DOE/OE Transmission Reliability Program

Enabling the Utilization of Distributed Energy Resources (DERs) for Provision of Frequency Regulation Services

Alejandro D. Domínguez-García

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

Email: aledan@ILLINOIS.EDU

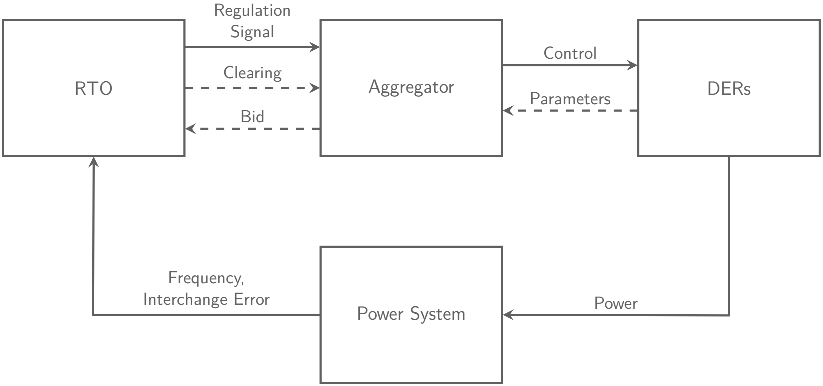
CERTS Transmission Reliability Program Review
Washington, DC
June 14, 2017

CERTS
Consortium for Electric Reliability Technology Solutions

Background and Motivation

- The need for frequency regulation is increasing as variable renewable energy is being integrated into the grid
- The value of fast and accurate frequency regulation has increased following FERC Order No. 755
- Power electronics, communications, and control are enabling the utilization of DERs to provide frequency regulation
- Individual DERs may not meet minimum size or performance requirements to participate directly in ancillary services market
  $\Longrightarrow$ They must be aggregated in order to participate

Aggregator's Role



Aggregator: Agent that coordinates DERs to provide ancillary services and participates, on their behalf, in the corresponding market as a single entity

Overall Project Objective

Objective: To develop decision-making tools for aggregators that enable the reliable utilization of DERs for provision of frequency regulation services under uncertainty

Uncertain phenomena include:

- Failures in communication and control hardware
- Un-modeled plant dynamics
- Forecast erros

Looking Back

- Developed reduced order models to capture the ability of DERs to provide frequency regulation
- Developed a framework to evaluate the impact of uncertainty on the capacity of aggregation systems
  - It takes into account communication link failures and control hardware failures between aggregator and DERs
  - Framework can be used to construct a probability-capacity duration contour
  - These curves are critical to enable aggregators to participate in the market with a quantifiable confidence level
- Developed a control architecture for coordinating the response of DERs to provide frequency regulation
  - It takes into account uncertainty in regulation signal
  - It takes into account un-modeled plant dynamics

Problem Setting

- An aggregator submits an offer to provide frequency regulation services
- To deliver the service if the offer is accepted, the aggregator must coordinate the response of a set of heterogenous DERs
- The DERs are compensated for participation through negotiated bilateral contracts agreed to ex ante
- The profit of the aggregator is the difference between
  - revenue obtained from selling the service, and
  - costs incurred by (i) payments to DERs, and (ii) penalties for not being able to follow the frequency regulation signal
- Revenue is determined by the market clearing price, which is fixed before service delivery

DER Individual Dynamics

- Flexibility: Ability to vary power consumption without compromising end function
- Generalized model describing DER flexibility

$$
\begin{aligned}
&\dot{p}^{(i)}(t) = u^{(i)}(t) \\
&\dot{x}^{(i)}(t) = -a^{(i)}x(i)(t) - p^{(i)}(t) \\
&-\underline{u}^{(i)} \le u^{(i)}(t) \le \overline{u}^{(i)}, \qquad -\underline{p}^{(i)} \le p^{(i)}(t) \le \overline{p}^{(i)}, \qquad |x^{(i)}(t)| \quad \le C^{(i)}
\end{aligned}
$$

$u^{(i)}$	resource input command
$p^{(i)}$	resource output (regulation power)
$x^{(i)}$	energy
$a^{(i)}$	dissipation constant
$-\underline{u}^{(i)}$, $\overline{u}^{(i)}$	up/down rate limit
$-\underline{p}^{(i)}$, $\overline{p}^{(i)}$	maximum variation around nominal power
$C^{(i)}$	energy capacity limit

DER Coordination Problem Formulation

- Aggregator maximizes profit by minimizing DER payments and penalties incurred for not following regulation signal
- Find functions $u^{(i)}$ that minimize total cost:

$$\int_{t_0}^{t_f} \pi_p |\sigma X r(t) - \sum_{i=1}^{n} p^{(i)}(t)| + \sum_{i=1}^{n} \left(\pi_1^{(i)} p^{(i)}(t) + \pi_2^{(i)} |x^{(i)}(t)| \right) dt$$

subject to DER dynamics

$\pi_1^{(i)}$	regulation power price paid to DERs
$\pi_2^{(i)}$	regulation energy price paid to DERs
π_p	imbalance penalty
X	regulation capacity bid
σ	fraction of bid dispatched
r	normalized regulation signal
$[t_0, t_f]$	regulation horizon

- Problem reduces to a linear program if regulation signal known in advance [Not the case in practice]

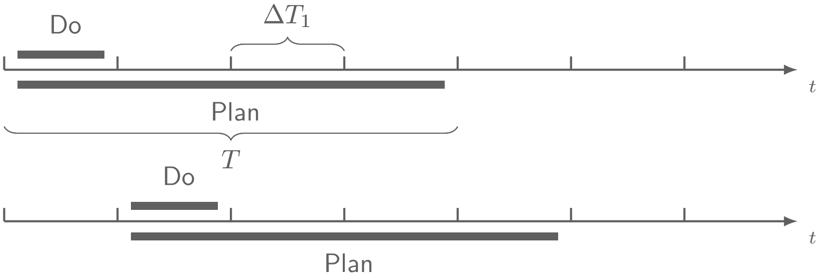
Solution under Imperfect Information

- Two primary sources of uncertainty:
  - Regulation signal
  - Virtual battery model parameters

- We developed a bilayer control architecture that provides a sub-optimal solution but accounts for uncertainty:
  - Top layer:
    - All costs are considered
    - A forecast of the regulation signal is used
    - Provides a reference signal to the DERs
  - Bottom layer
    - Closed-loop control for regulating around top layer solution
    - Mitigates error arising from forecast error and model mismatch

- Time-scale separation between the actions of both layers:
  - At slow time scales, MPC gives us foresight to make best use of resources with capacity constraints
  - At fast time scales, AGC-like control gives robustness, stability

Top Layer Control



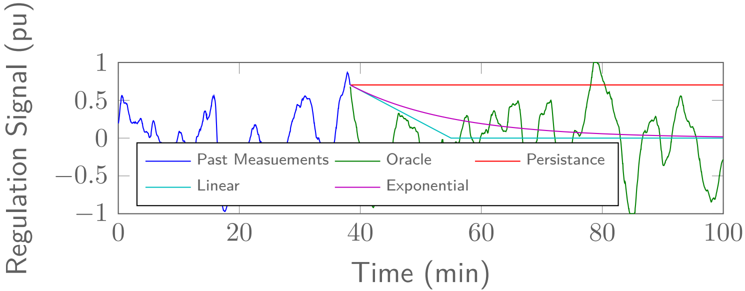
- Solution: Model Predictive Control with fixed prediction horizon T:
  - S1. At time t_0, calculate next $N = T/\Delta T_1$, control actions
  - S2. Apply only first action
  - S3. Recalculate based on new data

- MPC solution requires a forecast of the regulation signal

- Results can be improved by de-weighting future costs

Regulation Signal Forecast

- Methods considered:
  - Persistence $r_{k+l|l} = r_{l|l}$
  - Linear $r_{k+l|l} = r_{l|l} \cdot \max(1 - \alpha_1 k \Delta T_1, 0)$
  - Exponential $r_{k+l|l} = r_{l|l} \cdot e^{-\alpha_1 k \Delta T_1}$



Numerical Example

Parameter	Description	Value	Unit
$\overline{u}^{(1)}$, $\underline{u}^{(1)}$	Ramp Limit	0.04	MW/s
$\overline{u}^{(2)}$, $\underline{u}^{(2)}$	Ramp Limit	0.096	MW/s
$\overline{p}^{(1)} = \underline{p}^{(1)} = m^{(1)}$	Regulation Limit	11.9	MW
$\overline{p}^{(2)} = \underline{p}^{(2)} = m^{(2)}$	Regulation Limit	7.9	MW
$C^{(1)}$	Storage Energy Limit	0.45	MWh
$C^{(2)}$	Storage Energy Limit	0.15	MWh
$a^{(1)}$, $a^{(2)}$	Dissipation Constant	0	s^{-1}

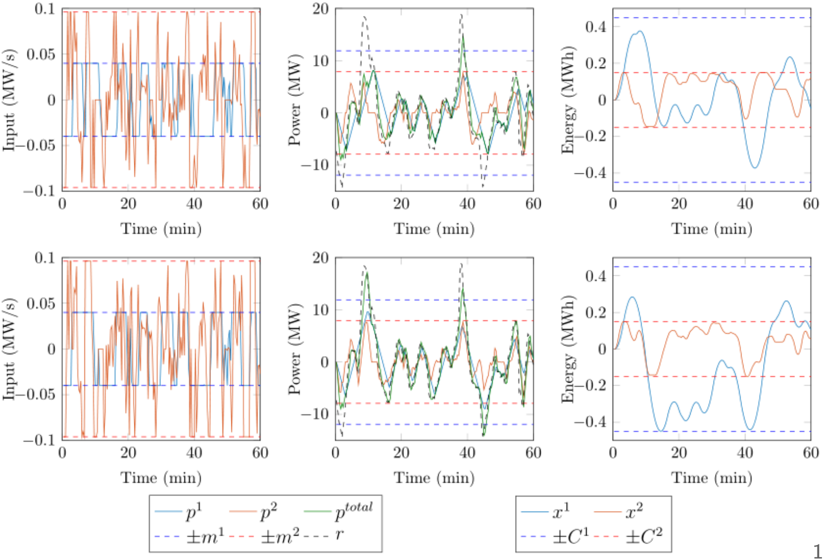
Parameter	Description	Value	Unit
$\pi_1^{(1)}$	Regulation Price	14.3	\$/MW
$\pi_1^{(2)}$	Regulation Price	42.9	\$/MW
$\pi_2^{(1)}$,$\pi_2^{(2)}$	Energy Price	0	\$/MWh
π_p	Imbalance Price	143	\$/MWh
σX	Regulation Signal Magnitude	18.9	MW
ΔT_1	Time Step	20	s
T	Prediction Horizon	600	s

Numerical Simulations

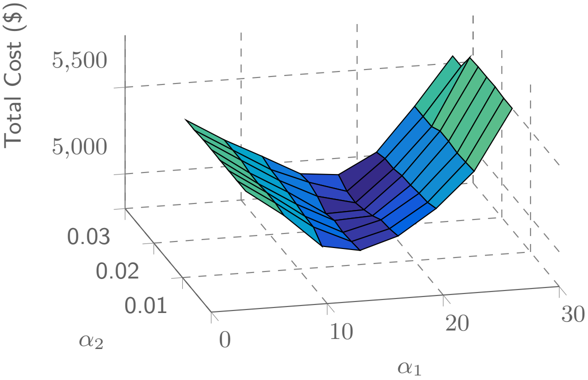
Forecast Method	Total Cost ($)
Persistence	481.32
Linear	466.91
Exponential	468.91
Oracle	365.05

- Solutions with different forecast methods benchmarked against oracle solution (i.e., perfectly known regulation signal)
  - PJM regulation signal historical data
- Linear and exponential both improve upon persistence forecast
- Forecasts can be improved by using dynamic prediction models
  - Use past data in regulation signal (e.g., ARMA)

Exponential and Oracle Forecasts



Parameter Sensitivity



α_1	rate of decay to mean value for linear and exponential forecasts
α_2	future cost de-weighting factor

Bottom Layer Control

Regulates DER outputs around the top layer solution:

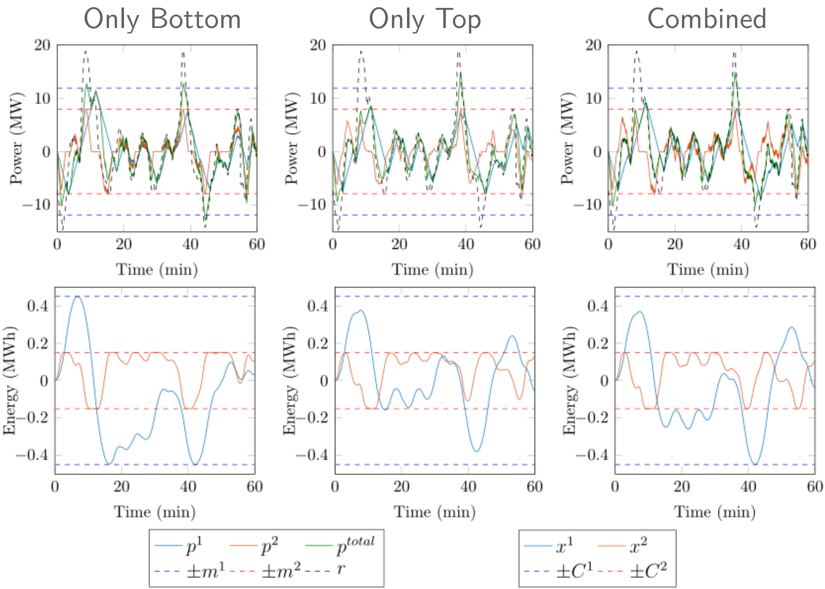
$$z_{k+1} = z_k + \Delta T_2 \eta_2 \overbrace{\left(\sigma X r_k - \sum_{i=1}^{n} p_k^{(i)}\right)}^{\text{regulation signal tracking error}}$$

$$p_{k+1}^{(i)*} = \beta^{(i)} \left(\eta_1 \left(\sigma X r_k - \sum_{i=1}^{n} p_k^{(i)}\right) + z_{k+1}\right) + \overbrace{p_{\mathrm{MPC}}^{(i)}}^{\text{top layer solution}}$$

$$u_k^{(i)} = \left[\frac{p_{k+1}^{(i)*} - p_k^{(i)}}{\Delta T_2}\right]^+ \leftarrow \text{ensures DER constraints are respected}$$

$p_{\mathrm{MPC}}^{(i)}$	Optimal power value as calculated by top layer control
$p_k^{(i)}$	Power output at instant k
z_k	Controller internal state at instant k
r_k	Regulation signal at instant k
ΔT_2	Controller time step
η_1, η_2	Controller gains
$\beta^{(i)}$	Participation factor

Numerical Example (Continued)

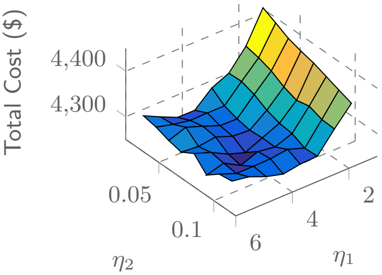


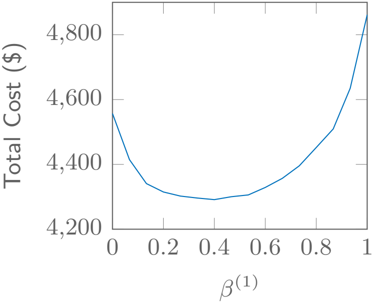
Cost vs Controller Type

- Bottom layer control better tracks small variations in regulation signal
- Top layer control uses prediction to spend less time bounded by energy constraints
- The bilayer controller combines these two advantages

Control	Time-Step	Total Cost ($)
Bottom Layer	20 s	584.39
Bottom Layer	2 s	480.58
Top Layer	20 s	470.37
Top Layer	2 s	362.10
Bilayer	2 s/20 s	387.13

Parameter Sensitivity





- Costs are more sensitive to gain η_1 than to gain η_2
- Optimal participation factor $\beta^{(1)}$ is 0.4

Concluding Remarks

- We developed reduced order models to capture the ability of DERs to provide frequency regulation

- We developed a control architecture to enable the utilization of DERs for provision of frequency regulation services
  - Two layers with time-scale separation between their actions
  - It accounts for uncertainty in regulation signal
  - It accounts for uncertainty in model parameters

- We proposed a framework to capture the impact of uncertainty on the capacity of DER aggregation systems
  - Scalable
  - Computationally efficient and accurate
  - Critical for aggregators to participate/bid in electricity markets with a quantifiable confidence level

- Ongoing work aims to take into account the lower-level distribution network to which the DERs are connected

Publications

Journal papers

[J1] J. Zhang, and A. D. Domínguez-García, “Evaluation of Demand Response Resource Aggregation System Capacity Under Uncertainty," *IEEE Transactions on Smart Grid*, to appear.

[J2] J. Zhang, and A. D. Domínguez-García, “On the Impact of Measurement Errors on Power System Automatic Generation Control," *IEEE Transactions on Smart Grid*, to appear.

[J3] J. T. Hughes, A. D. Domínguez-García, and K. Poolla, “Identification of Virtual Battery Models for Flexible Loads," *IEEE Transactions on Power Systems*, vol. 31, no. 6, 4660-4669, November 2016.

Conference papers

[C1] J. T. Hughes, A. D. Domínguez-García, and K. Poolla, “Coordinating Heterogeneous Distributed Energy Resources for Provision of Frequency Regulation Services," in Proc. of the Hawaii International Conference on System Sciences, Big Island, HI, January 2017.

[C2] J. Zhang and A. D. Domínguez-García, “Augmenting the Power System Toolbox: Enabling Automatic Generation Control and Providing a Platform for Cyber Security Analysis," in Proc. of the North American Power Symposium, Denver, CO, September 2016.

[C3] J. T. Hughes, A. D. Domínguez-García, and K. Poolla, “Virtual Battery Models for Load Flexibility from Commercial Buildings," in Proc. of the Hawaii International Conference on System Sciences, Kauai, HI, January 2015.