Microgrid Protection and Control Technologies

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Microgrid Evolution

Distribution Substation → Feeder N

- Power grid
- Circuit breaker
- Load
Microgrid Evolution

- Distribution Substation
- Feeder N

- Power grid
- Circuit breaker
- Load
- Energy source
- Smart inverter
Microgrid Evolution

Distribution Substation

Feeder N

- Power grid
- Circuit breaker
- Load
- Energy source
- Smart inverter
- Inverter for DC microgrid
- Control signal

Microgrid Central Controller
Microgrid Evolution

Diagram showing the evolution of a microgrid system, including components such as Distribution Substation, Feeder N, Power grid, Circuit breaker, Load, Energy source, Smart inverter, Inverter for DC microgrid, and Relay protection.
Microgrid Evolution

- Distribution Substation
- Feeder N
- Power grid
- Circuit breaker
- Load
- Energy source
- Smart inverter
- Inverter for DC microgrid
- Integrated signal
MG System Control: De-Centralized or Centralized?

Where is the balance?
Where is the global optimum with all the factors?
MG Requirements

Fundamental:
- Capable of operating at islanding and/or on-grid modes stably
- Mode switching with minimum load disruption and shedding during transitions
- After a transition, stabilize in a certain amount of time (how fast?)

Today’s:
- Decentralized peer-to-peer: no master controller or communication
- Plug-and-play concept for each component
- Transitions between modes
- Protection in the MG that does not depend on high fault current
- Voltage and frequency stability in islanding mode

Tomorrow’s:
- Layered control architecture: device – MG – grid, defined functions
- Device: local control and protection
- MG: info. exchange with device and grid, situation awareness, operation mode, power dispatch commands
- Limited dependence on MG control and communication
- Optimal power flow and energy utilization
- Standardize: modularized, plug-and-play
MG Requirements
Islanding Detection & Transition

Ride through

- Comply with IEEE 1547 in on-grid mode
- Voltage sag/swell ride through may be required for DER

Islanding detection

- Intentional and unplanned islanding
- Intentional: load shedding, system reconfiguration, device operation mode transition, system status broadcasting
- Unplanned: situation awareness, decision making,

Transition

- On-grid to islanding: load demand sharing, control the frequency and voltage within the safe ranges
- Islanding to on-grid: re-synchronize and re-connect to the grid, device operation modes transition
- Stabilization time and disruption level
MG Requirements
Operation Modes

Today’s:
- Droop control with artificial droop curves
- Different slopes to have different responses
- Applicable to P-f and Q-V control
- Open-loop, steady-state error
- No communication or central control required

Tomorrow’s:
- Secondary control in addition to droop control
- Secondary control: closed loop, zero steady state error
- Optimal power dispatch
- Communication needed
Technical Challenges and R&D Opportunities

MG control architecture
- Architecture
- Functionality definition of each component
- Interaction and collaboration between components
- Opportunities in both technology and cost

Communication
- Communication requirements and methods
- Sensors and data acquisition
- Opportunities in both technology and cost

Operation modes and transition
- On-grid mode: comply to IEEE1547, optimal DER utilization, grid services
- Islanding mode: frequency and voltage stability, optimal power flow
- On-grid to islanding: fast transition and stabilization, minimum load shedding and disruption
- Islanding to on-grid: re-synchronization and re-connection, minimum impact
- Opportunities in technology
Power Protection System

- **Ultimate emergency control:** Designed to prevent further damage and stabilize the power system during abnormal conditions by interrupting and isolating faulted or failed components from the system, as well as to provide safety for electrical workers and the public.

- Well established basic schemes since the early days of power systems attempt to achieve high level of reliability (security and dependability), speed, sensitivity, and selectivity.

- Modern digital relays maximize the conflicting requirements while adding flexibility, adaptability, communications and system integration.
Protection Systems Components

- **Sensing devices** (Instrument transformers, Temperature detectors, Pressure meters etc.)
- **Decision making devices** (Relays that detect abnormal or fault conditions and initiate protection actions such as circuit breaker trip command)
- **Switching devices** (Circuit breakers and other switchgear)
- **Power supply devices** (Batteries, Chargers, Pumps etc. that provide power for different elements of the protection system)
- **Control circuits** (Cables and other auxiliary connection and control equipment)
- **Communication channels and devices** (for communication assisted protection, remote indication, information storage etc.)
Protection Must Respond to Utility and MG faults

- **Utility faults:** Protection isolates the microgrid from the utility grid as rapidly as necessary to protect the microgrid loads.

- **MG faults:** Protection isolates the smallest possible section of the feeder to eliminate the fault.

Protection is one of the most important challenges facing the deployment of MGs!
Present MG Protection Philosophy

- Same protection strategies for both islanded and grid-connected operation.

- The main MG separation switch is designed to open for all faults. With the separation switch open, faults within the MG need to be cleared with techniques that do not rely on high fault currents.

- Microsources should have embedded protection functions and plug-and-play functionality.

- Peer-to-peer architecture without dependence on master device.
MG Example – AEP Testbed
## AEP Testbed – Base OC Relay Settings

<table>
<thead>
<tr>
<th>Protection</th>
<th>Relay</th>
<th>Up-stream SLG faults</th>
<th>Down-stream SLG faults</th>
<th>Line-to-Line faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>2</td>
<td>$I_d &gt; 15A$ delay=0 ms</td>
<td>$3</td>
<td>I_o</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>$I_d &gt; 15A$ delay=167 ms</td>
<td>$3</td>
<td>I_o</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>$I_d &gt; 15A$ delay=50 ms</td>
<td>$3</td>
<td>I_o</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>$I_d &gt; 15A$ delay=50 ms</td>
<td>$3</td>
<td>I_o</td>
</tr>
</tbody>
</table>

| 1st Back-up                 | 2     | $I^2t$ activation level $|I| > 480A$ |
|                             | 3     | $I^2t$ activation level $|I| > 225A$ |
|                             | 4     | $I^2t$ activation level $|I| > 125A$ |
|                             | 5     | $I^2t$ activation level $|I| > 125A$ |

| 2nd Back-up and under voltage protection | Relay | Peak current $|I| > 750A$ | Voltage power quality levels |
|------------------------------------------|-------|------------------|-------------------------------|
|                                          | 2     |                  |                               |
|                                          | 3     |                  | 50% under voltage delay 30 cycles |
|                                          | 4     |                  | 50% under voltage delay 20 cycles |
|                                          | 5     |                  | 50% under voltage delay 20 cycles |

*University of Wisconsin-Madison June 2007*
Distribution System with DG Protection Issues

General:
- Fault currents increase due to fault contribution from DGs, utility grid contributions at the same time decrease.
- Lack of overcurrent protection coordination
- Ineffective automatic reclosing
- Anti-islanding protection requirements

PE related:
- Power electronics can sense faults instantaneously and take action before high levels of fault current begin to flow.
- During a fault, DG can be controlled to be a voltage reduction device or an impedance alteration device to limit fault current.
- Traditional impedance-based fault current calculation/estimation methods may not work for power electronics interfaced DGs.

*Grid-connected mode: power control*  *Islanding mode: voltage control*
High Impedance Faults (HIFs)

- Faults with a fault current below pickups of conventional overcurrent (OC) protection
  - Incipient insulator failures
  - Fallen conductors on concrete, tree, soil, gravel, sand, asphalt, etc.
- $I_F < 100$ amps on grounded systems
- Rich harmonics and nonharmonics from random and nonlinear arcing
- Does not affect system operations in general
- Major public safety concern if related to a fallen conductor

Problem that gets even more difficult in microgrids!
MG Protection Challenges

Operating conditions are constantly changing:

- Intermittent DERs
- Network topology change including islanding
- Short-circuit currents vary (both amplitude and direction) depending on MG operating conditions
- Availability of a sufficient short-circuit current level in the islanded operating mode of MG.

A generic OC protection with fixed settings is inadequate. It does not guarantee fault sensitivity or selective operation for all possible faults!
MG Protection R&D Needs
Communication-Assisted and Adaptive Protection

- How to turn existing radial time-current-coordinated schemes into fast, selective, and sensitive, transmission system – like protection?
  - Incorporate existing protection devices (reclosers, sectionalizers, fuses)
  - Minimize additional transducers (CTs, VTs)

- What is the depth of protection awareness?
  - Complete MG state (topology, grid or island mode, type and amount of connected DERs)
  - Local and adjacent protection zones
  - Local protection zone only

- How to achieve reliable, fast, and cheap communications?
  - Bandwidth vs cost vs reliability

- What are the most appropriate backup protection schemes?

- What central (MG-level) protection functions are needed if any?
Microgrid Control and Protection
Present State Summary

- **Grid-connected operation**
  - Power control through current regulation
  - Power control through voltage regulation

- **Islanding operation**
  - Islanding detection
  - Load demand sharing
  - Load shedding

- **Microgrid protection**
  - Strategy independent of the mode of operation
  - Plug-and-play capable microsources
  - Peer-to-peer architecture
Active Power and Frequency Control

**On-grid**
- MPPT is a higher priority
- Response to high frequency
- Or can follow a P schedule

**Islanding**
- Frequency control is a higher priority
- 2 groups of DE and 2 control zones
- Frequency within $f_2$ and $f_3$: normal and only droop control
- Secondary control is kicked in when $f$ is out of normal range
Reactive Power and Voltage Regulation

- Voltage is a local variable
- Droop control is applicable
- Challenges:
  - Q sharing errors due to the impedances and local loads
    \[
    Q = Q_1 + Q_2 \\
    Q_1 = Q_{DER1} - Q_{Z1} \\
    Q_2 = Q_{DER2} - Q_{Z2} - Q_{Load}
    \]
  - Q circulation because of improper voltage references
- 3 approaches
  - Local voltages without communication
  - Local voltages with central dispatch
  - PCC voltage with central dispatch