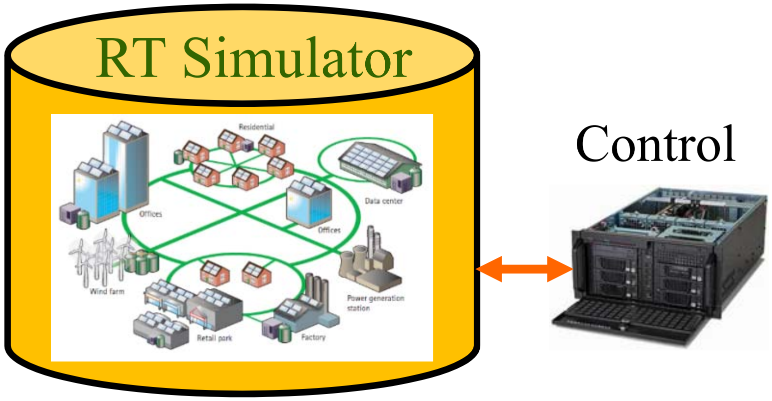
Control Hardware-in-the-Loop (CHIL) Simulation

Power Hardware-in-the-Loop (PHIL) Simulation



HIL Simulation of Microgrids

- Testing of Individual Generation Units
  - Rest of System Simulated in Real-Time
  - Power or Control Interface with Simulator
- System Control Development and Testing
  - Secondary and Tertiary Control
  - Physical System Simulated Along with Local Controls


RT Simulator

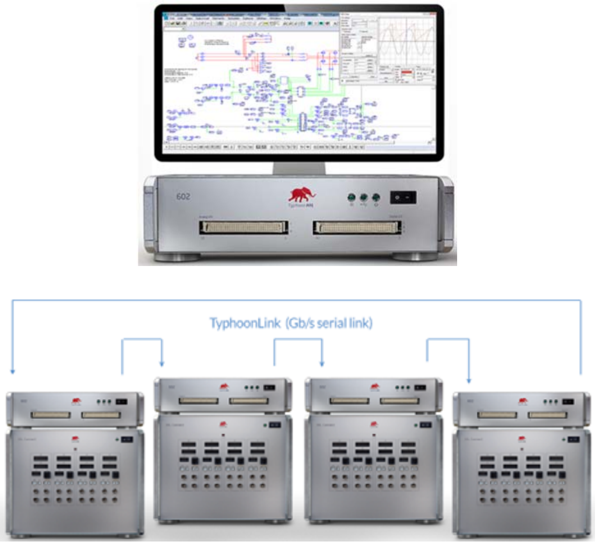
Control

RT Simulation Platforms

- Simulation Time Steps, PWM Control Accuracy; System (Physical) Size and Complexity

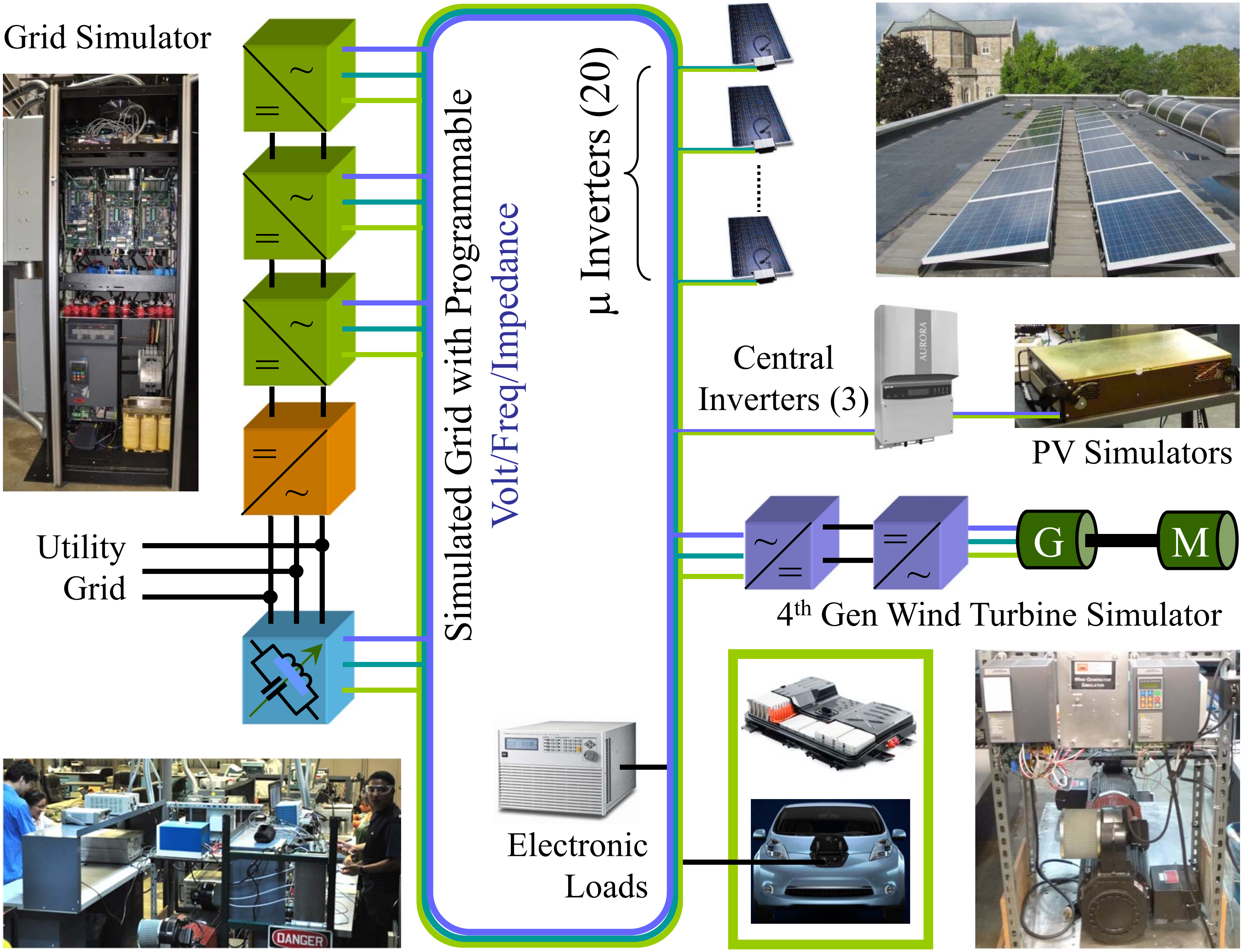
Power Electronics -------------- Power Systems

Typhoon HIL



OPAL-RT TECHNOLOGIES

RTDS Technologies



Grid Simulator

Simulated Grid with Programmable
Volt/Freq/Impedance

μ Inverters (20)

Central
Inverters (3)

PV Simulators

Utility
Grid

4th Gen Wind Turbine Simulator

Electronic
Loads

Summary

- Control is to Share Power Among Multiple Sources
- Functionality is Easy, Performance is the Key
- A Microgrid is a Weak Grid by Definition
  - Network Dynamics Affect Inner Control Stability
  - Primary Control Stability is not Guaranteed
- Use of Secondary and Tertiary Control Should be Minimized to Reduce Complexity and Cost, Improve Reliability and Flexibility
- Analysis and Control Design Tools are Available