ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Assessing the Impact of Distributed Energy Resource Coordinated Aggregation on the Bulk Power System

Alejandro D. Domínguez-García

Coordinated Science Laboratory
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

CERTS Program Review
Cornell University
Ithaca, NY
August 4, 2015

Motivation

- If properly aggregated and coordinated, Distributed Energy Resources (DERs) such as
  - plug-in electric vehicles (PEVs)
  - thermostatically-controlled loads (TCLs)

  provide new opportunities and added flexibility in the procurement of ancillary services, for instance
  - frequency regulation
  - load following
- Benefits of coordination (via an aggregator) of DERs to provide regulation and load following services are relatively well understood
- Virtually no work on understanding the potential negative impact on power system performance of aggregate DER coordination

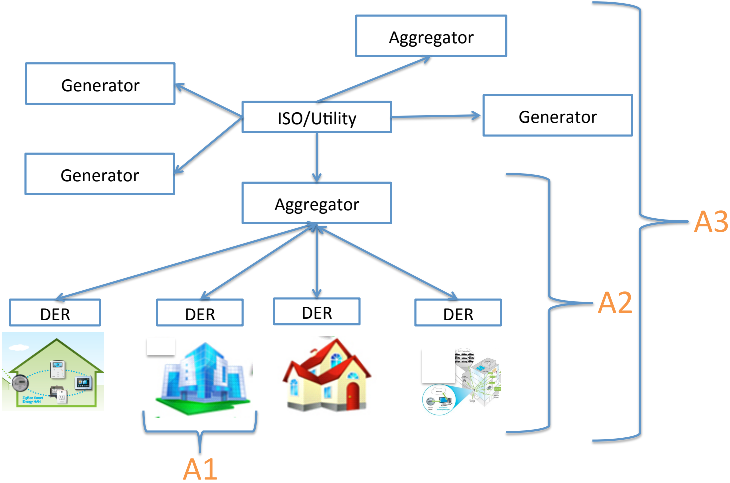
Objective

To develop a framework to assess the impact on bulk power system performance of distributed energy resources (DERs) when coordinated (via an aggregator) to provide ancillary services, e.g., frequency regulation

Of special interest is to understand the effect of:

- Delays, packet drops, and permanent failures in communication channels between aggregator and DERs
- Random failures in the processors utilized to implement DER local control and other hardware
- Uncertainty in external disturbances to DER dynamics, e.g., occupancy level and ambient temperature

Overview of Research Activities



A1. Virtual Battery Modeling of DER Dynamics
A2. Stochastic Modeling of Aggregator/DER Collective Dynamics
A3. Assessing the Impact on Bulk Power System Performance

Part I

Virtual Battery Modeling of DER Dynamics

Definition (Load Flexibility)

Ability to vary power consumption without compromising end function

- Prior work:
  - Aggregation of thermostatically controlled loads (TCLs)
  - Captured by a battery model: simple, intuitive, accurate
  - Model parameters determined by analytical method
- Analytical method does not scale to more complex loads

Objective

Develop a general method to identify battery model parameters for complex loads:

(i) *Based on stress-testing a detailed software model of the physical system*

(ii) *Idea illustrated using commercial building HVAC system*

Commercial Building HVAC system

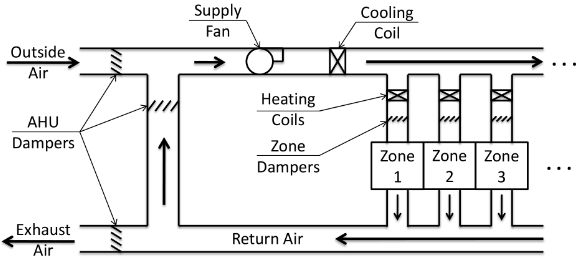


Figure: VAV with reheat HVAC [Kelman et al., 2011]

- Load flexibility
  - Small deviations from nominal temperature are acceptable
  - Achieved by adjusting power consumption of supply fan and cooling coil
- Heating coils may not be electric

Building/HVAC System Open-Loop Dynamics

- Nonlinear state-space model:

$$\frac{d}{dt}T(t) = h_1(T(t), s(t), w(t))$$

- Fan and cooling coil power consumption:

$$P(t) = h_2(T(t), s(t), w(t))$$

- Equipment ratings and occupant comfort constraints:

$$h_3(T(t), s(t)) \leq 0.$$

T	zone temperature vector
s	control input vector (e.g., mass flow rate, recirculation fraction)
w	external disturbance vector (e.g., thermal load, ambient temperature)

Baseline and Regulation Power

Baseline Power $P^0(t)$:

- Power consumption to maintain zone temperatures at their midpoint
- Obtained as the steady-state solution of the state-space model:

$$0 = h_1(T^{\mathrm{m}}, s^0(t), w(t))$$
$$P^0(t) = h_2(T^{\mathrm{m}}, s^0(t), w(t))$$

Regulation Power $\Delta P(t)$:

- Actual fan and cooling coil power minus baseline power:

$$\Delta P(t) = P(t) - P^0(t)$$

T^m	midpoint zone temperature vector

Closed-Loop Controller Design

Objective

Control $P(t)$ via $s(t)$ to

- *track desired power consumption profile $P^*(t)$*
- *respect equipment rating and occupant comfort constraints*

Solution Approach:

- Choose $s(t)$ so that $T(t)$ is driven to T^{m}
- Cast as an optimization problem:

$$
\begin{aligned}
s^*(t) = \underset{s(t)}{\text{arg min}} \quad & h_4(T(t), s(t)) \\
\text{subject to} \quad & h_3(T(t), s(t)) \leq 0 \\
& |\underbrace{P^*(t) - P^o(t)}_{u(t)} - \Delta P(t)| \leq \delta,
\end{aligned}
$$

δ	acceptable power deviation
$u(t)$	commanded deviation from baseline power

Virtual Battery Model

- Hypothesis: Closed-loop Building/HVAC System flexibility can be accurately described by a *virtual battery model*:

$$\frac{d}{dt}x(t) = -ax(t) - u(t)$$
$$x(0) = x_0$$
$$-C \leq x(t) \leq C$$
$$-\underline{n} \leq u(t) \leq \overline{n}$$

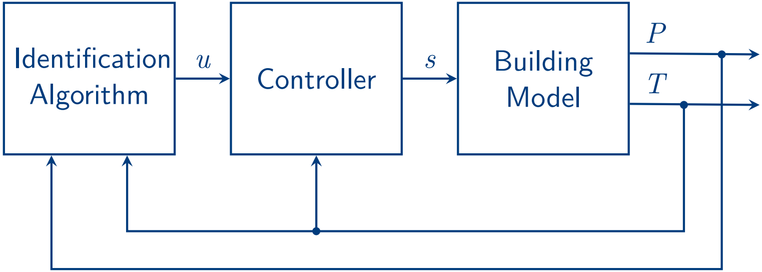
where $x(t) \in \mathbb{R}$ is the "state of charge"

Objective

Develop a numerical method to identify virtual battery model parameters

a	dissipation
C	up/down capacity
$\underline{n}$, $\overline{n}$	discharge/charge rate limits
x_0	initial conditions

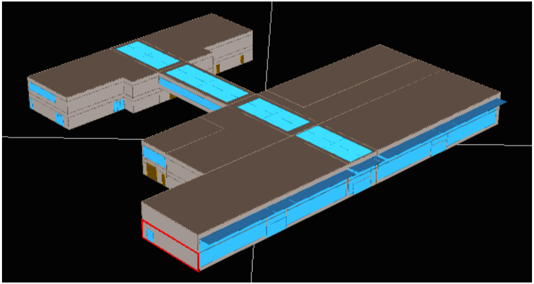
System Identification Setup



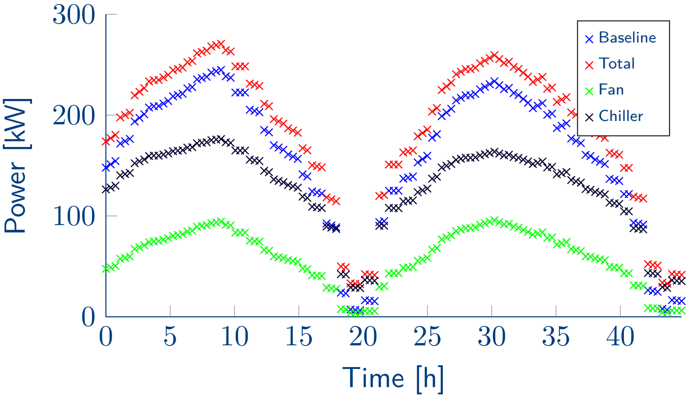
- Uses detailed model of building/HVAC system dynamics
- Key idea: software-based stress tests based on carefully constructed $u_i(t) = P_i^*(t) - P^o(t),\ t \geq 0,\ i = 1, 2, \ldots$
  - For each $u_i(t)$, ID algorithm records time, τ_i, it takes for optimization embedded in the controller to be unfeasible
  - The pairs $(u_i(t), \tau_i)$ are fitted to virtual battery model

University of Illinois Willard Airport Terminal Building

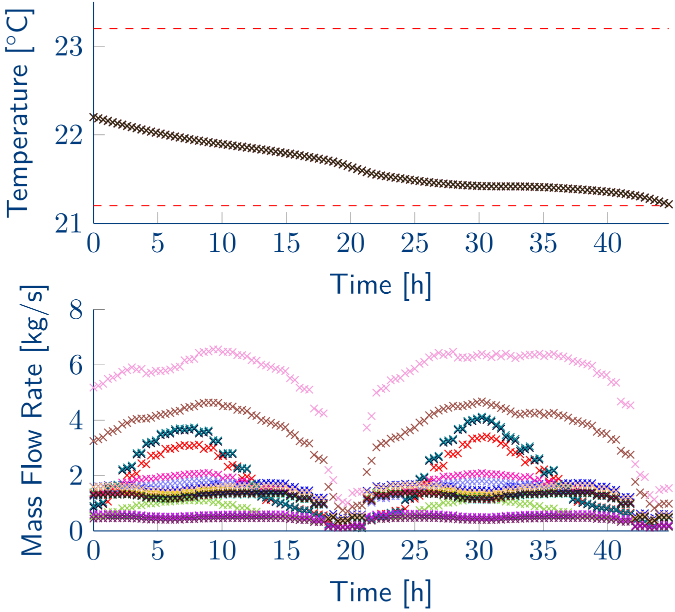
- Model created in eQuest by the Illinois Smart Energy Design Assistance Center (SEDAC) at the University of Illinois
- 41 zones, 19 of which are conditioned
- 5 air handlers
- Ambient temperature and thermal load are time-varying; this results in time-varying
  - power consumption
  - temperature
  - mass flow rates



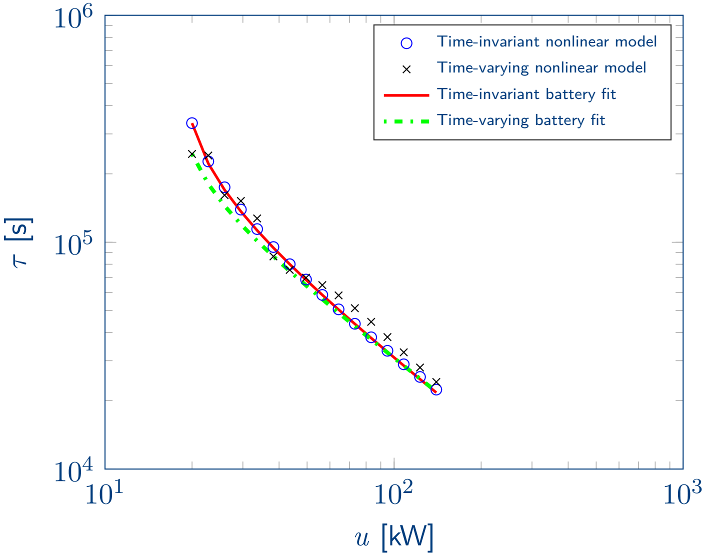
Power Consumption



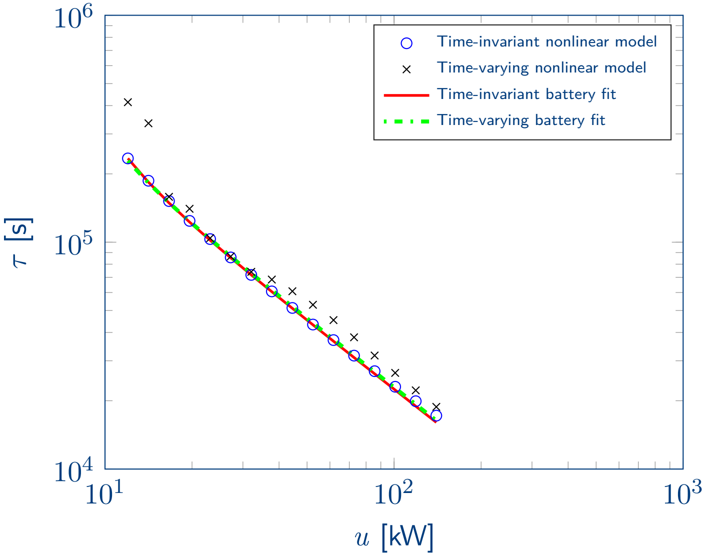
Temperature and Mass Flow Rate



Simulation Results for June 10th, 2013



Simulation Results for July 6th, 2013



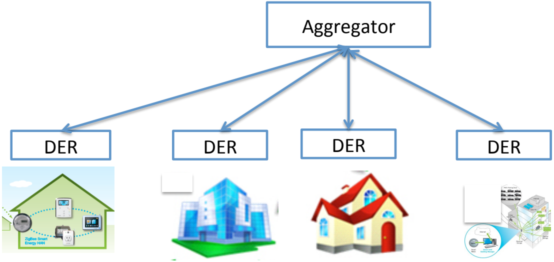
Numerical Results Summary

Date	Time-varying	$\overline{n}$ (kW)	$\underline{n}$ (kW)	a (Ms^{-1})	C (MWh)	x_0 (MWh)
Jun 10, 2013	no	138	148	8.92	0.580	0.228
Jun 10, 2013	yes	138	148	11.7	0.424	0.424
Jul 6, 2013	no	239	46.8	7.60	0.312	0.312
Jul 6, 2013	yes	239	46.8	6.86	0.318	0.317
Aug 26, 2013	no	140	145	7.92	0.633	0.147
Aug 26, 2013	yes	140	145	7.06	0.708	0.0174

Part II

Stochastic Modeling of Aggregator/DER Collective Dynamics

DER Aggregation System Modeling



Objective

Develop dynamic models for collections of aggregated DERs that take into account

(i) *failure in communication channels*

(ii) *failures in hardware used to implement the DER local control*

(iii) *Uncertainty in external disturbances to DER dynamics*

Model for Collection of DERs

- Aggregator coordinates response of $1, 2, \cdots, n$ DERs
- Virtual battery model for DER i:

$$\frac{d}{dt}x_i(t) = -a_i x_i(t) - u_i(t))$$
$$-C_i \leq x_i(t) \leq C_i$$
$$-\underline{n}_i \leq u_i(t) \leq \overline{n}_i$$

a_i	dissipation
C_i	up/down capacity
$\underline{n}_i$, $\overline{n}_i$	discharge/charge rate limits
$x_i(t)$	state of charge
$u_i(t)$	commanded signal from aggregator

DER Coordination Scheme

- Adopt integral control similar to that used in conventional AGC:

$$\frac{d}{dt}u(t) = c\left(r(t) - \sum_{i=1}^{n} \Delta P_i(t)\right)$$

$$u_i(t) = \beta_i u(t)$$

with $\sum_{i=1}^{n} \beta_i = 1$, and $c > 0$

$r(t)$	regulation signal from ISO/RTO
$\Delta P_i(t)$	power output deviation from baseline power for DER i
$u_i(t)$	commanded signal from aggregator

- We assume DER instantaneous response, i.e., $\Delta P_i(t) = u_i(t)$, then

$$\begin{aligned}\frac{d}{dt}u(t) &= c\left(r(t) - \sum_{i=1}^{n} u_i(t)\right)\\ &= -cu(t) + cr(t);\end{aligned}$$

i.e., the DER collection/Aggregator system is closed-loop stable

Incorporating Communication Failure Behavior

- Consider a failure mode in which the communication channel between the aggregator and DER i is permanently down
- Define an indicator variable capturing the occurrence of such a failure:

$$\eta_i = \begin{cases} 1, & \text{channel between aggregator and DER } i \text{ is UP} \\ 0, & \text{channel between aggregator and DER } i \text{ is DOWN} \end{cases}$$

- Then, DER collection/Aggregator closed-loop dynamics becomes

$$\frac{d}{dt}u(t) = c(r(t) - \sum_{i=1}^{n} \eta_i \beta_i u(t))$$

$$\frac{d}{dt}x_i(t) = -a_i x_i(t) - \eta_i \beta_i u(t)$$

$$-C_i \leq x_i(t) \leq C_i$$

$$-\underline{n}_i \leq u_i(t) \leq \overline{n}_i$$

with $i = 1, \cdots, n$

DER Collection/Aggregator Stochastic Model

- Let $\eta = [\eta_1, \eta_2, \ldots, \eta_n]^T$ and map the $N = 2^N$ this vector takes into the elements of $\mathcal{Q} = \{1, 2, \ldots, N\}$
- Let $z = [u, x_1, x_2, \ldots, x_n]^T$; then, the DER collection/Aggregator closed-loop dynamics can be compactly written as:

$$\frac{d}{dt} z(t) = Az(t) + B(q(t))r(t)$$

  with $q(t)$ taking values in $\mathcal{Q}$
- Communication channel failure/repair process is random:
  - failures occur at constant rate $\lambda_i, \; i = 1, 2, \ldots, n$
  - repairs occur at constant rate $\gamma_i, \; i = 1, 2, \ldots, n$

  Then
  - The evolution of $q(t)$ is described by a Markov process $Q(t)$
  - The evolution of $z(t)$ is described by a continuous-time continuous-state stochastic process $Z(t)$

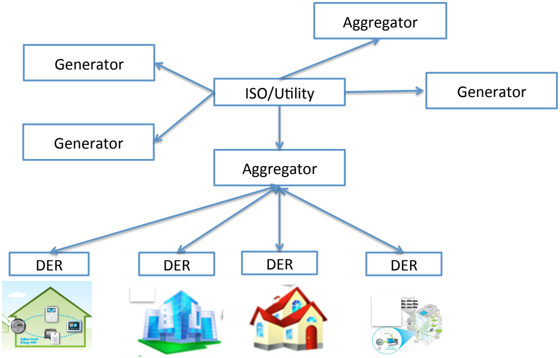
DER Collection/Aggregator Stochastic Model

- The pair $(Q(t), Z(t))$ belongs to a class of stochastic processes referred to as Stochastic Hybrid Systems [Hespanha '05]
- Use the generator of $(Q(t), Z(t))$ together with Dynkin's formula to derive a set of ODEs describing the evolution of its moments
- Once the moments of $(Q(t), Z(t))$ are available, they can be utilized in numerous types of analysis:
  - Time it takes the aggregator to fail to follow the regulation signal
- The model can also be used to generate realizations of $(Q(t), Z(t))$ for bulk power system-level studies

Part III

Assessing the Impact on Bulk Power System Performance

Bulk Power System Modeling



Objective

Develop a system-level dynamic model that will enable us to assess overall system dynamic performance (including the response of the AGC system) as measured by standard frequency metrics, i.e., CPS1, CPS2, and BAAL

Bulk Power System Standard Dynamic Model

Synchronous Generator Dynamics	$\frac{d}{dt}x(t) = f(x(t), y(t), u(t))$
Power Flow Equations	$0 = g(x(t), y(t), \ell(t))$
Automatic Generation Control Dynamics	$\frac{d}{dt}z(t) = h(x(t), y(t), z(t))$
Conventional Generation Allocation	$u(t) = k_1(z(t))$

x	Vector of synchronous machine state variables
y	Vector of algebraic variables
u	Vector of synchronous generator power settings
ℓ	Vector of load demands
z	Vector of inputs to the generation allocation logic

Bulk Power System Augmented Dynamic Model

Synchronous Generator Dynamics	$\frac{d}{dt}x(t) = f(x(t), y(t), u(t))$
Power Flow Equations	$0 = g(x(t), y(t), \ell(t), v(t))$
Automatic Generation Control Dynamics	$\frac{d}{dt}z(t) = h(x(t), y(t), z(t))$
Conventional Generation Allocation	$u(t) = k_1(z(t))$
DER Allocation	$v(t) = k_2(z(t))$

x	Vector of synchronous machine state variables
y	Vector of algebraic variables
u	Vector of synchronous generator power settings
v	Vector of DER commands
ℓ	Vector of load demands
z	Vector of inputs to the generation allocation logic

Incorporating Failures in DERs

Synchronous Generator Dynamics	$\frac{d}{dt}x(t) = f(x(t), y(t), u(t))$
Power Flow Equations	$0 = g(x(t), y(t), \ell(t), \eta v(t))$
AGC Dynamics	$\frac{d}{dt}z(t) = h(x(t), y(t), z(t))$
Conventional Generation Allocation	$u(t) = k_1(z(t))$
DER Allocation	$v(t) = k_2(z(t))$

where $\eta = [\eta_{ij}]$:

- $\eta_{ij} = 0, \;\; i \neq j$
- $\eta_{ii} = 1$ if DER i follows its command
- $\eta_{ii} = 0$ if DER i fails to follow its command

Recap

- Overall objective of this project is to develop a framework to assess the impact on bulk power system performance of distributed energy resources (DERs) when coordinated to provide ancillary services

- Of special interest is understanding the effects of failures in channels utilized by the aggregator to exchange information with the individual DERs and the hardware used to implement the DER local control

- A key objective of the project will be to develop dynamic models for collections of aggregated DERs that take into account the aforementioned sources of uncertainty

- These models must be compatible with standard dynamic models used in bulk power system dynamic simulations—this is key to be able to conduct system-level studies