Lessons Learned From Hardware-in-the-Loop Testing of Microgrid Control Systems

E. Limpaecher, R. Salcedo, and E. Corbett
Massachusetts Institute of Technology Lincoln Laboratory

S. Manson, B. Nayak, and W. Allen
Schweitzer Engineering Laboratories, Inc.
Standardized Test Sequence for All Microgrid Controller Suppliers
Protective Relay at PCC Provides ~50% of Control Functionality

- Grid reconnection
- Unintentional islanding
- Protection for expensive assets
- IEEE 1547 compliance
- Metering
- Pass-through control
Microgrid Controller Load Shedding, Dispatch, and Islanded Regulation

- Load shedding
- Intentional islanding
- PCC dispatch
- PF control
- Voltage regulation
- Frequency regulation
Directional Current Protection (67) Opens PCC During Short-Circuit Conditions

High Current
Low Voltage
Normal Load Angle

Trip PCC
Fast (67)

Loads

Import

Export

PCC

Fault

\[ \vec{I} (+0.8 \text{ pf}) \]

\[ \vec{I} (-0.8 \text{ pf}) \]

\[ \vec{V} \]

\[ \vec{I} (-0.8 \text{ pf}) \]

\[ \vec{I} (+0.8 \text{ pf}) \]

Normal Loading
Relay Recording of Utility Disconnection Event in 2016

Fault Starts
Relay Trips
Microgrid Controller Sheds Load
CB Opens
Load Current Interrupted
Frequency Recovers!
Fast 81RF Element Detects Open Circuit Conditions

IEEE 1547-2003

Frequency (Hz)

Trip Region

Microgrid

Blackout

df/dt (Hz/s)

DF/DT Element Detects Open Circuit Conditions

Frequency (Hz)

60

57

PCC Relay Trips

PCC Opens

81RF Microgrid Survival

PCC Trip

DER Trip

Macrogrid Disturbance

PCC Opens

Conventional Blackout

t
Fast 81RF Element Improves Seamless Islanding

IEEE 1547-2003

Frequency (Hz)

df/dt (Hz/s)

Grid Connection

Load Shedding

PCC Opens

81RF Trips

Microgrid Survives

Microgrid Blackout

Trip Region

Macrogrid Disturbance

81RF Microgrid Survival

PCC Relay Trips

PCC Opens

DER Trips

Conventional Blackout

PCC Trip

DER Trip
Simple Grid Reconnecting Method Works With All DERs

Macrogrid

Microgrid

PCC Relay

Controller

DER

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

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

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

\[ \Delta \delta \]

\[ \Delta V \]

\[ \delta (\text{slip}) \]
<table>
<thead>
<tr>
<th>Problem to Mitigate</th>
<th>Load-Shedding Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency collapse</td>
<td>Fast</td>
</tr>
<tr>
<td>Voltage collapse</td>
<td>Fast</td>
</tr>
<tr>
<td>DERs out of step</td>
<td>Fast</td>
</tr>
<tr>
<td>Der overload</td>
<td>Slow</td>
</tr>
<tr>
<td>Synchronization assist</td>
<td>Slow</td>
</tr>
<tr>
<td>PCC curtailment</td>
<td>Slow</td>
</tr>
<tr>
<td>PCC demand charge avoidance</td>
<td>Slow</td>
</tr>
</tbody>
</table>

Subcycle (faster than 16 ms)

Slow (~1 second)
Controller Redispatches DER Power Contribution After Sudden Loss of Load
Controller Redispatches DER Reactive Power Contribution After Sudden Loss of Load

![Graph showing reactive power contribution over time for Diesel, BESS, PV, CHP, and Utility systems.](image-url)
The Ultimate: Triple Seamless Islanding Event!
Only Possible With Integrated Relays and Controllers
Triple Seamless Islanding Event Only Possible With Fast, Intelligent Load Shedding
MGC Drives Bus Voltage Back to Normal After Same Triple Islanding Event

![Graph showing bus voltage over time for different areas and events](image)
Relays and Controllers Work Together

PCC Relay

Grid-Tied Operation

Islanded Operation

Reconnection

Unintentional Islanding
## Differences Between Industrial and Community Microgrids

<table>
<thead>
<tr>
<th>Feature</th>
<th>Community Microgrid</th>
<th>Industrial Microgrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Reliability</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Payback Period</td>
<td>Years</td>
<td>Days</td>
</tr>
<tr>
<td>Intermittent Energy Sources</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Inverter-Based Generation</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>
Questions?