Restoration Methods and Applications in China and the Development of EPRI’s Restoration Tool

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Outline

• Background
• Functionary requirements of restoration tools
• System Restoration Navigator (SRN): the EPRI’s restoration tool
• Restoration tools in China
Outline

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  • Functionary requirements of restoration tools
  • System Restoration Navigator (SRN): the EPRI’s restoration tool
  • Restoration tools in China
Power System Restoration: Basic Concept

Following a complete or partial outage, dispatchers in the control center work with field crews to re-establish the generation and transmission systems and then to pick up load and restore service.
Power System Operating States

- Preventive Control
- Corrective Control
- Emergency Control
- Restorative Control
- Cascade Events

Transition due to control action
Transition due to a disturbance

Restoration State
Emergency State

Tom DyLiacco
Restoration Scenario
Collaborators

• EPRI: Pei ZHANG, Shanshan LIU, Kai SUN,
• WSU: Chen-Ching Liu
• SDU: Wei SUN
• Industry: En LU (Guangdong Power Grid)
  Dahu LI (Hubei Power Grid)
• HKU: Felix WU, David Hill, Zhijun QIN,
  Shunbo Lei, Chaoyi Peng
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• Functionary requirements of restoration tools

• System Restoration Navigator (SRN): the EPRI’s restoration tool

• Restoration tools in China
## Functionary Requirements for Restoration Tools

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Requirements of the Systematic Restoration Toolbox

**Generic Restoration Decision Support Toolbox**

Different strategies of restoration can be established within one framework.

**Adaptive Restoration Decision Support Toolbox**

Strategy of restoration can adapt different scenarios.
Challenges for generic restoration strategy construction

- Policies
- System Characteristics
- Constraints

Strategy-Oriented → Objective-Oriented
Restoration Process

Preparation
- Optimal Generator Start-up Sequence to Maximize Overall System Generation Capability

System Restoration
- Optimal Transmission Path Search and Power Flow Check to Implement the Sequence

Load Restoration
- Optimal Load Pick-up Sequence to Minimize Unserved Load
Generic Restoration Milestones (GRMs)

1. Ascertain System Status
2. Start Black Start Units
3. Find Path to Crank Non Black Start Units
4. Establish Transmission Grid
5. Pick up Load
6. Connect Islands
7. Returns to Normal Operation
8. Sectionalizing
9. Synchronize Islands
10. Establish Network
11. Build Island
12. Serve Area
13. Restoration
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From Off-line to On-line Tools

off-line decision support  on-line
Branch-bus Model to Breaker-based Model

- **Branch-bus model**: the order of restoration bus
- **Breaker-based model**: the breaker operation
Equivalent Problem in Graphic Theory

- The weighted graph for substation
- Weighting criteria: the priority operation of breakers, the constraints of breaker operation
- Equivalent problem: the shortest path problem, Dijkstra algorithm
Implementation

Calculation result: the sequence of switching operations can be searched, which is 20-17-14-3-15-18.
# Functionary Requirements for Restoration Tools

## Methodology
- **State-of-the-art**: Customized
- **Restoration Toolbox Requirements**: Generic

## Functionality
- **State-of-the-art**: Off-line
- **Restoration Toolbox Requirements**: On-line

## Renewables
- **State-of-the-art**: Switch-off
- **Restoration Toolbox Requirements**: Participation

## Implementation
- **State-of-the-art**: Operation
- **Restoration Toolbox Requirements**: Planning & Operation
Reliability Requirements

- Various participants: independent system operator (ISO), transmission owner (TO), distribution owner (DO), generation owner (GO)
- Restoration control should be coordinated for reliability (NERC, UCTE)
- Industry practice suggestion
  » Coordinate the **sizing** and **location** for load pickup (PJM)
  » DO picks up loads at the **amount /rate** specified by ISO/TO (IESO)
  » Wait for voltage and frequency to stabilize before picking up the next block of load (IESO)
Renewable’s Participation

Preparation

Optimal Generator Start-up Sequence to Maximize Overall System Generation Capability

System Restoration

Optimal Transmission Path Search and Power Flow Check to Implement the Sequence

Load Restoration

Optimal Load Pick-up Sequence to Minimize Unserved Load
Enabling Renewables in Load Restoration

- Manage the generation portfolio
  - Mindful of the *variability* and *uncertainty* of wind energy
  - Match load pickup amount with generation capability (subject to transmission constraints)
  - Timing to re-connect wind power plants: adequate reserve level
  - Guard against loss of wind energy contingency with *spinning reserve*
  - Perform frequency control with *responsive reserve*

![Graph showing active power output](image)
Enabling Renewables in Load Restoration

- Model extension with reserve constraints
  - Spinning reserve
    
    $\bar{P}_{\text{wind}i} \leq \sum_{j \in \Omega_{G}^{m}} \left( P_{Gj}^{m} + \tau_{j}^{m} R_{j} \right), \quad \forall i \in \Omega_{\text{windG}}^{m}$

  - Responsive reserve
    
    $K_{j}^{m} \leq \rho_{j} C_{j}$,
    
    $K_{j}^{m} \leq C_{j} - P_{Gj}^{m}$,
    
    $\max \{ |\bar{P}_{\text{wind}i} - P_{\text{wind}i}^{m}|, |\bar{P}_{\text{wind}i} - P_{\text{wind}i}^{m}| \} \leq \sum_{j \in \Omega_{G}^{m}} K_{j}^{m}$
Load restoration duration drops from 379 mins. to 333 mins.
# Functionary Requirements for Restoration Tools

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Black-start Resources Planning

- BS units installed on different buses (locations) significantly change the self-healing capability. The problem is: it is possible to change locations of BS units
FCB Units in Post-separation Controls

BS

FCB

IEEE Power & Energy Society
# Functionary Requirements for Restoration Tools

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• Functionary requirements of restoration tools
• System Restoration Navigator (SRN): the EPRI’s restoration tool
• Restoration tools in China
System Restoration Navigator (SRN)

The program has the following functional features:

• Following a complete or partial outage.

• Graphical user interface allows the user to enter or modify the input parameters, execution modules and view the outputs.

• Establish strategy automatically and interactively.
Objective and Constrains of SRN

- **Objective**
  Finding a *sequence* to crank generating *units* and to pick up *critical loads*, which is feasible and has shortest time duration.

- **Constrains**
  - Components characteristics
  - Operating constrains
  - Stability constrains
To minimize the total duration for restoring generating units

\[ f_S(x_i, \theta_S) = \min_{x_i \in \theta_S} \{ \Delta t_{x_i,x_j} + f_{S+1}(x_j, \theta_{S+1}) \} \]

**Primary problem:**
- Find sequence of generating units
- Find transmission path to implement this sequence

**Secondary problem:**
- Outputs of generating units at this stage
- Levels of loads at this stage
- Path to pick up dispatchable loads
- Energized block of the system
- Outputs of generating units at the last stage
- Levels of loads at the last stage

**Diagram:**
- Dynamic Programming
- Graph Search
- Binary Optimization
- Sequence of Generating Unit
- Sequence of Transmission Path
- Optimal Power Flow with Steady-State and Dynamic Constraints
- Power Flow Analysis
- Transient Stability
- Voltage Stability
- Small Signal Stability
- Interface with Commercial Software
Algorithms for GRM3~6

- **GRM3:** Serve Load in Area

- **GRM4:** Synchronize Electrical Islands
  - Finding path for synchronization
  - Adjusting voltages and phase angles
  - Closing breaks

- **GRM5:** Form Electrical Island
  - Pickup loads, establish transmission path
  - Adjusting voltages and phase angles

- **GRM6:** Connect with Neighboring System
  - the voltage in the neighboring system cannot be adjusted
Restoration from Arbitrary Initial State

• From arbitrary initial state
  ➢ Total blackout with one black start unit
  ➢ Total blackout with multiple black start units
  ➢ Partial outage with one survived island (defined by a PSS/E file)
  ➢ Partial outage with multiple survived islands (defined by a PSS/E file)
User interface of SRN

• Friendly User Interface
Running Modes of SRN

• Running modes

  ➢ **Automatic** — trying to find a feasible restoration plan with minimum users’ interaction

  ➢ **Iterative** — trying to crank one generating unit or critical load step by step under users’ instruction

  ➢ **Advisory** — performing feasibility check for optional generating units or critical loads in each step
Running Mode: Automatic

Calculation Settings

Search Depth:

4  (Within which to search unenergized generators)

Active Search Depth:

8  (Within which to search dispatchable loads)

Estimated Time for Cranking: 10  (Minutes)

- Trace back to previous step if no feasible power flow solution
- Voltage relaxation to (0.8~1.2) when no feasible solution can be found
- Ignore the charging capacitors of branches in power flow calculation
Automatic Mode: Robust Algorithms

• Robust algorithms in automatic mode
  - **Trace Back** — Go back to previous step, try to crank another generating units/critical load.
  - **Active Search** – Extend search depth to find dispatchable loads, and pick up dispatchable load if needed
  - **Constrains adjustment** — Relax normal operational constrains bounds to find a restoration plan
Running Mode: Iterative

System Restoration Navigator - Iterative Approach

Load Step: 0 (Select 0 for computation from initial state)
Search Depth: 4 (Within which to search unenergized generators)
Active Search Depth: 3 (Within which to search dispatchable loads)

Unenergized generators within the depth above:

<table>
<thead>
<tr>
<th>Bus Nbr</th>
<th>Component ID</th>
<th>Component Type</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>102</td>
<td>1</td>
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</tbody>
</table>

Estimated Time for Cranking: 10 (Minutes)

- Voltage relaxation from (0.9-1.1) to (0.8-1.2) when no feasible power flow can be found
- Ignore the charging capacitors of branches in power flow calculation

Calculate  Back  Close
Running Mode: Advisory

- Running mode-Advisory
Iterative mode and advisory mode: Summary

• Iterative mode and advisory mode
  ➢ Find NBS units within the assigned range
  ➢ Try to crank the selected unit
  ➢ Calculation setting can be adjusted by users
  ➢ Pre-defined restoration plan can be validated in these modes
  ➢ Active search is also provided
Transient Stability Constrains

• Check for transient stability constrains
  ➢ Energize transmission lines
  ➢ Energize transformers
  ➢ Energize bus bars of power plants/substations
  ➢ Pick up critical loads
  ➢ Crank NBS generating units
Finding Feasible Operating Points by OPF with Transient Stability Constraints

Perform an OPF
Set $k=1$, choose contingency $k$
Dynamic simulation and trajectory sensitivity computation.
At each time step $m$, monitor $\max (\delta_{ij})$

$\Delta P_{i,j} = \delta_j^0 - \delta_j^0 \frac{\partial \delta_{ij}}{\partial P_i} - \frac{\partial \delta_{ij}}{\partial P_j}$

$P_i^{\text{new}} = P_i^0 - \Delta P_{i,j}$
$P_j^{\text{new}} = P_j^0 + \Delta P_{i,j}$

$P_i^{\text{new}} \geq P_i^M$
$P_j^{\text{new}} \leq P_j^M$

Adjustment of each generating unit
Power flow limits of variables

- Standing angles involved in OPF
- Trajectory sensitivity technique

$$\Delta P_{i,j} = \frac{\delta_j - \delta_j^0}{\partial \delta_{ij} - \frac{\partial \delta_{ij}}{\partial P_i} \partial P_i - \frac{\partial \delta_{ij}}{\partial P_j} \partial P_j} \max \delta_{ij}=\pi$$

$$P_i^{\text{new}} = P_i^0 - \Delta P_{i,j} \quad P_j^{\text{new}} = P_j^0 + \Delta P_{i,j}$$
Finding feasible operating points by OPF with transient stability constraints
Transient Stability Constrains (Cont’d)

• Transient stability constrains

![Diagram showing transient stability constrains]

- Frequency
- Phase Angle Swing Curve
Integration with Experts’ Knowledge

• Integration with experts’ knowledge

Sequence

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<tr>
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Bus Number: 193
Generator ID: '1'
Sequence: 5 (Please input different number 1,2,3...)

[Update Sequence]
Integration with Experts’ Knowledge (Cont’d)

• Integration with experts’ knowledge

Milestone/Priority

User-Defined Milestone:

Generator Milestone:

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Integration with Experts’ Knowledge (Cont’d)

• Integration with experts’ knowledge

  ➢ Sequence to crank units can be input into SRN
  ➢ Milestone is defined to restore certain region/area
  ➢ Priority is defined within milestone
  ➢ Sequence and Milestone/Priority will be satisfied if no constrains are violated
  ➢ Experts’ knowledge will be guideline for SRN
Hawaiian Electric Company (HECO)

<table>
<thead>
<tr>
<th>Bus</th>
<th>Generator</th>
<th>Line</th>
<th>Transformer</th>
<th>Dispatchable Load</th>
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Find solution within 8 min
Outline

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• System Restoration Navigator (SRN): the EPRI’s restoration tool
• Restoration tools in China
Restoration Tools Development in China: Fast-Cut-Back Unit Applications

Development for self-healing decision support system

Risk accumulation Large scale blackout System self-healing

Modeling for FCB units

Steady model Dynamic model Numerical simulation

FCB test

Dynamic test Field test

Function analysis for FCB Identification for vulnerable area Evaluation for economic benefits

Establishment and evaluation for the planning of FCB

Enhancement for the vulnerable area based on FCB Self-healing strategy based on FCB
Fast-Cut-Back Unit’s Applications

• Non-blackstart unit significantly affects emergency control and restoration

• A generating unit with fast-cut-back (FCB) function can
  – reduce its output down to the auxiliary power level within seconds
  – restore to a normal level promptly

• The benefits of FCB units
  – to maintain generation balance during controlled separation
  – to reduce the restoration duration
FCB vs. Non-blackstart Unit

- Output of the FCB unit can be reduced to the auxiliary power instantaneously from a normal operating condition without the disconnection from the network after a blackout.
FCB Units in Post-separation Controls

BS

FCB
BPA data, off-line or on-line

Automatic mode

Optimal FCB location

Interactive mode

Data Management

Dta Manageme
<table>
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<tr>
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<th>中文名</th>
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On-line and Off-line Data
Field Test: Load shedding under 50% & 100% Loading
Load Shedding under 50% Loading

Load Shedding under 100% Loading
Field Test

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- **Speed (r/min)**: 20, 25, 30, 35, 40, 45, 50
- **Time (s)**: 2900, 2950, 3000, 3050, 3100, 3150, 3200

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- **Graphs and Data Analysis**: Includes various measurements and tests, such as speed, pressure, and temperature, with specific readings and trends.

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- **IEEE PES Power & Energy Society**: Logo and branding.
Voltage Simulation VS. Field Test

发电机励磁电压波形

机端电压波形

厂用电母线电压波形

主变高压侧电压波形

电压仿真与实地测试比较
Conclusions

• The systematic system restoration tools should involve generic methodology, on-line applications requirements, planning/operation considerations, and highly efficient algorithms.

• The current tools are still on the way.

• Renewables, microgrids, and storage systems provide new dimensions for system restoration.
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<td>Generic</td>
</tr>
<tr>
<td><strong>Functionality</strong></td>
<td>Off-line</td>
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</tr>
<tr>
<td><strong>Renewables</strong></td>
<td>Switch-off</td>
<td>Participant</td>
</tr>
<tr>
<td><strong>Implementation</strong></td>
<td>Operation</td>
<td>Planning &amp; Operation</td>
</tr>
</tbody>
</table>
Self-healing Grids

On-line Tools
Renewable Participation
Adequate Resources
Generic Methodology

Restoration
- Customized
- Off-line
- Switch-off
- Operation

Self-healing
- Generic
- On-line
- Participant
- Planning & Operation
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