Resilient and Sustainable Electric Power and Communications Infrastructures

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NSF RESIN: Resilient and Sustainable Interdependent Electric Power and Communications Systems
Definition of Robustness and Resilience

- **Robustness** to a class of perturbations is defined as the ability of a system to maintain its normal state under the application of any perturbations of this class.

- **Resilience** to a class of unanticipated failures is defined as the ability of a system to gracefully degrade and to quickly self-recover to a normal state (self-heal).
Resilient Power and Communications Systems

- **Robustness:** We are extending the Highly Optimized Tolerance (HOT) approach developed by Carlson and Doyle (1999) to multiple events and multiple resources while modeling dependent cascading failures.

- **Resilience:** We are developing a multiagent distributed control scheme together with a communication system of a collection of microgrids connected to a power distribution system.

- **Trade-off between robustness, resilience and sustainability:** It is formulated as a risk-based optimization problem in the design process.
Multiagent System for Microgrid Control

Retail Market

Multiagent System Performing a Distributed Control

Communication Network

Microgrid

Microgrid

Microgrid

Microgrid

Microgrid

Microgrid

Microgrid

Microgrid
Resilient Power and Communications Systems

• Development of new resilient communications protocols for Power Grid (other than IEC 68150):
  • Some applications require fast data transfer while others can tolerate more latency;
  • Design communication protocols so that the control/protection tasks can be effected in time.
  • Apply HOT to optimally place barriers in interdependent power and communications systems

• Development of multi-scale decision theory for hierarchical decision making in a self-healing network to achieve resiliency
We are carrying out studies in:
- Topology Evaluation
- Congestion control
- Hierarchical decision making for routing protocols

A testbed for practical control scheme is being developed:
- Improved accuracy in simulation
- Best way to study interdependency
- Useful for future applications
Discrete System Simulation (Network)

- Event-driven
- Advance to the next event on the timeline
- Events call their associated processes
- Process can generate and eliminate events
- Simulation stops when there are no events left or certain process is called

Timeline

T0  T1  T2  T3  T4

Event 1
e1_proc1
e1_proc2
e1_proc3
... 
e1_procn

Event 2
e2_proc1
e2_proc2
... 

Event 3
e3_proc1
... 

Event 4
e4_proc1
e4_proc2
e4_proc3
... 

........
Continuous System Simulation (Power)

- Advance states by solving differential equations
- Each iteration increase the timeline by $\Delta t$
- Simulation stops when reaching a predefined duration
Co-Simulation (Power + Network)

- Treat continuous states as discrete events
- Share timeline and data
Error-resilient Data Fusion (ERDF)

• Use of error-resilient data fusion (ERDF) methodology to provide real-time adaptive multi-agent capability for microgrids in client-server (CS) and peer-to-peer (P2P) network environments
  • overcomes network communications breakdowns and decision making error
  • provides time-advantage for taking action to adapt
• P2P enables concurrent agent action
• integrates emergent systems capability
Error Resilient Data Fusion (ERDF)

- ERDF methodology works for multiple agents in client-server (CS) and peer-to-peer (P2P) network environments.

- The number of microgrid agents in a power park can be controlled to maximize error-resilient efficiency in CS and P2P situations.

- Other properties of the data fusion process such as the complexity of the decision task, agent preferences and reliability, and voting system effect ERDF efficiency.

- P2P ERDF systems avoid single-point-of-failure issues connected with CS systems, but P2P ERDF systems may not operate as efficiently when the number of microgrid agents is increased.

- The tradeoffs between CS and P2P ERDF performance may be clarified experimentally by taking account of systemic, operational attributes that explain deviation from predictions.
Centralized Data Fusion

Normal Data Flow

10 Microgrids choose A or B

Abnormal data flow

Majority choice cannot be found
Peer-to-Peer Data Fusion

Normal Data Flow

Abnormal Data Flow

Failed Microgrid

Complete data flow, Majority choice can be found  Concurrent action possible
Peer-to-Peer Data Fusion

Normal Data Flow

Abnormal Data Flow

Failed Microgrid

- Microgrid 1
- Microgrid 2
- Microgrid 3
- Microgrid 4
- Microgrid 5

NETWORK

Incomplete data flow, Majority choice unclear No concurrent action
• Development of theoretical foundations of a two-level sustainability assessment framework (SAF):
  • **Upper level**: multicriteria analysis and optimization approach to determine the most sustainable communications network and global energy and technologies mix consistent with the criterion of resiliency.
  • **Lower level**: an environomic approach to assess and optimize, in greater detail, the results targeted by the upper level as the most promising for overall sustainability and resiliency.
Elements for achieving this goal:

- Inventory of existing sustainability metrics and methodologies. Sensitivity assessment of subjectivities due to the choice of boundaries and damage assessment methodologies.

- Use of the thermodynamic concept of exergy as a common metric across SAF levels.

- Development and integration into the two-level SAF of a set of metrics and methodologies.

  - Application and validation of the upper-level SAF to a Northwestern European power utility network with micro-grids test-bed.
  - Development of the thermodynamic model and the exergy analysis of a Brazilian 600 MWe CC Power Plant test bed configuration as part of the lower-level SAF.
Sustainable Power Systems

- Development of different micro-grid configurations (20, 110 and 200 MWe) including renewables and non-renewables tied to an NE European network; will be used in a first application of an upper-level SAF.

![Graph showing total load demand vs. time (hour of the day) with reserve margin, peak load, intermediate load, and base load.]

<table>
<thead>
<tr>
<th>Size (kWe)</th>
<th>20,000</th>
<th>110,000</th>
<th>200,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Customers</td>
<td>1300 residential, 1 commercial, 1 industrial</td>
<td>2800 residential, 10 commercial, 5 industrial</td>
<td>7000 residential, 15 commercial, 10 industrial</td>
</tr>
<tr>
<td>Base load (kWe)</td>
<td>9,000</td>
<td>46,000</td>
<td>90,000</td>
</tr>
<tr>
<td>Intermediate load (kWe)</td>
<td>4,000</td>
<td>29,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Peak load (kWe)</td>
<td>3,000</td>
<td>13,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Total load (kWe)</td>
<td>16,000</td>
<td>88,000</td>
<td>160,000</td>
</tr>
<tr>
<td>Reserve margin (kWe)</td>
<td>4,000</td>
<td>22,000</td>
<td>40,000</td>
</tr>
</tbody>
</table>
• Development of an exergy and exergoeconomic analysis of a 1.5 MW SOFC/GT, 272.8 MWe Combined Cycle and a 1.0 MWe Wind Turbine configuration as part of the lower level SAF development.
Review of the inventory of existing sustainability metrics and methodologies, including EcoInvent, the US-LCA and the US-EPA databases and the CO$_2$-eq and Ecoindicator 99 environmental indicators; for use in the upper/lower level SAF.

[GER-4194, The 7FB: The next evolution of the F gas turbine, R. Eldrid et al.]