Distributed Control and Intelligence Using Multi-Agent Systems

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Underfrequency Load Shedding (UFLS)

• Conventional UFLS schemes
  — In operation for decades;
  — Local decision by relays distributed in various locations (no communication);
  — Developed by off-line analysis;
  — Excessive or insufficient load shedding is not uncommon.
Underfrequency Load Shedding (UFLS)

• Centralized UFLS schemes
  — Optimal load shedding decision can be achieved;
  — Relevant information must be transmitted to a central processing facility;
  — Optimization calculation is performed;
  — Delay of a measurement may result in a slow response of the global computational process.
Underfrequency Load Shedding (UFLS)

• Distributed UFLS schemes
  — Distributed computation with information sharing;
  — Adaptive for contingency scenarios and operating conditions;
  — Adaptive to a change in system topology;
  — Amount of load to be shed may not be optimized for lack of global information;
  — Effectiveness is the goal, e.g., quickly stop the frequency decay beyond a tolerance of frequency deviation.
Distributed UFLS

• Agent framework
  – Classifications
    ▪ Power plant agent (PA)
    ▪ Substation agent (SA)
  – Sensors
    ▪ Phasor measurement unit (PMU)
    ▪ Phasor data concentrator (PDC)
    ▪ Circuit breaker monitor (CBM)
  – Actuators
    ▪ Relays and circuit breakers
Distributed UFLS

• Multi-agent based UFLS scheme
  — Monitoring step
    ▪ $f_i$: out of frequency range [59.8, 60.2];
    ▪ $\frac{df_i}{dt}$: in the frequency derivative range [-1.0, -0.3];
    ▪ Results of both triggers must be true to activate the estimating step.
  — Estimating step
    $\Delta P_{G_j}(t_0) = \frac{2H_j S_j}{f_n} \cdot \frac{df_j(t)}{dt} |_{t=t_0}$  \hspace{1cm} $\Delta P_i(t_0) = \sum_{j=1}^{M} \Delta P_{G_j}(t_0)$
    $M$ is the number of generators that belong to agent $i$. 
Distributed UFLS

• Multi-agent based UFLS scheme
  — Distributing step
    ▪ Distributed load shedding amounts should be determined quickly;
    ▪ Load buses closer to generators are more effective;
    ▪ Bus voltage magnitudes and angles are acquired from PMUs locally, and shared by *reaching agreement* among agents.
Reaching Agreement

• Sharing information among agents
  – Consensus problem
    ▪ Each agent has an initial state and all agents must agree on the same value in the final state (not necessarily the original initial state).
  – Average-consensus problem
    ▪ Each agent has an initial state and all agents agree on the average of their initial states;
    ▪ If the initial state of an agent is a vector, the average of the corresponding elements among all vectors is reached and a state with the same dimension is obtained.
Reaching Agreement

- **Problem formulation**
  - A network of $n$ agents is modeled as a directed graph, denoted by $G = (V, A)$;
  - $V = \{1, 2, \ldots, n\}$ is the set of agents;
  - The topology of this network is specified by a nonnegative $n \times n$ adjacency matrix $A = [a_{ij}]$;
  - If an active communication link exists from agent $i$ to agent $j$, $a_{ij}$ is a positive value, otherwise $a_{ij} = 0$;
  - The state of agent $i$ at time $t$ is denoted by $x_i(t)$, which can be a single value or a vector with $m$ elements.
Reaching Agreement

- Protocol - average consensus method


- \( x_i(t) = u_i(t) = \sum_{j=1}^{n} a_{ij}(x_j(t) - x_i(t)) \)

- \( \Delta = \text{diag}(\sum_{j=1}^{n} a_{1j}, \ldots, \sum_{j=1}^{n} a_{ij}, \ldots, \sum_{j=1}^{n} a_{nj}) \)

- \( L = \Delta - A \)

- \( X(t) = \text{col}(x_1(t), x_2(t), \ldots, x_n(t)) \)

- \( \dot{X}(t) = (A - \Delta)X(t) = -LX(t) \)

- \( L \) is the Laplacian matrix, \( A \) is the adjacency matrix, and \( \Delta \) is the degree matrix;

- The diagonal element of \( \Delta, \sum_{j=1}^{n} a_{ij} \), denotes the number of agents.
Reaching Agreement

- Sharing information among agents

  - Average-consensus problem
    - To reach \((1/n)\left(\sum_{i=1}^{n} x_i(0)\right)\) by applying inputs \(u_i(t)\) that only depend on the state of agent \(i\) and the states of its neighboring agents in a dynamic graph;
    - \(x_i(0)\) is the initial state of agent \(i\) at time \(t = 0\);
    - Communication network topology is balanced;
    - If agents \(i\) and \(j\) are not connected directly or \(i = j\), then \(a_{ij} = 0\); Otherwise, \(0 < a_{ij} = a_{ji}\).
Distributed UFLS

<table>
<thead>
<tr>
<th>Agents</th>
<th>PA1</th>
<th>PA2</th>
<th>PA3</th>
<th>PA4</th>
<th>PA5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>2, 30</td>
<td>6, 31</td>
<td>25, 37</td>
<td>29, 38</td>
<td>39</td>
</tr>
<tr>
<td>Initial Values</td>
<td>[-16.59, 0, 0, 0, 0]</td>
<td>[0, -63.37, 0, 0, 0]</td>
<td>[0, 0, -23.71, 0, 0]</td>
<td>[0, 0, 0, -78.72, 0]</td>
<td>[0, 0, 0, -425.34]</td>
</tr>
</tbody>
</table>

Information sharing process of five PAs (from the perspective of PA1)

$$\overline{\Delta P} = 5 \times \text{sum}([-3.322, -12.692, -4.738, -15.672, -85.121]) = -607.73 \text{ MW}$$

![Graph showing active power imbalance over iterations for five PAs](image)
Distributed UFLS

• Comparison – “Advanced” load shedding strategy

<table>
<thead>
<tr>
<th>Relay Group</th>
<th>G1 – 1st Group</th>
<th>G2 – 2nd Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Shedding in Each Step</td>
<td>2.5%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Number of Steps</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Frequency Threshold (Hz)</td>
<td>59.8, 59.72, 59.64, ..., 59.08</td>
<td>59.0, 58.9, 58.8, ..., 57.5</td>
</tr>
<tr>
<td>Frequency Derivative Threshold (Hz/s)</td>
<td>[-1.0, -0.3]</td>
<td>NULL</td>
</tr>
<tr>
<td>Time of Frequency Measurement (s)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Time to Open the Circuit Breaker (s)</td>
<td>0.075</td>
<td>0.075</td>
</tr>
</tbody>
</table>
## Distributed UFLS

### Contingency scenario

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Event</th>
<th>Active Power from SI to NI (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Tripping of line 6-11</td>
<td>320.48</td>
</tr>
<tr>
<td>1.5</td>
<td>Tripping of line 4-14</td>
<td>264.05</td>
</tr>
<tr>
<td>2.2</td>
<td>Tripping of line 16-17</td>
<td>238.96</td>
</tr>
</tbody>
</table>

Total active power deficiency in NI: 823.49 MW

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Power grid splitting

North Island

South Island
Distributed UFLS

• Comparison

![Comparison of load shedding distribution](image)
Distributed UFLS

• Comparison

<table>
<thead>
<tr>
<th>Methods</th>
<th>Advanced</th>
<th>Multi-agent based distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Decay Ends (sec)</td>
<td>8</td>
<td>4.5</td>
</tr>
<tr>
<td>Active Power Load (MW)</td>
<td>643.35</td>
<td>607.73</td>
</tr>
<tr>
<td>Reactive Power Load (MVAR)</td>
<td>162.07</td>
<td>83.79</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>59.8</td>
<td>59.86</td>
</tr>
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</table>

643.35 - 607.73 = 35.62 MW
162.07 - 83.79 = 78.28 MW

System responses (no secondary control)
Agent-Based Modeling: Market Rules Evaluation

• Evaluation of market rules
  – Complexity of the market structure
    • Strategic interaction between participants;
    • Underlying physics.
  – Difficult to evaluate implications of potential changes to market rules;
  – Day-ahead market (DAM) is modeled as a MAS;
  – Each participant is modeled as an agent.
Agent-Based Modeling: Market Rules Evaluation

- System structure and message flowing sequence
Architecture of MASs

• Strategic power infrastructure defense (SPID) system
  – Hierarchical, layered multi-agent system concept;
  – Hybrid multi-agent system model.
Distributed Control

• Distributed control systems (DCSs)
  – Control units are distributed throughout the system;
  – Large, complex industrial processes, geographically distributed applications;
  – Utilize distributed resources for computation with information sharing;
  – Adapt to contingency scenarios and operating conditions;
  – Self-adapt to a change in system topology.
Distributed Intelligence

• Distributed artificial intelligence (DAI)
  – Used by distributed solutions for complex problems that require intelligence;
  – Based on different technologies, e.g., distributed expert systems, planning systems, or blackboard systems;
  – Closely related to the field of MASs;
  – Consisting of autonomous learning agents;
  – Agents are often heterogeneous.
  – Example: VOLTTRON by Pacific Northwest National Lab
For Further Information


