DDDAMS-based Real-time Assessment and Control of Electric-Microgrids

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DDDAS Program PI Meeting, IBM TJ Watson, NY
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December 2014
Outline

➤ Motivation

➤ Proposed DDDAMS Framework
  • Measurements and Data Collection
  • A1: Fault Detection and Isolation
  • Agent-based Simulation of MGs
  • A2: MG Control Design Selection
  • A3: Multi-Objective Optimization

➤ Experiments and Results

➤ Conclusion and Future Work
USA and Canada, August 2003: Affected 55 million people

Italy, September 2003: Affected 55 million people

Java and Bali, August 2005: Affected 100 million people

Brazil and Paraguay, November 2009: Affected 87 million people

India, July 2012: Affected 670 million people

**Economic Losses (in Billion $)**

- **Direct Effect Loss Earning**
- **Indirect Effect Loss Earning**
- **Industry and Residents**
- **Government**
- **Power Industry**
- **Total Economic Impact**
Motivation for a Safety-critical Air Force Base

Several questions arise in case of a power outage that affects an AF Base:

• How should a real-time diagnosis and forensics analysis be performed automatically?
• Was the root cause a technical incident or a power contingency?
• Did it occur because of an accidental failure or malicious and possibly ongoing attack?
• A wide spread disturbance or just a localized outage of a few minutes?
• How should the AFB microgrid respond to this abnormality (or catastrophe)?
• What actions should be taken to secure the AFB power supply?

Quick responsive and corrective actions are needed via autonomous control for **System Resilience**
Challenges in Power Dispatch

Objectives: Min Cost & Emissions
Constraints: Power Balance

To produce electricity economically, environmentally, reliably, and securely

...about power networks
- large # of variables, nonlinearities, and uncertainties
- operate at various scales
- resources => more distributed
- generation => more intermittent
- system => more conducive to demand-response

...about dispatch control
- changing demands
- very large range for the solution space
- Intense and time-critical information exchange
- significant burden on computational resources (processing of massive datasets)
Proposed DDDAMS Approach

- Originates from the DDDAS paradigm that was first introduced by Darema (2000)
- Investigates new algorithms and instrumentation methods for RT data acquisition and timely control of electricity microgrids in AF bases
- Dynamically incorporates data into an executing application simulation
- Dynamically steers the measurement process
- Accurate analysis and prediction, precise controls, and reliable outcomes
- Other application areas include
  - Natural disaster forecasting
  - Social and behavioral cognition
  - Biological system prediction
  - Supply chain management
  - Contaminant tracking...
Investigates new algorithms and instrumentation methods for RT data acquisition and timely control

Self-configuring fidelity formation and adaptation

=> Information needs to be updated wisely in the model for savings in computing and networking resources

Estimation of system states under uncertainty

Modular modeling
Collection of Data from Various Sources

- Effective control of microgrid systems requires all-embracing acquisition of data about major system components
- Fluctuating demand profiles, power generation (conventional /renewable), differences in power planning technologies, costs and availabilities of primary energy resources, transmission/distribution capacities etc.

AFB Site Visits
- Tyndall AFB map
- Energy consumption in the base
- List of AF bases with renewables
- Structure of the electricity network in base
- Voltages and angles for buses
- Power losses in branches
- Apparent power for the transformers

Power generation/ Energy consumption from the AF, NREL, and EIA

CMP-11 Pyranometer
- Solar Irradiance

Electrical Sensors
- Voltages, Current, Real and Reactive Power Injections

Database

Power Systems Literature

Power Systems Test Case Archive
University of Washington

Sub-networks Split of the IEEE-30

IEEE-30 Bus System Data

Weather Profiles and Temperature

Atmospheric Science Data Center (NASA)/ Weather Underground

Wind Integration Datasets
National Renewable Energy Laboratory (NREL)

Wind Speed
- 4 sources of power generation within the microgrid
  - Diesel Generation
  - Solar Generation
  - Wind Generation
  - Wave Generation
  + Main Grid

- 3 types of demand
  - Critical
  - Priority
  - Non-Critical

- 5 feeders
  - 1 Critical
  - 2 Priority
  - 2 Non-Critical

- Type of demand does not necessarily match the type of feeder (priority demands in critical feeder)
Components of DDDAMS Framework

- **A1: Fault Detection and Isolation**
- Agent-based Simulation
- **A2: MG Control Design Selection**
- **A3: Multi-objective Optimization**

Detects system abnormalities

Initial system state is used for the appropriate control design
A1: Fault Detection and Isolation (FDI)

- FDI is a crucial element of numerous automation systems
- Detection => identifies system faults even if the origin cause is not known yet
- Isolation => locates the origin causes, allowing system to take corrective action
- FDI using equation-based analytical models involves and necessitates a static set of state variables and measurements
- Event-driven FDI does not require a predetermined storage size to represent their state
## A1: Fault Detection and Isolation (FDI)

- Events that may be triggered in the DDDAMS Framework:

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Event</th>
<th>Possible Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>Increased Voltage</td>
<td>Load-shedding</td>
</tr>
<tr>
<td></td>
<td>Decreased Voltage</td>
<td>Short-circuit/Motor Start-up</td>
</tr>
<tr>
<td></td>
<td>Neutral Voltage</td>
<td>Ground-fault</td>
</tr>
<tr>
<td></td>
<td>Negative Voltage</td>
<td>Sensor Fault</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>Overcurrent</td>
<td>Overload/Short Circuit</td>
</tr>
<tr>
<td></td>
<td>Differential Current</td>
<td>Short Circuit</td>
</tr>
<tr>
<td></td>
<td>Negative Current</td>
<td>Sensor Fault</td>
</tr>
<tr>
<td><strong>Impedance</strong></td>
<td>Low Impedance</td>
<td>Short-circuit</td>
</tr>
<tr>
<td></td>
<td>Abnormal Ratio X/R</td>
<td>Short-circuit/Sensor Fault</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>Low Frequency</td>
<td>Increased Load/Sensor Fault</td>
</tr>
<tr>
<td></td>
<td>High Frequency</td>
<td>Loss of Load/Sensor Fault</td>
</tr>
<tr>
<td><strong>Phase Angle</strong></td>
<td>Phase Angle Change</td>
<td>Short-circuit/Sensor Fault</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>Increased Temperature</td>
<td>Overload</td>
</tr>
<tr>
<td></td>
<td>Decreased Temperature</td>
<td>Short-circuit</td>
</tr>
<tr>
<td></td>
<td>Negative Temperature</td>
<td>Sensor Fault</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>Active Power in Zero-Sequence Component</td>
<td>Short-circuit/Sensor Fault</td>
</tr>
<tr>
<td></td>
<td>Change of Direction of Power Flow</td>
<td>Ground-fault/Sensor Fault</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>Change of Oil Flow in Transformer</td>
<td>Overload/Short-circuit</td>
</tr>
<tr>
<td><strong>Solar Irradiance</strong></td>
<td>Abnormal Solar Irradiance</td>
<td>Sensor Fault</td>
</tr>
<tr>
<td><strong>Wind Speed</strong></td>
<td>Abnormal Wind Speed</td>
<td>Sensor Fault</td>
</tr>
</tbody>
</table>
Components of DDDAMS Framework

- A1: Fault Detection and Isolation
- **Agent-based Simulation**
- A2: MG Control Design Selection
- A3: Multi-objective Optimization

Algorithm 1: Fault Detection & Isolation

Algorithm 2: Isolated MG Control Design Selection

Algorithm 3: Multi-objective Optimization

Simulation and A2 are linked and operate in synch

Data from sensors ➔ Data from main grid ➔ Data from modules and algorithms
Agent-based Simulation
## Overview of Agents Defined in Simulation

<table>
<thead>
<tr>
<th>Device/System</th>
<th>Information Sensed</th>
<th>Information Derived</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generator</strong></td>
<td>• Magnitude of voltage (V)</td>
<td>• Power output (kW)</td>
</tr>
<tr>
<td></td>
<td>• Magnitude of current (Amps)</td>
<td>• Fuel used (gallons)</td>
</tr>
<tr>
<td></td>
<td>• Environmental measurements (temperature, solar irradiance,</td>
<td>• Emission produced (lbs.)</td>
</tr>
<tr>
<td></td>
<td>wind speed, etc.)</td>
<td></td>
</tr>
<tr>
<td><strong>PV Array</strong></td>
<td>• Solar irradiance (W/m²)</td>
<td>• Power output (kW)</td>
</tr>
<tr>
<td></td>
<td>• Temperature (°F)</td>
<td>• Purchase cost</td>
</tr>
<tr>
<td><strong>Wind Turbine</strong></td>
<td>• Wind speed (m/s)</td>
<td>• Power output (kW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Purchase cost ($)</td>
</tr>
<tr>
<td><strong>Wave Generator</strong></td>
<td>• Wave speed (m/s)</td>
<td>• Power output (kW)</td>
</tr>
<tr>
<td></td>
<td>• Wave period (s)</td>
<td>• Purchase cost ($)</td>
</tr>
<tr>
<td><strong>Load</strong></td>
<td>• Magnitude of voltage (V)</td>
<td>• Power consumed (kW)</td>
</tr>
<tr>
<td></td>
<td>• Phase of voltage (°)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Current consumption (kW)</td>
<td></td>
</tr>
<tr>
<td><strong>Power Network</strong></td>
<td>• Electricity price ($/kWh)</td>
<td>• Microgrid frequency (Hz)</td>
</tr>
<tr>
<td></td>
<td>• Main grid frequency (Hz)</td>
<td>• Microgrid voltage (V)</td>
</tr>
<tr>
<td></td>
<td>• Main grid voltage (V)</td>
<td>• Status (whether the above factors are in the safe operation range)</td>
</tr>
</tbody>
</table>
Simulation Video
Components of DDDAMS Framework

- A1: Fault Detection and Isolation
- Agent-based Simulation
- **A2: MG Control Design Selection**
- A3: Multi-objective Optimization

Algorithm 1: Fault Detection & Isolation

Algorithm 2: Isolated MG Control Design Selection

Algorithm 3: Multi-objective Optimization

Agent-based Simulation

<table>
<thead>
<tr>
<th>M1: Demand</th>
<th>M2: Batteries</th>
<th>M3: Solar Generators</th>
<th>M4: Wind Turbines</th>
</tr>
</thead>
<tbody>
<tr>
<td>M5: Diesel Generators</td>
<td>M6: Computational Resource Availability</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Selects the appropriate control design (fidelity) for accuracy considering limited comp. resources

Selected fidelity is used to solve the problem more efficiently
Fidelity Selection

- **Purpose**
  - Set level of detail in simulation for each predefined region (critical, priority and non-critical)

- **Goal**
  - Manage tradeoff between computational resources and accuracy of decisions
    - Decrease computational burden in steady states
    - Increase segregation mechanism and enhance fault detection in abnormal instances

- **Depends on**
  - Simulation model
  - Optimal costing budget allocation (OCBA) scheme

- **Higher fidelity means**
  - More frequent collection of data
  - More frequent update to decision variables
  - Increased control of microgrid
  - Improved segregation mechanism
  - Enhanced fault detection
  - Additional computational resources
Examines the system with fewer nodes

Control is limited to only one isolation point
- Examines the system with fewer nodes
- Control is limited to only three isolation points
- Examines the system with regular number of nodes
- Control is limited to five isolation points (one for each feeder)
- Examines the system with high number of nodes

- Control is extended to 104 isolation points (critical nodes (41) + priority nodes (61) + number of non-critical feeders (2))
- Examines the system with extreme number of nodes

- Control is extended to 186 isolation points (critical nodes 41 + priority nodes 61 + number of non-critical feeders 84)
A2: MG Control Design Selection

- Selecting the best design alternative **traditionally**
  - Equal allocation=> runs all designs with same # of replications
  - Proportional to variance=> runs designs with higher uncertainty with more replications
  - Commonly fails to assign optimal or near optimal number of replications

- Selecting the best design alternative **with OCBA**
  - Assigns # of replications to different design alternatives optimally
  - First introduced by Chen leading to significant research work
  - **Simulation Alternatives**: Combination of fidelities for every 5 min that optimizes the performance function
  - **Performance Function**: Combination of energy surety and cost
A2: MG Control Design Selection (cont’d)

Performing $n_0$ replications for each Design during initialization.

\[ l \leftarrow 0; \]
\[ n_1^l = n_2^l = \ldots = n_k^l = n_0 \]

\[ PCS_l < PCS_d \]

Yes

Calculation of the mean and variance for each design

\[ \bar{f}_i = \frac{1}{n_i^l} \sum_{j=1}^{n_i^l} f_{ij} \]
\[ S_{f_i}^2 = \sum_{j=1}^{n_i^l} (f_{ij} - \bar{f}_i)^2 / (n_i^l - 1) \]

Calculation of the new replications

\[ \frac{n_i^{l+1}}{n_j^{l+1}} = \left( \frac{s_{f_i} (\bar{f}_b - \bar{f}_j) / s_{f_j} (\bar{f}_b - \bar{f}_i)}{s_{f_b}} \right)^2, \text{for } i > j, \]
\[ i, j \neq b \quad n_b^{l+1} = \frac{s_{f_b} \sqrt{\sum_{i=1, i \neq b}^{k} (n_i^{l+1} / s_{f_i})^2}}{\sum_{i=1}^{k} (n_i^{l+1} / s_{f_i})^2} \]

Performing additional replications (design $i$);

\[ \left[ \max(n_i^{l+1} - n_i^l, 0) \right] \]

$k$ Number of alternative designs

$N$ Total simulation budget

$\Delta$ available budget for one iteration of the algorithm

$n_0$ initial replications for each design

$l$ current iteration in OCBA

$PCS_l$ Probability of correct selection in iteration $l$

$PCS_d$ Desired probability of correct selection

Cost

Alternative Designs
A2: Experiments w. Synthetic/Partial Real Data

- Experiments on a multi-scale test-bed (1, 2 and 3-MGs with synthetic/partial real data)
- Varying alternative control designs (5, 25 and 125)
- Objective functions for the test-bed
  - Min. total cost of operations
  - Max. percentage of the energy surety
- Light red shade Pareto solutions are highly undesirable with low energy surety & low cost
- Objective function that captures both the energy surety and cost

\[
f(X) = a.P_{\text{crit}} + b.P_{\text{pr}} + b.P_{\text{ncrit}} + d\cdot\frac{C_{\text{max}} - C}{C_{\text{max}}}
\]

\( P_{\text{crit}}, P_{\text{pr}}, P_{\text{ncrit}} \): % of energy surety of critical, priority and noncritical loads
\( C_{\text{max}} \): Max cost
\( C \): Cost of the current replication for design X
\( a, b, c, d \): Coefficient given to priority of different objectives
OCBA reached over 98% probability of CS 60% and 85% faster than those of PTV and EA algorithms

OCBA reached over 98% probability of CS 200% and 235% faster than those of PTV and EA algorithms

After 40,000 reps. PTV and EA algorithms had not reached the 98% probability of CS, while OCBA reached after 6500 reps
Components of DDDAMS Framework

- A1: Fault Detection and Isolation
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- **A3: Multi-objective Optimization**

**Algorithm 1:** Fault Detection & Isolation

**Algorithm 2:** Isolated MG Control Design Selection

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**Agent-based Simulation**

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<td></td>
<td></td>
</tr>
</tbody>
</table>

Solves the load dispatch at the selected fidelity

State Information

Number of Replications for Designs

Evaluation of Designs

Control Configuration
## A3: Nomenclature

### Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_i$</td>
<td>Demand in building $i$</td>
</tr>
<tr>
<td>$p_w$</td>
<td>Production from wind turbines</td>
</tr>
<tr>
<td>$p_s$</td>
<td>Production from photovoltaic solar panels</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of buildings in MG</td>
</tr>
<tr>
<td>$m$</td>
<td>Number of segregation points</td>
</tr>
<tr>
<td>$l_j$</td>
<td>Number of buildings associated with segregation point $j$</td>
</tr>
<tr>
<td>$s_j$</td>
<td>Indices of buildings associated with segregation point $j$</td>
</tr>
<tr>
<td>$k$</td>
<td>Number of diesel generators</td>
</tr>
<tr>
<td>$P_z^{\text{max}}$</td>
<td>Maximum operating power of generator $z$</td>
</tr>
<tr>
<td>$o_z$</td>
<td>Operation and maintenance cost of generator $z$</td>
</tr>
<tr>
<td>$a_y$</td>
<td>Cost of emission type $y$</td>
</tr>
<tr>
<td>$e_{zy}$</td>
<td>Emission factor of generator $z$ for type $y$</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Fuel cost per liter</td>
</tr>
<tr>
<td>$u_z, v_z, w_z$</td>
<td>Parameters of diesel generator $z$</td>
</tr>
<tr>
<td>$cr_i$</td>
<td>$\begin{cases} 1, &amp; \text{if building } i \text{ is critical} \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td>$pr_i$</td>
<td>$\begin{cases} 1, &amp; \text{if building } i \text{ is priority} \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
</tbody>
</table>

### Binary Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_i$</td>
<td>$\begin{cases} 1, &amp; \text{if building } i \text{ is priority} \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td>$g_i$</td>
<td>$\begin{cases} 1, &amp; \text{if building } i \text{ is priority} \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
</tbody>
</table>

### Continuous Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_z$</td>
<td>Production from diesel generator $z$</td>
</tr>
</tbody>
</table>
A3: Formulation of MO Optimization Problem

- Formulation of the problem objectives:

\[ \text{Min } Z_1 = \sum_{z=1}^{k} f_c(u_z + v_z P_z + w_z P_z^2) \]  
\[ \text{(Energy Surety Objective)} \]

\[ \text{Min } Z_2 = \sum_{z=1}^{k} \sum_{y=1}^{3} a_y e_{zy} P_z \]  
\[ \text{(Emissions Objective)} \]

\[ \text{Max } Z_3 = \sum_{i=1}^{n} 6cr_i x_i d_i + 3 pr_i x_i d_i + (1 - cr_i - pr_i) x_i d_i \]  
\[ \text{(Cost Objective)} \]

- Constraints of the problem:

\[ p_W + p_S + \sum_{z=1}^{k} P_z = \sum_{i=1}^{n} d_i x_i \]  
\[ \text{(Demand Satisfaction)} \]

\[ P_{z_{\text{min}}} < P_z < P_{z_{\text{max}}} \quad \forall z = 1, \ldots, k \]  
\[ \text{(Generators’ Capacity)} \]

\[ g_j = \frac{\sum_{i \in s_j} x_i}{l_j} \quad \forall j = 1, \ldots, m \]  
\[ \text{(Bldgs- Segregation Pts Links)} \]

\[ x_i \in \{0,1\} \quad \forall i = 1, \ldots, n \]  
\[ \text{(Binary Property)} \]

\[ g_j \in \{0,1\} \quad \forall j = 1, \ldots, m \]  
\[ \text{(Binary Property)} \]
**A3: -constraint Method**

- $\epsilon$-constraint method is used rather than a weighting method

- Multiple advantages:
  - Produces efficient solutions for MO integer prog. problems
  - No need to scale the objective functions to obtain a weighted sum
  - Total # of efficient soln. can be controlled by adjusting # of grid points

- Appropriate $\epsilon$- for each constraint can be achieved by a parametrical variation of the right-hand-side part of each constraint

\[
\begin{align*}
\text{max} & \quad (f_1(x), f_2(x), \ldots, f_m(x)) \\
\text{s.t.} & \quad x \in S, \\
\text{max} & \quad f_1(x) \\
\text{s.t.} & \quad f_2(x) \geq \epsilon_1, \\
& \quad f_3(x) \geq \epsilon_2, \\
& \quad \ldots \\
& \quad f_m(x) \geq \epsilon_{m-1} \\
& \quad x \in S,
\end{align*}
\]
A3: Pareto Frontier Solutions

- **Energy surety** is the highest priority function (**z-axis**)
  - **Cost/emissions** objectives are treated as constraints (**x- and y-axis**)

- Fidelity 5 model (left figure) contains significantly more binary variables (segregation points) => leads to more Pareto frontier solutions
Computational Results

- DDDAMS framework requires significantly less time to calculate the solution
- Reduction of the computational time is 50.38% ± 11.09%
- In some cases a reduction up to 70% is observed
Experiments on Self-Healing Microgrids

- To ensure that primary electrical needs are satisfied while total cost is minimized
- To maintain MGs’ stability and security by
  - Meeting requested demands within each individual MG
  - Searching for neighboring MGs for back-up

MBM: 186 buildings, 5 feeders
UM: 64 buildings, 3 feeders
GCM: 58 buildings, 3 feeders
Experiments on Self-Healing Microgrids

We test our proposed DDDAMS approach against MGs that do not share energy in the following cases:

- **Scenario A**: A major hurricane completely wipes out power to GCM for 48 hrs
- **Scenario B**: A terrorist attack within the borders of UM forces MBM to isolate from the local utility for 2 hrs until the threat is cleared (damage on UM link will require 6 hrs to repair)

### Demand Satisfaction

<table>
<thead>
<tr>
<th>Scenario</th>
<th>MBM Loads</th>
<th>UM Loads</th>
<th>GCM Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cr</td>
<td>Pr</td>
<td>NCr</td>
</tr>
<tr>
<td>No Sharing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>B</td>
<td>97.6%</td>
<td>79%</td>
<td>66.4%</td>
</tr>
<tr>
<td>Sharing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>100%</td>
<td>10%</td>
<td>95.7%</td>
</tr>
<tr>
<td>B</td>
<td>98.6%</td>
<td>94%</td>
<td>66.4%</td>
</tr>
</tbody>
</table>

Cr: Critical  Pr: Priority  NCr: Non-critical
Conclusions and Future Work

A DDDAMS framework has been proposed for load dispatching in power networks

- Assesses the system status
- Determines a simulation fidelity leading to near optimal decisions/solutions
- Embeds algorithms for state estimation, fidelity selection, and multi-objective optimization
- Saves significantly from critical computational resource utilization
- Enables autonomous MG control ability
- Generic to incorporate MGs of any size

What is next?

- Incorporating
  - agents for additional power sources
  - power balancing (re-apply)
  - isolation-desolation procedures
  - automatic fidelity generation via discovery
- Establishing and experimenting with a lab-scale MG
Questions and Comments

This project is supported by the AFOSR via 2013 Young Investigator Research Award (Award No: FA9550-13-1-0105)