NSF Center for GRid-connected Advanced Power Electronic Systems (GRAPES)

GR-XX-XX Model-Predictive Autonomous Control Concept and Architecture for Microgrids

Adel Nasiri and Rob Cuzner

University of Wisconsin-Milwaukee

Semi-Annual Meeting

May 24, 2016
Project Overview

- Anticipated Project Dates: Jan 1, 2016-Dec 31, 2016
- PI Names: Adel Nasiri and Rob Cuzner
- Overall Project Budget: $40,000
  - 50% annual support for a graduate student: $34,620 (including tuition remission)
  - Supplies: $2,000
  - Indirect cost: $3,380
Microgrid Concept

- A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid.
- A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.
- Technical drives behind microgrids:
  - Transmission constraints requiring supplies closer to loads
  - Demand for improved power reliability, efficiency, and quality
  - Demand for energy security.
  - Integration of renewable energy and DG.
  - Military demand for enhanced energy security: Surety, Survivability, Supply, Sufficiency, and Sustainability.
Microgrid Controls

- **Primary Control: P/Q Droop Control (Autonomous)**
  - Generators: The exciter regulates $V$, $Q$
  - Generators: The governor adjusts $\theta$, $P$
  - Renewables: MPPT, P,Q Adjustment of $\theta$, $|P|$(Current Mode)
  - Energy Storage: Regulate $f$, $V$
    - (Voltage Mode, Current Mode)

- **Secondary control: Frequency-Voltage Restoration and Synchronization.**

- **Tertiary control: P/Q Import and Export (Ancillary services)**
Centralized methods of operation are more susceptible to single point failures.

Emerging smart grid concept compels microgrids to adopt decentralized methods as a result of the highly dynamic behavior for microgrids.

Two research areas are being targeted in decentralized control systems for microgrids:
1. The distributed control algorithm.
2. Data management for decentralized control systems.
   *No communication delay considerations.
   *No recovery algorithms established.

Most efforts neglect communication delays and assume no failures in system.
Recent Research Efforts

- A Decentralized Control Architecture for a Microgrid with Power Electronic Interfaces in [1]: control architecture is based on a multi-agent system (MAS) in which all agents are hierarchically equal and there is no central agent (software based).
  - No communication delay considerations.
  - No recovery algorithms established.
  - Focus on algorithm for managing active/reactive power.

  - No communication delay considerations.
  - No recovery algorithms established.
  - Focus on concepts of microgrid control and how to decentralize.

Similar focus efforts:

Decentralized Voltage Control to Minimize Distribution Power Loss of Microgrids [3].
Scientific Contribution

GRid-Connected Advanced Power Electronic Systems

- Development of true decentralized microgrid control architecture.
- Development of Hardware-in-the-Loop platform intended for complex microgrids studies related to their cyber-physical architectures.
- Communication delay impact analysis and state space modeling of delayed microgrid systems due to cyber transmission.
- Microgrid control architecture reliability analysis.
- Development of microgrid failure model over cyber-physical layer.
Decentralized MG Control Architecture (Main Characteristics)

- **Decentralized**: Multiple local controllers in order to achieve seamless transients during the operation and acts as if the system has one central controller.

- **Resource sharing**: Every controller shares the status of its own DER with other controllers in real-time.

- **Concurrency**: Each controller must have an up-to-date status all peers. Otherwise, inconsistent algorithm outputs and control commands may arise, which can lead to disturbance in the microgrid operation.

- **Scalability**: The architecture allows the microgrid to be scaled up. Minimum engineering time.

- **Fault-tolerance/Self-healing**: The system must maintain available and operating at the minimum level of reliability. This also include the recovery process in case of faults and possible redundancy that may boost the reliability of the microgrid.
Decentralization of control has two major advantages:
1. Control commands to power components will be generated locally, thus avoiding long distance command (based on the physical location of the controller).
2. Improvement of reliability by eliminating the single-point-of-failure formed by the centralized controller.

- Primary and secondary control will be combined into one physical layer.
- Tertiary control will be a responsibility of the controller located at the PCC.
- Each controller must be aware of its peers and their status. This shall form general awareness of the microgrid status.
- Each controller will be responsible of broadcasting its status (plus the power source).
Each controller runs the *entire algorithm* including other controllers’
controls (based on inputs from local sensors and peers reports).

- **Natural Gas Generators**: Synchronization before connection,
  breaker control, active/reactive power commands, and unit
  commitment following Energy Storage SOC.

- **Energy Storage**: Voltage/Frequency regulation based on the
  operation mode of the microgrid, power commands, and
  charging/discharging.

- **Wind/Solar**: Running on MPPT, operates breakers for isolation in
  case of emergency or frequent disturbing fluctuations.

Each controller commands its designated power source based on local output of the control algorithm. Others’ commands are buffered for verification purposes (diagnosing faults or performance degradation).
\[ \Delta P_s = P_{G1} + P_{G2} + P_{ES} - P_{Demand} \]

\[ P_{Demand} = P_L - P_{wind} - P_{Solar} \]

For Natural Gas Generator 1:

\[ P_{G1}(s) = \frac{1}{sT_{g1} + 1} \]

\[ U_g(s) = U_l + U_p \]

\[ = -\left(\frac{K_i}{s} + K_p\right) \]

\[ \dot{P}_{G1} = \frac{U_l}{T_{g1}} + \frac{K_p\Delta f}{T_{g1}} - \frac{P_{G1}}{T_{g1}} \]

For the integral part of the PI Controller \( U_l \)

\[ U_l(s) = \frac{K_i}{s} \Delta f \]

\[ \dot{U}_l = K_i \Delta f \]

MG Bus frequency deviation

\[ \frac{\Delta f(s)}{\Delta P_s(s)} = \frac{1}{M \cdot s + D} \]

\( D \) Load Damping constant. \( M \) Inertia constant.

Similarly for Natural Gas Generator 2 and Energy Storage System:

\[ \frac{P_{G2}(s)}{U_{g2}(s)} = \frac{1}{sT_{g2} + 1} \]

\[ \dot{P}_{G2} = \frac{U_{l2}}{T_{g2}} + \frac{K_p\Delta f}{T_{g2}} - \frac{P_{G2}}{T_{g2}} \]

\[ \frac{P_{ES}(s)}{U_{g_{ES}}(s)} = \frac{1}{sT_{ES} + 1} \]

\[ \dot{P}_{ES} = \frac{U_{l_{ES}}}{T_{ES}} + \frac{K_p\Delta f}{T_{ES}} - \frac{P_{ES}}{T_{ES}} \]
Microgrid Frequency Control

State space model for the Microgrid:

\[
\Delta P_s = P_{G1} + P_{G2} + P_{ES} - P_{Demand}
\]

\[
P_{Demand} = P_L - P_{wind} - P_{Solar}
\]

\[
\mathbf{x}(t) = \begin{bmatrix} \Delta f & P_{G1} & P_{G2} & P_{ES} & U_{I1} & U_{I2} & U_{I,ES} \end{bmatrix}
\]

\[
A \dot{\mathbf{x}}(t) = \begin{bmatrix}
\Delta f & \dot{P}_{G1} & \dot{P}_{G2} & \dot{P}_{ES} & \dot{U}_{I1} & \dot{U}_{I2} & \dot{U}_{I,ES} \\
-D & \frac{1}{M} & \frac{1}{M} & \frac{1}{M} & 0 & 0 & 0 \\
-K_p & -1 & 0 & 0 & 0 & 0 & 0 \\
-K_p & T_{G1} & 0 & 0 & 1 & T_{G1} & 0 \\
-K_p & T_{G2} & 0 & -1 & 0 & 0 & 0 \\
-K_p_{ES} & T_{ES} & 0 & 0 & -1 & T_{ES} & 0 \\
-K_i & 0 & 0 & 0 & 0 & 0 & 0 \\
-K_i & 0 & 0 & 0 & 0 & 0 & 0 \\
-K_{I,ES} & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} \begin{bmatrix}
\Delta f \\
-P_{G1} \\
-P_{G2} \\
-P_{ES} \\
U_{I1} \\
U_{I2} \\
U_{I,ES} \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T
\]

\[
C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}
\]

---

Parameter | Value
---|---
Inertia Constant M | 0.008 puMWs/Hz
Damping Constant D | 0.15 puMWs/Hz
Generator Time Constant $T_{G1,2}$ | 5 s
Battery time constant $T_{ES}$ | 0.1 s
$K_i, K_p$ | 3.4, 5
$K_{ES}, K_{p,ES}$ | 0.5, 1.3
System has \( k \) components, each component has two states:

\[
x_i = \begin{cases} 
1 & \text{if } i \text{ is functioning} \\
0 & \text{if } i \text{ is not functioning}
\end{cases} \quad i \in (1, k)
\]

Structure function of System State:

\[
\varphi(x) = \begin{cases} 
1 & \text{if the system is functioning} \\
0 & \text{if the system is not functioning}
\end{cases}
\]

\[
h(1,i, P) = (x_1, \ldots, x_{i-1}, 1, x_{i+1} \ldots, x_k) \quad i \in (1, k)
\]

\[
h(0,i, P) = (x_1, \ldots, x_{i-1}, 0, x_{i+1} \ldots, x_k) \quad i \in (1, k)
\]

**B-P structure Importance (Barlow-Porschan)**

\[
I_\varphi(i) = \int_0^1 (h(1, i, P) - h(0, i, P)) \, dp
\]
Reliability Assessment

- Discuss reliability at controller level.
- Determine failure metrics MTBF, MTTR, MTTF and FIT for three architectures.
- Generate reliability curves.
PE-LAB HIL MG System

Grid-Connected Advanced Power Electronic Systems
PE-LAB HIL MG System (Decentralized MG Control)
Controller model

- Leveraging the capabilities of NI CompactRIO.
- Two Processing Units (Real-time module, FPGA)
- Network sharing of variables and data verification is embedded.
Decentralized MG Control Architecture (System Design)

- Interaction model
- Data Propagation method.

<table>
<thead>
<tr>
<th>DG Type</th>
<th>Wind, Solar, Energy Storage, Generator…etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP Address</td>
<td>Unique IP address within the control network</td>
</tr>
<tr>
<td>Attributes</td>
<td>Status, active power, reactive power, bus voltage, frequency, breaker status, commands.</td>
</tr>
</tbody>
</table>

Synchronous Distributed System?

<table>
<thead>
<tr>
<th></th>
<th>Synchronous</th>
<th>Asynchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower and Upper bound for execution time are set</td>
<td>No execution time bounds are set</td>
<td></td>
</tr>
<tr>
<td>Predictable Behavior (time)</td>
<td>Unpredictable (delays has no bounds)</td>
<td></td>
</tr>
<tr>
<td>Synchronized time between all components</td>
<td>No synchronization</td>
<td></td>
</tr>
<tr>
<td>Timeouts can be used to determine communication faults</td>
<td>Timeouts can’t be used</td>
<td></td>
</tr>
</tbody>
</table>
Decentralized MG Control Architecture (System Design)

- Interaction model
- Network Topology.
  - Multipath (reliable)
  - Minimum data congestion (bandwidth).
Decentralized MG Control Architecture (System Design)

- Failure model
- Development of feasible dynamic diagnostic algorithm (proof-of-concept).
Decentralized MG Control Architecture (Additional Challenges)

- Ancillary services propagation

- Controller at Static switch receives requests and broadcasts.

- Failure of Static Switch local controller islands the MG and the reliability condition is satisfied.
Main Deliverables

- A distributed microgrid control concept and architecture
- Hardware-in-the-loop implementation of the control concept
- Communication delay analysis
- Reliability analysis
- Two publications on the proposed concept and system.
- Possible IP development.
Broader Impact of the Project

- This work will create expertise in the center on MG controls.
- The developed distributed control concept and analysis can be applied to other systems, e.g. DC MG.
- The work will lead to more reliable control systems for MGs and other electrical systems.
References


