Microgrid System Design, Control, and Modeling Challenges and Solutions

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SEL ES Technology Director
Agenda

• Example Projects
• Challenges
• Design Principles
• Reconnection
• Seamless Islanding
• Frequency Resilience
• Visualization
• Modelling
• What is Next?
Microgrid Examples
## PowerMAX® System Family Tree

<table>
<thead>
<tr>
<th>PowerMAX Technology</th>
<th>Typical Customer</th>
<th>System Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilities</td>
<td>Bulk Electric Power Transmission &amp; Generation</td>
<td>&gt; 1 GW</td>
</tr>
<tr>
<td>Industrial Power Management</td>
<td>Oil &amp; Gas, Heavy Industries</td>
<td>&gt; 100 MW</td>
</tr>
<tr>
<td>Commercial Microgrids</td>
<td>Communities, Universities</td>
<td>&gt; 10 MW</td>
</tr>
<tr>
<td>Garrison Microgrids</td>
<td>Fixed Military Installations</td>
<td>&lt; 10 MW</td>
</tr>
<tr>
<td>Mobile Microgrids</td>
<td>Disaster Relief, Forward Operating Bases</td>
<td>&lt; 0.5 MW</td>
</tr>
</tbody>
</table>
POWERMAX® Experience Uncontested
Over 28,000 MW in Service Worldwide
# How Others Use SEL Equipment for Microgrids and DERs

<table>
<thead>
<tr>
<th>Segement</th>
<th>Simple Microgrids</th>
<th>Simple DER PCC Interconnection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Relays</td>
<td>Relays, RTACS + Grid connect library</td>
</tr>
<tr>
<td>Project Funding</td>
<td>any</td>
<td>Independent power producers or Utilities</td>
</tr>
<tr>
<td>Customer Examples</td>
<td>Entergy</td>
<td>Utilities - XM (Columbia) Southern companies, Also Energy, New York Power Authority with Tesla batteries</td>
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<tr>
<td>Approximate Project Cost</td>
<td>$5K</td>
<td>$20K</td>
</tr>
<tr>
<td>Approximate Project Size</td>
<td>&lt; 10MW</td>
<td>&lt;100MW</td>
</tr>
<tr>
<td>ES office</td>
<td>Local Office</td>
<td>Local Office</td>
</tr>
</tbody>
</table>
PowerMAX® for Utilities is Purpose Built for Gigawatt Scale Generation
PowerMAX® for Industrials
Designed for Heavy Industrial Customers
PowerMAX® for Commercial Customers
Award Winning Controls for Complex Grids > 10MW

The Navigant Research Leaderboard Grid

Followers
Challengers
Contenders
Leaders

- Emerson Automation Solutions
- S&G Electric
- Sprae
- ABB
- Eaton
- Lockheed Martin
- Opus One Solutions
- EnCorp
- PowerSecure
- Siemens
- Schneider Electric
- Schweitzer Engineering Laboratories

Source: Navigant Research (used with permission)
Paris Island PowerMAX® Garrison

- Awarded to Ameresco via ESPC
- SEL PowerMAX being commissioned now

“This is most comprehensive seamlessly integrated DoD Project” - Ameresco
PowerMAX® Mobile Technology
Interoperable, Simple solution for <0.5MW Microgrids

- Red Cross
- FEMA
- Private Disaster Relief
- Forward Operating Base (FOBB)
Microgrid Challenges
Protective Relays Are Mandatory
Protect Assets, Environment, and People
Not Resilient
Power System Split Into Six Islands Collapses

<table>
<thead>
<tr>
<th>Time</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:25</td>
<td>51</td>
</tr>
<tr>
<td>6:25</td>
<td>50.5</td>
</tr>
<tr>
<td>7:25</td>
<td>49.5</td>
</tr>
<tr>
<td>8:25</td>
<td>50</td>
</tr>
<tr>
<td>9:25</td>
<td>51</td>
</tr>
<tr>
<td>10:25</td>
<td>50.5</td>
</tr>
</tbody>
</table>

Island 1
Island 2
Island 3
Island 4
Island 5
Island 6
Resilient
Same Six Islands With Mature Microgrid Technology
Frequency and Voltage are Resilience Metrics

- Frequency (Hz)
- Voltage (V)

**Generation Shedding**

**Load Shedding**

**Allowable Operation**

- Frequency: 65 Hz
- Voltage: 0.7 V

- Frequency: 63 Hz
- Voltage: 0.8 V

- Frequency: 57 Hz
- Voltage: 1.3 V

- Frequency: 55 Hz
- Voltage: 1.2 V

- Frequency: 1.3 Hz
- Voltage: √2V

- Frequency: 1.2 Hz
- Voltage: 2V

**Inverter Technology**

**Rotating Generator Sets**

**t**
Engines Cannot Respond Instantaneously
Frequency Decay Is Extraction of Kinetic Energy From Inertia

Note Lag in Response
System inertia (H) is $J \cdot (kg \cdot m^2)$ in terms of pu

$$H = \frac{J \cdot (kg \cdot m^2)}{MVA} = \text{seconds}$$

Frequency decay is driven by power disparity and inertia

$$\frac{df}{dt} = \frac{P_{\text{disparity}}}{2Hf}$$
Load Composition Affects Frequency Stability
Noninertial Effects

- Electric loads increase transients
- Motors reduce transients
Distributed Energy Resource (DER) Inverter-Based Generation Has Limited Overload Capacity

Rotating Generators

Inverter-Based Generation

Short-Term Capacity Limit

Long-Term Capacity Limit
Load Balancing Must Happen *Faster* With DER Inverter-Based Generation

Power, Frequency

- Rotating Generation Power
- Inverter-Based Power
- Rotating Generation Frequency
- Inverter-Based Frequency

Time

Load

Power

Frequency
Controller Must Understand DER Capability

- Q (MVAR) Turbine Capability
- Allowable Operational Region
- Operator-Entered Regulation Limits
- Generator Capability Curve

- Q (MVAR) Turbine Capability
- Allowable Operational Region
- Short-Term Capacity Limit
- Long-Term Capacity Limit

Operator-Entered Regulation Limits
Protection Must *Adapt* to Changing Fault Conditions

- Fault levels
- Grounding
- Directions
- Impedances
DER Inverter Behavior Is Subject to Human Preference

Inverter A
Fault
Current Limit

Inverter B
DER Inverter Behavior Is Subject to Human Error

- 4-Quadrant Battery
- Power-Only Battery
- Software Engineer Mistake
- Software Engineer Mistake
DER Inverter Phase-Locked Loops (PLLs) Fail When You Need Them Most

\[ V_d \rightarrow DQ \rightarrow \text{Mod.} \rightarrow \text{PWM} \]

\[ V_q \rightarrow ABC \rightarrow \text{PLL} \rightarrow \text{Measured Frequency} \]

\[ \text{Measured Frequency} \rightarrow \int \text{dt} \rightarrow \text{Best Guess Frequency} \]

\[ \sim 60 \text{ Hz} \rightarrow 4 \text{ kHz} \]

NERC

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California 8/16/2016 Event

June 2017
Design
Requirements for Technology

1. Safe
2. Reliable (resilient)
3. Economical
Relays Are the Foundation of Microgrid Controls

- Multifunction protection
- Remote I/O
- Metering
- Power quality monitoring
- Programmable logic controller function
- IEC 61850 compliance

- MIRRORED BITS® high-speed communications
- Continuous self-diagnostics
- Synchrophasors
- DC battery monitoring
- Front-panel interface that replaces all control switches and pushbuttons
Relays Provide Distributed Protection and Control for Small Microgrids

- Reconnection
- Load Shedding
- Short- and Open-Circuit Protection
- IEEE Compliance
- Power and Power Factor Control

Protection
- Governor and Exciter Dispatch
- Inverter Dispatch
- Load Sharing
- Voltage and Frequency Regulation

Reconnection
- Load Shedding
- Short- and Open-Circuit Protection
- IEEE Compliance
- Power and Power Factor Control

IEEE Compliance
- Power and Power Factor Control
Centralized Controllers Communicate to Relays

Visualization and Diagnostic System

SEL POWERMAX Control Systems

Ethernet Communications Network

Substation

Substation Front-End Processor (FEP)

SEL-3555

SEL-3530-4

SEL-751

SEL-849

SEL-451

Other IED
Relay-Based Controls
Scale to Any Size Power System
Use Relays for Small Grids; Use Relays and Controllers for Larger Grids

Control Functionality in Relay (%)

Size of Islanded Grid (kW)

Community Microgrids  Industrial Microgrids  Bulk Electric Power Systems
Distributed Energy Resource (DER) is a catch-all name for traditional and intermittent sources.
IEEE 2030.8-2018 Requires Three Types of Mandatory Data Collection Which are in SEL relays!

Requirement

Sequence of Events (SOE)

Event oscillography

Continuous data collection
Reconnection
PCC Reconnection Is a Relay Function

Macrogrid

Microgrid

\[ \Delta V, \text{ Slip} \]

PCC Relay

\[ \Delta \delta \]

\[ V_{\text{MACROGRID}} \]

\[ V_{\text{MICROGRID}} \]

\[ \delta \text{ (slip)} \]

DER Relay

Dispatch
Synchronization Done Wrong

Synchronization Done Right
Seamless Islanding
PCC Disconnection Is Protective Relay Function

Current (A)

Voltage (V)

Relay

Loads
PCC Disconnection Is Protective Relay Function

- **Fault Starts**
- **Relay Trips**
- **Breaker Opens**
- **Microgrid Controller Sheds Load**
- **Load Current Interrupted**
- **Frequency Recovers!**
Fast 81RF Element Improves Seamless Islanding

IEEE 1547-2003

Frequency (Hz)

Microgrid Blackout

Trip Region

df/dt (Hz/s)

Macrogrid Disturbance

PCC Relay Trips

PCC Opens

81RF Microgrid Survival

PCC Trip

DER Trip

Conventional Blackout

PCC Opens

DER Trips

PCC Relay Trips
Fast 81RF Element Improves Seamless Islanding

IEEE 1547-2003

Microgrid Survives

Grid Connection

Load Shedding

PCC Opens

81RF Trips

Frequency (Hz)

Trip Region

Microgrid Blackout

df/dt (Hz/s)

Macrogrid Disturbance

PCC Relay Trips

PCC Opens

81RF Microgrid Survival

PCC Trip

DER Trip

Conventional Blackout

PCC Opens

DER Trips
Integrated Relays and Controllers Provide Resilient Behavior
Seamless Islanding Requires Fast Load Shedding

- Grid-Tied Operation
- Automatic Decoupling
- Load Shedding
- Synchronization Systems
- Islanded Operation
- Subcycle FAST

Controller
- Relay
  - Status
  - Trip
Make Sure Your Controller Is up to the Task

- Process Control Systems
- Industrial Control Systems
- SEL Controllers

Load-Shed Time (ms) vs Quantity of IEDs
Fast and Scalable Architectures Are Required

- **Small (<20 ms)**
  - Controller
    - Scan Time: 2 ms
  - 20 Relays
    - Scan Time: 2 ms

- **Medium (<30 ms)**
  - Controller
    - Scan Time: 2 ms
  - Substation FEP
    - Scan Time: 2 ms
  - 200 Relays
    - Scan Time: 2 ms

- **Large (<40 ms)**
  - Controller
    - Scan Time: 2 ms
  - Central FEP
    - Scan Time: 2 ms
  - Substation FEP
    - Scan Time: 2 ms
  - 1,000 Relays
    - Scan Time: 2 ms
Contingency Load-Shedding Calculation

\[ L_n = P_n - \sum_{g = 1}^{m} IRM_{ng} \]

where:

- \( n \) = contingency (event) number
- \( m \) = number of generators in system
- \( g \) = generator number, 1 through \( m \)
- \( L_n \) = amount of load selected for \( n \) event (kW)
- \( P_n \) = power disparity caused by \( n \) event (kW)
- \( IRM_{ng} \) = incremental reserve margin of all remaining generators after \( n \) events (kW)
Inertial Based Load-Shedding Systems
Operate when a Contingency Load Shedding System is out of service

- Broken wires
- DC battery failures
- Breaker contact failures
- Governor problems
- Fuel or air problems
- Improper maintenance
- Incomplete commissioning
Inertia and Load Composition Compensated
Load Shedding Systems stop Blackouts

<table>
<thead>
<tr>
<th>MW Load to Shed</th>
<th>DFDT</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 0.5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.5 to 1.0</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>&gt; 1.0</td>
<td>12</td>
</tr>
</tbody>
</table>

Load Shed ~ H • DFDT = 8 • 1 = 8 MW
Load Shed ~ H • DFDT = 4 • 2 = 8 MW
Fast Load Shedding Makes Seamless Islanding Possible

- Fastest
  - Contingency based
  - Inertial compensated
  - Frequency based
- Slowest
  - Overload
  - Manual
Frequency Resilience
What Affects Power System Resilience?

- Frequency response characteristic (FRC)
- Major disturbances
- Inverter misoperation
- Voltage and MVAR margins
- Frequency and MW margins
- Economics
FRC Example – Large Offshore Natural Gas Liquefaction Plant
Sudden 0.3 pu Load Increase

Frequency (Hz)

4% Drop

Locked

A

B

C
<table>
<thead>
<tr>
<th>Location</th>
<th>FRC Type</th>
<th>Calculation</th>
<th>FRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point A</td>
<td>Transient</td>
<td>$50 \cdot 0.3 / (50 - 48.7)$</td>
<td>11.5</td>
</tr>
<tr>
<td>Point B</td>
<td>Locked rotor (extraction mode)</td>
<td>$50 \cdot 0.3 / (50 - 48)$</td>
<td>7.5</td>
</tr>
<tr>
<td>Point C</td>
<td>System long-term (system droop characteristic)</td>
<td>$50 \cdot 0.3 / (50 - 49.4)$</td>
<td>25</td>
</tr>
</tbody>
</table>
Solutions for Poor FRC

- Use better engine and voltage controls
- Add inertia
- Add motor loads with windage
- Limit electronic loads with variable speed drive (VSD)
- Use batteries
- Include load shedding or curtailment
- Include generation shedding or runback
Step 1 – Identify Grid Time Constants

How Much Responsive Generation Is Required to Ensure Stability?

Steady-State Electrical Load

DER Frequency / Droop Controller

\[ \frac{1}{JS} \]

\[ \frac{1}{R} \]

Simplification

\[ \frac{R}{1 + S\tau_2} \]

Power System | \( \tau_2 \) (seconds)
--- | ---
Utility | 0.5–1.2
Microgrid | 0.25–2.5
Step 2 – Tabulate Incremental Reserve Margin (IRM)

<table>
<thead>
<tr>
<th>DER</th>
<th>Rating (kW)</th>
<th>IRM (%)</th>
<th>IRM (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic</td>
<td>200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Battery (slow)</td>
<td>1,000</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Battery (fast)</td>
<td>1,000</td>
<td>100</td>
<td>1,000</td>
</tr>
<tr>
<td>Steam extraction turbine</td>
<td>1,200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Combined heat and power</td>
<td>900</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>1,500</td>
<td>40</td>
<td>600</td>
</tr>
<tr>
<td>Diesel generator set</td>
<td>1,000</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>6,800</strong></td>
<td><strong>31.5</strong></td>
<td><strong>2,140</strong></td>
</tr>
</tbody>
</table>
Step 3 – Compare Total IRM to Largest Disturbance

<table>
<thead>
<tr>
<th>Event</th>
<th>kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small motor</td>
<td>200</td>
</tr>
<tr>
<td>Load commutated inverter drive</td>
<td>2,000</td>
</tr>
<tr>
<td>Large feeder</td>
<td>5,000</td>
</tr>
<tr>
<td>Small feeder</td>
<td>800</td>
</tr>
<tr>
<td>Available IRM</td>
<td>2,140</td>
</tr>
</tbody>
</table>

- Frequency (Hz)
  - 50
  - 49.4
  - 49
  - 48

DERs Will Trip
Visualization
Time-Synchronized Condition Monitoring
Load Selection Screens Teach Operators to Dispatch Grid Differently
**Simplified Graphics for Small Microgrids**

<table>
<thead>
<tr>
<th>GEN</th>
<th>STATUS</th>
<th>CONTROL ENABLE</th>
<th>RATING kVA</th>
<th>kW</th>
<th>kVAR</th>
<th>START/STOP TIMER (Sec)</th>
<th>EFFICIENCY (kWH/Gal)</th>
<th>FUEL REMAINING (HRS)</th>
<th>FUEL REMAINING (Gal)</th>
<th>WET STACKING ALARM</th>
<th>WET STACKING CONTROL STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gil1</td>
<td>On</td>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>36.0</td>
<td></td>
<td>Disabled</td>
</tr>
<tr>
<td>Gil2</td>
<td>On</td>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>38.4</td>
<td></td>
<td>Disabled</td>
</tr>
<tr>
<td>Tay1</td>
<td>On</td>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>67.0</td>
<td></td>
<td>Disabled</td>
</tr>
<tr>
<td>Tay2</td>
<td>On</td>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>73.5</td>
<td></td>
<td>Disabled</td>
</tr>
<tr>
<td>TQG1</td>
<td>On</td>
<td></td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>43.0</td>
<td></td>
<td>Disabled</td>
</tr>
<tr>
<td>TQG2</td>
<td>On</td>
<td></td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>41.3</td>
<td></td>
<td>Disabled</td>
</tr>
<tr>
<td>CAT1</td>
<td>On</td>
<td></td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>101.4</td>
<td></td>
<td>Disabled</td>
</tr>
<tr>
<td>CAT2</td>
<td>On</td>
<td></td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0.33</td>
<td>999</td>
<td>112.2</td>
<td></td>
<td>Disabled</td>
</tr>
</tbody>
</table>

**TOTAL kW**: 0.0 kW
**TOTAL kVAR**: 0.0 kVAR
**% P**: 0.0 %

**GEN ADD (%)**
current value: 0

**GEN ADD THRESHOLD**: 60 %

**GEN REMOVE (%)**
current value: 0

**GEN REMOVE THRESHOLD**: 30 %

**MIN # GENSETS**
current value: 0

**MIN # GENSETS**: 1
### Automatic Generation Control

<table>
<thead>
<tr>
<th>GENERATOR</th>
<th>DESCRIPTION</th>
<th>PRESENT P (MW)</th>
<th>MV BASE SETPOINT</th>
<th>MV LOWER REGULATION LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEN-8A</td>
<td>E24-P-0009A COT GENERATOR</td>
<td>0.02</td>
<td>BASE</td>
<td>5</td>
</tr>
<tr>
<td>GEN-8B</td>
<td>E24-P-0008B COT GENERATOR</td>
<td>0.02</td>
<td>BASE</td>
<td>5</td>
</tr>
<tr>
<td>GEN-8C</td>
<td>E24-P-0008C COT GENERATOR</td>
<td>0.02</td>
<td>BASE</td>
<td>5</td>
</tr>
</tbody>
</table>

### Voltage Control System

<table>
<thead>
<tr>
<th>GENERATOR</th>
<th>DESCRIPTION</th>
<th>PRESENT P (MW)</th>
<th>MV BASE SETPOINT</th>
<th>MV LOWER REGULATION LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEN-8A</td>
<td>E24-P-0009A COT GENERATOR</td>
<td>0.00</td>
<td>BASE</td>
<td>5</td>
</tr>
<tr>
<td>GEN-8B</td>
<td>E24-P-0008B COT GENERATOR</td>
<td>0.00</td>
<td>BASE</td>
<td>5</td>
</tr>
<tr>
<td>GEN-8C</td>
<td>E24-P-0008C COT GENERATOR</td>
<td>0.00</td>
<td>BASE</td>
<td>5</td>
</tr>
</tbody>
</table>
Simplified Load-Shedding Configuration

**PRIMARY LOAD SHED CONTINGENCIES**
- OK 1 - L1 TRIP
- OK 2 - G1 20kV TRIP
- OK 3 - G1 10kV TRIP
- OK 4 - G2 TRIP
- OK 5 - L2 TRIP
- OK 6 - G3 20kV TRIP
- OK 7 - G3 10kV TRIP
- OK 8 - G4 20kV TRIP
- OK 9 - G4 10kV TRIP
- OK 10 - TIE TRIP/BUS A
- OK 11 - TIE TRIP/BUS B

**SECONDARY LOAD SHED CONTINGENCIES**
- OK 15 - UNDER FREQ 1 BUS A
- OK 16 - UNDER FREQ 2 BUS A
- OK 17 - UNDER FREQ 1 BUS B
- OK 18 - UNDER FREQ 2 BUS B

**LOAD SHED CONFIGURATION**
- LSP1 CODE RUNNING: 339917
- CONTINGENCY: 1
- AVAILABLE CAPACITY (MW): 104.00
- MEASURED LOAD (MW): 108.00
- REQUIRED TO SHED (MW): 4.00
- SELECTED TO SHED (MW): 4.14
- 20 KV BUS: A B
- ENABLED: YES
- TRIGGER SIGNALS AVAILABLE: YES
- SATISFIED: YES

**UNDER FREQUENCY LOAD SHED (MW)**
- MW TO SHED AT LEVEL 1: 2.00
- MW TO SHED AT LEVEL 2: 2.00
Modeling
cHIL Modelling Mandatory for big PowerMAX jobs
Hardware-in-the-Loop (HIL) Testing Controls Quality

Macrogrid

Microgrid

PCC Controls and Protection
CT, PT, DI, DO

Hardware Interface

Real-Time Digital Simulator

Modbus
UDP

Dispatch and Load Shedding
DNP3

Automation Controller
IEC 61850

Macrogrid

Microgrid

Macrogrid

Microgrid

Loads

Photovoltaic and Battery System

Combined Heat and Power

Diesel Generator
Capturing Live System Dynamics Enables Engineers to Build Accurate Models

System Response to Unit Trip

Phase Angle of West Texas With Respect to UT Austin
Not All Simulation Software Is Appropriate for Testing Microgrid Control and Protection

<table>
<thead>
<tr>
<th>Function</th>
<th>Simplified</th>
<th>EMTP (Not Real Time)</th>
<th>EMTP (Real Time)</th>
<th>cHIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay coordination</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor angle stability</td>
<td>✔</td>
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<td>Frequency stability</td>
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<tr>
<td>Voltage collapse</td>
<td>✔</td>
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<td>Power flow</td>
<td>✔</td>
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<td>IRM / DRM and UF / OF coordination</td>
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<td>Voltage collapse</td>
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<tr>
<td>Motor starting</td>
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<td>FAT simulation</td>
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<tr>
<td>Operator training</td>
<td>✔</td>
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</tbody>
</table>
Testing Improves Quality
What Is Next?
“Self Driving” Power System
Publish - Subscribe Communications

Hi! I’m a generator.

Great! Send me data.
Complete Interoperability Between Generators of Different sizes & Manufacturers
Interoperable
Making All DERs Play Nicely Together

100 kW CAT

60 kW TQG

30 kW Taylor

30 kW Gillette

Loads

Loads

Loads

Loads

Loads
Resilience Mode
Superior Load Sharing and Frequency Control Performance

- No overshoot
- No integral windup
- No oscillations
- No tuning
- Fully interoperable

Engine Manufacturer

SEL State-Space Energy-Packet Controls

Frequency (Hz)

Power (W)
Conclusions

- Design for resilience
- Use relays for simple microgrid systems
- Use relays + centralized controllers for complex microgrid systems
- Test all controls and protection systems with cHIL
- Use OT SDN for networking and security