Microgrid Fundamentals and Control

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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

Microgrid 1

- Primary Control
- Inner Control
- Loads

Secondary & Tertiary Control

Primary Control

Inner Control

Power Grid

- Tertiary Control (Grid Interface)
- Secondary Control (EMS)

Communication

50/60 Hz

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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

\[
\begin{align*}
I_1 &= V_1/R_1 \\
I_2 &= V_2/R_2 \\
I &= I_1 + I_2
\end{align*}
\]

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)

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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

\[ I = I_1 + I_2 \]

\[ V = -IR \]

\[ V_0 = \frac{V_1}{R} - I_2 \]

\[ R_1 = 0 \]

\[ R_1 = \infty \]
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

\[ v \times i = P \]

\[ v_{\text{max}} \]

\[ i_{\text{max}} \]
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

\[ \hat{V}_0 \]

\[ |i_1| \quad |i_2| \]
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

\[ I_1 = \frac{\dot{E}_0 - \dot{V}}{R_1} = \frac{E_0 \cos \delta_0 - V}{R_1} + j \frac{E_0 \sin \delta_0}{R_1} \]

\[ I_2 = \frac{\dot{E}_0 - \dot{V}}{R_2} = \frac{E_0 \cos \delta_0 - V}{R_2} + j \frac{E_0 \sin \delta_0}{R_2} \]
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

\[
\begin{align*}
\dot{I}_1 &= \frac{\dot{E}_0 - \dot{V}}{R_1 + Z_1} = \frac{E_0 \cos \delta_0 - V}{R_1 + Z_1} + j \frac{E_0 \sin \delta_0}{R_1 + Z_1} \\
\dot{I}_2 &= \frac{\dot{E}_0 - \dot{V}}{R_2} = \frac{E_0 \cos \delta_0 - V}{R_2 + Z_2} + j \frac{E_0 \sin \delta_0}{R_2 + Z_2}
\end{align*}
\]
Pure Inductive Network

\[ i = \frac{E \cos \delta - V}{jX} + j \frac{E \sin \delta}{jX} = \frac{E \sin \delta}{X} - j \frac{E \cos \delta - V}{X} \]

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

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

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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

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

\[ \omega_i = \omega_0 - m_i (P_0 - P_{0i}) \quad E_i = E_0 - n_i (Q_i - Q_{0i}) \]
Frequency Deviation

- Large P Droop Improves Active Power Sharing Control
  - But Results in Large $\Delta f$ – Undesirable for Certain Loads
  - Also Increases Coupling with Reactive Power Control
- Secondary Control can be Used to Restore Nominal Frequency after Transient by Adjusting $\omega_0$

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

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

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

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

• Integral Relationship from $\omega$ to $\delta$ 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

\[
\delta = -m_p P - m_d \frac{dP}{dt} - m_i \int P \, d\tau
\]

\[
\omega = \omega_0 - m_i P_i - m_p \frac{dP}{dt} - m_d \frac{d^2 P}{dt^2}
\]

\[
E = E_0 - n_p Q - n_d \frac{dQ}{dt}
\]
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 Masters
  – Democratic Master-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

Frequency (Hertz)

- Prime Mover Control
- Excitation Control
- DC-Link Control
- Grid Synchronization
- Turbine Speed Control
- Grid Q & V Control
- Current Control
- Semiconductor Switching

Primary Control

Inner Control

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Weak-Grid Problem
Solar Farm
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 Impedance Network
  – State-Space Analysis – Overall System Analysis
  – Input-Output Analysis – Individual Unit Stability under the Influence of the System
Master-Slave Control Stability

- 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

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

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

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

Power Electronics  --------------  Power Systems
Simulated Grid with Programmable Volt/Freq/Impedance PV Simulators

Central Inverters (3)

μ Inverters (20)

Utility Grid

Grid Simulator

Electronic Loads

4th Gen Wind Turbine Simulator

PV Simulators
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