Self-healing Control of Distribution Systems

Xuzhu Dong
China Southern Power Grid, EPRI

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Outlines

1. Introduction
2. Concept of Self-healing Control
3. Self-healing Control Technologies
4. Simulation and demonstration
5. Conclusions
Introduction – CSG Overview

- Main Business: TSO/DSO/Retail in Southern China
- Fortune Global 500 (2014): 115th
- Customers:
  - 71.9 million
  - Serving population: 230 million
- Generation Capacity: 225 GW
  - Clean Energy: 47%
- Peak Load: 136 GW
- Distribution asset: 207.5 B RMB (32%)
Introduction - Asset

- Number of 10 kV feeders: 56358
  - Length of feeders: 703953.2 km
  - Cables: 120077km (17.1%)

- Number of 10kV distribution transformers: 1.25 million (2013)

- Renewable energy
  - Wind: 6200 MW
  - PV: 460 MW

- Battery Energy Storage System (BESS)
  - Located in Shenzhen
  - Li-Ion Battery, 4MW, 4hrs
Introduction – Natural disaster

CSG service territory spans over 2000 km, with complex meteorological and geological conditions.

- Ice Storm
- Lightning
- Earthquake
- Typhoon
Introduction – Reliability

AIHC Comparison (2013)

AIHC has decreased over years

Ice disaster deceased power supply reliability in 2008
Distribution automation (DA) has been deployed in 39 cities with the purpose of:

- Shorten outage duration
- Improve measurability, observability, and controllability of distribution network
- Improve distribution asset utilization

Average outage duration:

W/o DA: 3.38hr /customer → 1.56hr /customer (W/ DA)
Introduction – Distribution Automation

- DA development at CSG:
  - Multi-function integration: FA -> DA -> DMS
  - Integration of DA with other information systems
  - Various communication means are applied: Fiber optic, PLC, GPRS, CDMA, TD-LTE, and etc

- Lessons: difficulty to justify the benefit from DA; maintenance cost of DA terminals is high due to their quality; communication is a challenge.
- New rules for DA deployment: simple, applicable, economic
Introduction – Drivers to Smart Distribution

- Expectation of higher reliability and better power quality.
- Friendly integration of large scale distributed generation (DG) and electric vehicles.
- More intelligent and flexible control.
- Efficient distribution asset management.

Solutions:

- Self-healing control technologies for distribution system.
- Active distribution systems.
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Concept of Self-healing Control

Definition:

➢ Inherits and advances distribution automation.

➢ Enables self-perception, self-diagnosis, self-decision making and self-restoration of the distribution system, with integration of a large number of DG, energy storage devices, and electric vehicle charge facilities.

Objective:

➢ Improves observability and controllability, thus to operate the system reliable, secure and economic.
Strategy of Self-healing Control
Phase 1: Preventive control (Pre-fault): In normal operation

- Optimize the system continuously, improve the robustness and minimize loss.

- Identify early signs of system risk and potential equipment fault with self-perception and self-diagnosis, the potential risk will be alarmed.

- System state transition: Optimal state <-> Secure state <-> Alert state
Phase 1: Preventive control (Pre-fault): In normal operation (Cont.)

➢ Preventive actions will be taken to avoid the potential failure. Possible actions:

➢ DG output regulation
➢ Load tap changer adjustment
➢ Capacitor bank switching
➢ Network reconfiguration

➢ Key technologies: risk assessment, system state identification, economic network reconfiguration, and coordination of DG control.
Phase 2: Emergency control (Inter-fault, Fault self-healing): When the fault occurs

- Perform intelligent fault detection, location, isolation, load transfer, and restoration (FLIR), with or without human intervention.

- With DGs and energy storage devices, minimize outage duration and limit the fault area.

- System state transition: Alert state <-> Emergency state <-> Island state

- Key technologies: FLIR, network reconfiguration, islanding with DGs/energy storage devices.
Phase 3: Post control (Post-fault): If the fault is cleared or isolated

- Restore all lost load, and return the system to the optimal status.

- System state transition: Restoration state <-> Alert state <-> Secure state

- Key technologies: Coordination of local control and main-station control, black start with DGs/energy storage devices, risk assessment, and network reconfiguration
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Self-healing Control Technologies

1. Mitigate the risk and minimize the loss (Pre-fault)

2. Critical load support with DG and ES (Inter-fault)

3. Accurate fault location to minimize affected customers (Inter-fault)

4. Minimize outage duration (Post fault)
Self-healing Control Technologies

- Fast simulation and modeling (DFSM)
- Critical load support with DG and ES
- 3-ph state estimation
- Coordination between local and master control
- Online risk assessment
Self-healing Control Technologies

- Distribution fast simulation and modeling (DFSM)
- Model database for distribution systems
  - Passive components
    - Overhead lines and cables
    - Transformers
    - Load
  - DGs (Steady state and transient models)
    - PVs
    - Wind turbines
    - Fuel cells
    - Micro turbines
    - Energy storage devices

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Self-healing Control Technologies

- **Distribution fast simulation and modeling (DFSM)**

- **Time-series based simulation**: Simulation and replica of the distribution system operation, and validation of various control strategies.

- Case study: Validation of control strategy with integration of energy storage device/ small hydro plant/ wind turbine, in order to keep certain power flow and voltage at the tie line.

Regulation with energy storage

**DG output**
Self-healing Control Technologies

- On line risk assessment

- Relative risk:
  
  \[ R = health\ index\ (H) \times\ importance\ index\ (I) \]

- Four levels of risk assessment:
  - Equipment
  - Feeder
  - Feeder group
  - System

Risk assessment and preventive control
Self-healing Control Technologies

- On line risk assessment

<table>
<thead>
<tr>
<th></th>
<th>Health</th>
<th>Importance</th>
<th>Risk</th>
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<td>2.32</td>
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<tr>
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<tr>
<td>Dis System</td>
<td>1.00</td>
<td>2.24</td>
<td>2.24</td>
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</table>

- Case study
  - Weather
    - Weakness evaluation
  - Customer criticality
  - Power quality
  - Load
  - Voltage

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Self-healing Control Technologies
Self-healing Control Technologies

- Coordination between local and master control for Fault location, isolation and load restoration (FLIR)
Simulation and Demonstration

62-node CSG Distribution System Case
Simulation and Demonstration

Case 1: Risk control before fault

- Objective: Elimination of voltage violation
- Tools: Time series simulation
- Actions: DG output regulation and network reconfiguration
  - PQ adjustment of the battery bank at Node 47
  - PQ adjustment of micro turbine at Node 42
- Results: Voltage at Node 47 is reduced from 1.0506 to 1.0499 p.u.

The 24-hour profiles of load and DG output

Voltage at Node 47
Case 2: Critical load support with DG by islanding

- Fault occurred between Line 44-45.
- Reconfiguration couldn’t take effect.
- Islanding with DG and energy storage devices to support the load within the island.
- BES as slack source in the island, is to provide voltage and frequency support.

<table>
<thead>
<tr>
<th>Nodes for load shedding</th>
<th>Nodes with critical load</th>
<th>Total output of DER /kW</th>
<th>Load /kW</th>
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<tbody>
<tr>
<td>45, 47-49</td>
<td>46, 60-62</td>
<td>1000</td>
<td>960.5</td>
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</table>
Simulation and Demonstration

- Sponsored by National High Technology Research and Development Program of China (863 Program): “Research and Development of Self-Healing Control Technology in Smart Distribution System”.

- Objective: To develop a smart distribution grid with diversified distributed generation, energy storage devices, with support of self-healing control. SAIDI is expected less than 5.2 min with completion of the project.

- Location: Guangdong High Tech Financial Service Park, Foshan, Guangdong

- Coverage:
  - Four substations
  - 23 feeders
  - 89 switch board rooms
  - Five DGs, including PVs, CHP, and BESS
Simulation and Demonstration
Simulation and Demonstration

Field fault test on a 10 kV feeder

- Objective: To validate the function of fault location, isolation, and load restoration (FLIR) of the self-healing control system.
Field fault test on a 10 kV feeder

- Fault is generated by switching on a 16ohm grounding resistance between Phase A and C.
Field fault test on a 10 kV feeder

- Results:
  - Fault duration: 94.2ms
  - Load restoration: 1.7s (1.5s delay on tie switch).
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Conclusion

- Self-healing control can improve distribution system reliability, reduce customer outage, and especially, help friendly integration and control of DG and energy storage devices.

- The proposed self-healing control system has been developed, tested, and implemented in a distribution network.
Together we make our grid smarter!

Thanks for your attention!

Dongxz@csg.cn