GRID MODERNIZATION INITIATIVE PEER REVIEW

GMLC 1.4.10—Control Theory

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Sheraton Pentagon City – Arlington, VA

Control Theory
High-Level Summary

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Project Description

Develop new integrated optimization and control solutions, including architectures, algorithms, and deployment strategies to transition to a large number of distributed energy resources (DERs) participating in grid control.

Value Proposition

- ✓ Integrated optimization and control systems that are more effective at maintaining operating margins.
- ✓ A 33% decrease in cost of reserve margins while maintaining reliability by 2025.
- ✓ Interconnection of intermittent power generation with less need for electrical storage and lower integration costs.

Project Objectives

- ✓ Ensure architectural compatibility of control theory and solutions.
- ✓ Coordinate time and grid scales across architecture to enable tractable control and optimization of >10,000 DERs.
- ✓ Coordinate and "homogenize" diverse DERs with widely different responses.
- ✓ Incorporate power flow physics and network constraints into control solutions.
- ✓ Systematically manage uncertainty from intermittent generation and from controlled response of a large number of DERs.
- ✓ Enable integration with legacy systems and bulk power system markets.

Control Theory
Project Team

Project Participants and Roles

R&D Team:
- ✓ LANL (lead)—risk-aware optimization, aggregate device modeling
- ✓ PNNL (co-lead)—real-time control, aggregate device modeling, simulation-based testing
- ✓ INL—metrics
- ✓ ANL—power flow
- ✓ ORNL, LLNL, SNL—testing and control design
- ✓ NREL—real-time control, aggregate device modeling

Industry Advisors:
- ✓ Oncor Electric Delivery
- ✓ PJM Interconnection LLC
- ✓ United Technologies Research Center

PROJECT FUNDING			
Lab	**FY16 $**	**FY17 $**	**FY18 $**
LANL	905,000	670,000	405,000
PNNL	785,000	525,000	720,000
INL	185,000	225,000	0
ANL	290,000	220,000	145,000
ORNL	50,000	50,000	0
LLNL	50,000	100,000	60,000
SNL	100,000	100,000	0
NREL	215,000	245,000	425,000

Control Theory
Relationship to Grid Modernization MYPP

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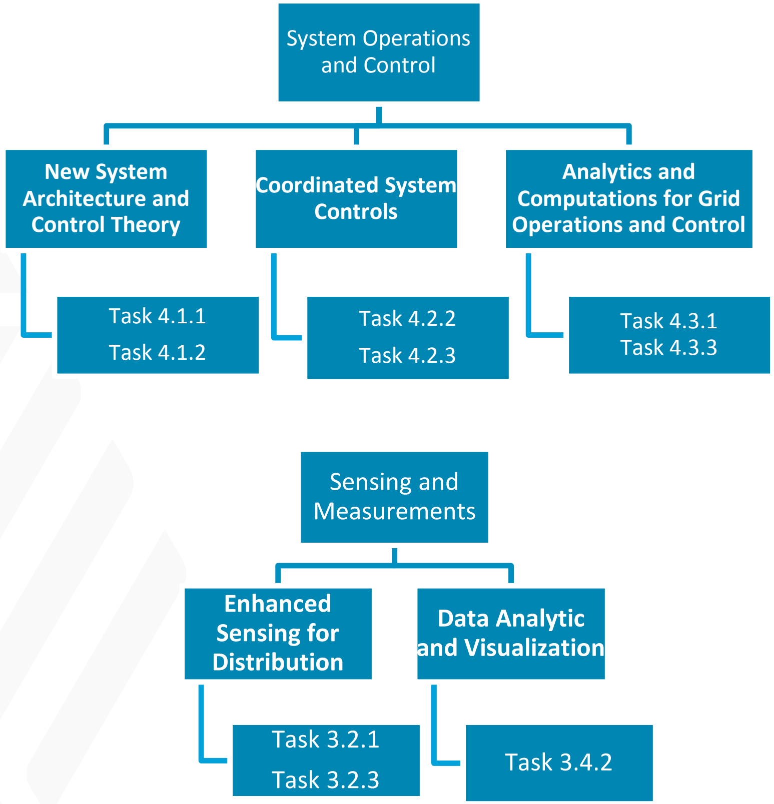
Relationship to Systems Operations, Power Flow, and Control area:

- ✓ Develop comprehensive architectural models, control theory, and algorithms
- ✓ Integrate bulk power systems, distribution systems, and end-use DERs
- ✓ Improve analytics and computation for grid operations and control.

The control theory effort will support the GMLC multi-year program plan vision for transitioning the power grid to a state where a huge number of DERs are participating in grid control.



Control Theory
Approach

Task 1: Architecture and metrics

- ✓ Develop new and evaluate existing control system architectural decompositions.
- ✓ Develop and apply metrics for architecture and control system performance evaluation.

Task 2: Integrated optimization and control

- ✓ Develop individual and aggregate DER flexibility models and associated constraints.
- ✓ Design real-time control strategies for aggregated DERs with uncertainty quantification.
- ✓ Develop power flow relaxation and approximation methods for distribution systems.
- ✓ Develop optimization methods that integrate uncertain real-time control into risk-aware power flow optimization.

Task 3: Numerical testing

- ✓ Specify and develop simulation test bed requirements.
- ✓ Test control strategies for aggregated DERs, including power flow models on ~10 distribution feeders including~10,000 DERs

Control Theory
Approach

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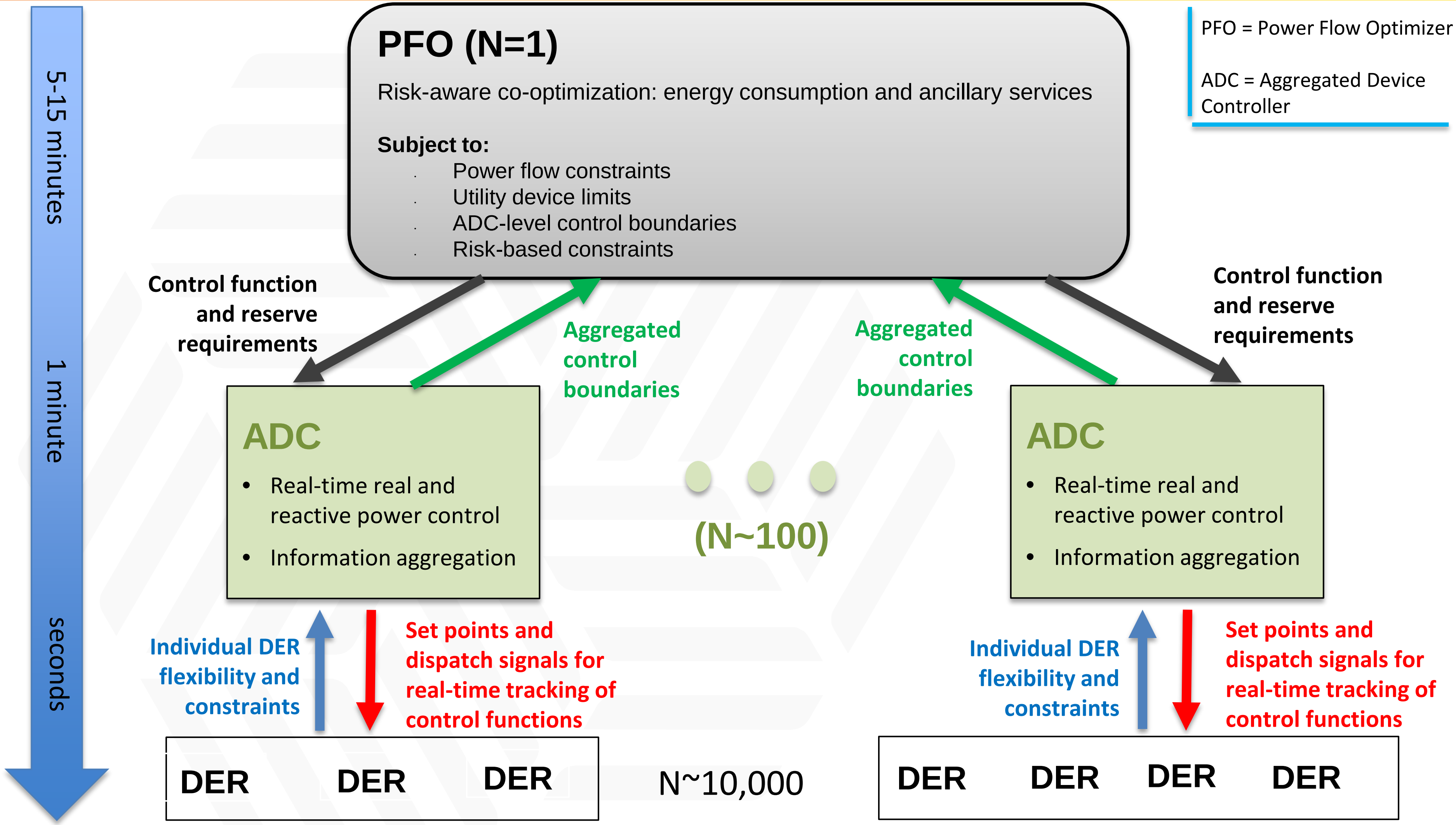
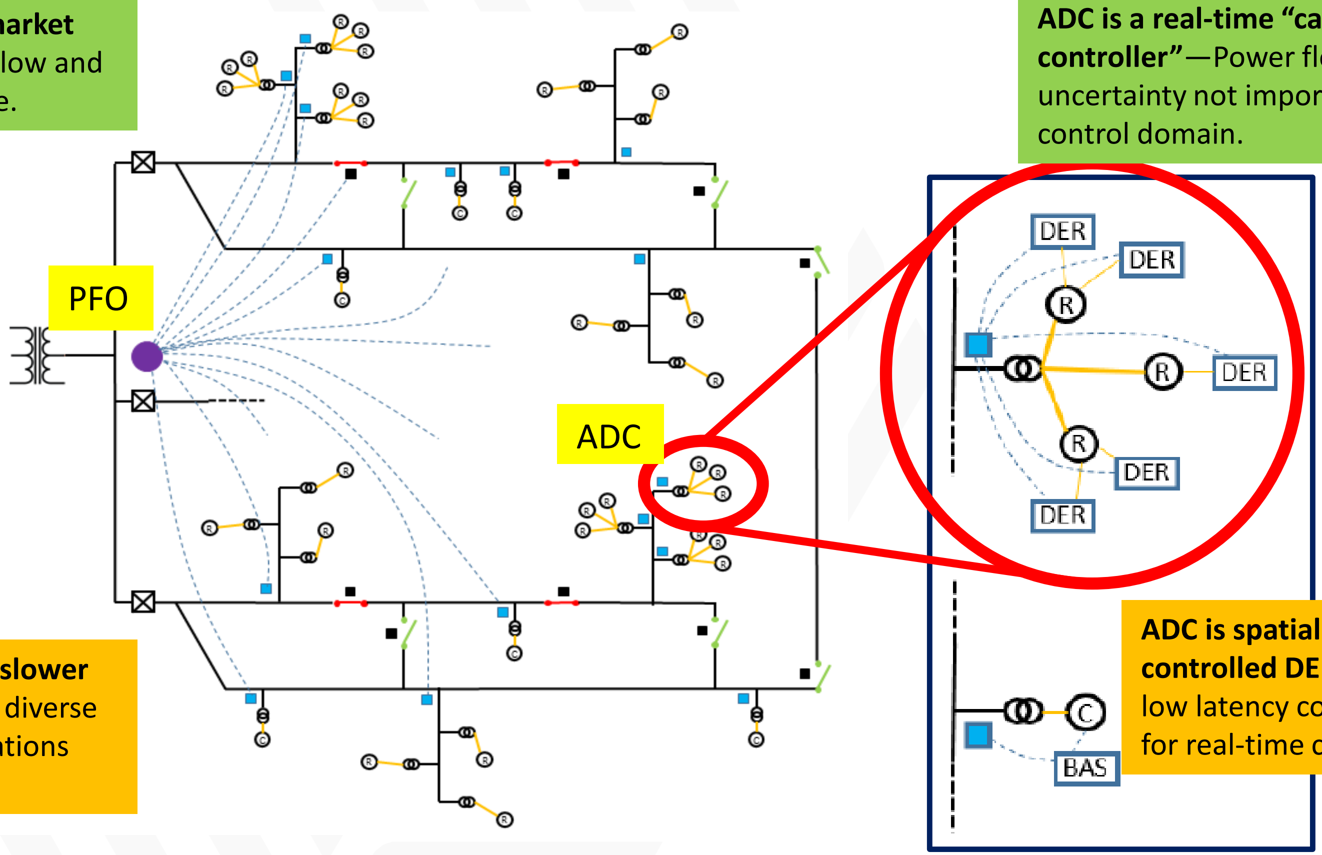


Coordination over both temporal and spatial/grid scales creates a theoretical framework for architecturally compatible solutions that integrate optimization and control.

PFO is a "network/market optimizer"—Power flow and uncertainty dominate.

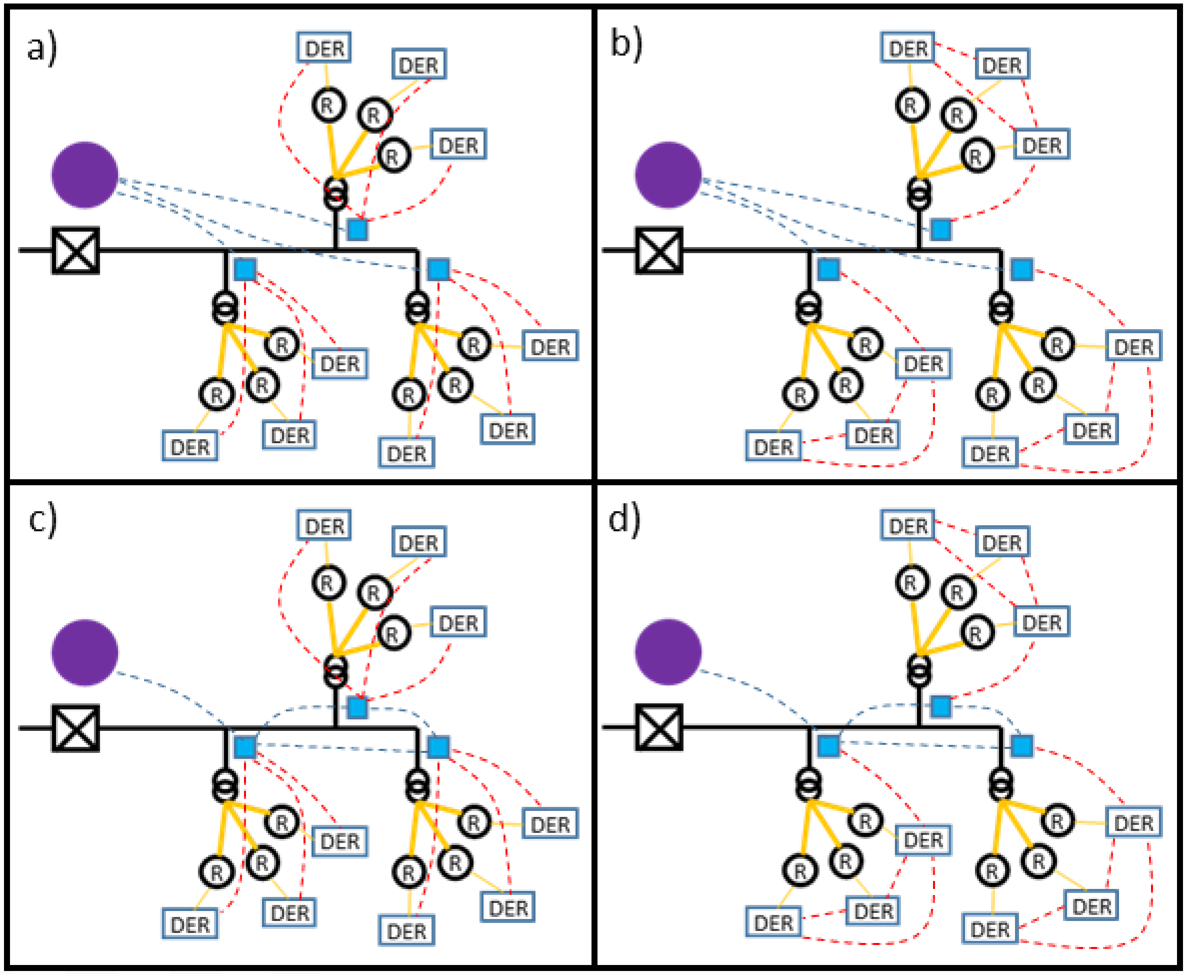
ADC is a real-time "capacity controller"—Power flow and uncertainty not important in ADC control domain.



PFO optimization on slower time scales—enables diverse siting and communications options.

ADC is spatially adjacent to controlled DERs—enables fast, low latency communications for real-time control.

Control Theory
Approach—Alternative Frameworks



Planned work

ADC distributed control

PFO distributed optimization

Distributed PFO and ADC

Control Theory

Key Project Milestones

Milestone (FY16-FY18)	Status	Due Date
Control Theory Road Map Milestone	**Completed**	**11/1/16**
Task 1.1: Documented architectural reference models for control that includes three key scenarios: legacy systems, communications-heavy systems, and communications lite systems.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.1: Documented catalog of required individual and aggregate load/DER models and roadmap of theoretical development steps to achieve tractable load/DER models.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.2: Documented catalog of existing and alternative power flow relaxations and approximations for distribution systems with discussion of applicability to optimization and control of distribution networks and down select for further numerical testing.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.3: Documented preliminary formulation and development roadmap for risk-aware control of multiple distribution circuits with >10,000 DERs including power flow physics, legacy equipment and network constraints.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.4: Documented initial design of control methodologies for aggregated and individual load/DER models.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**

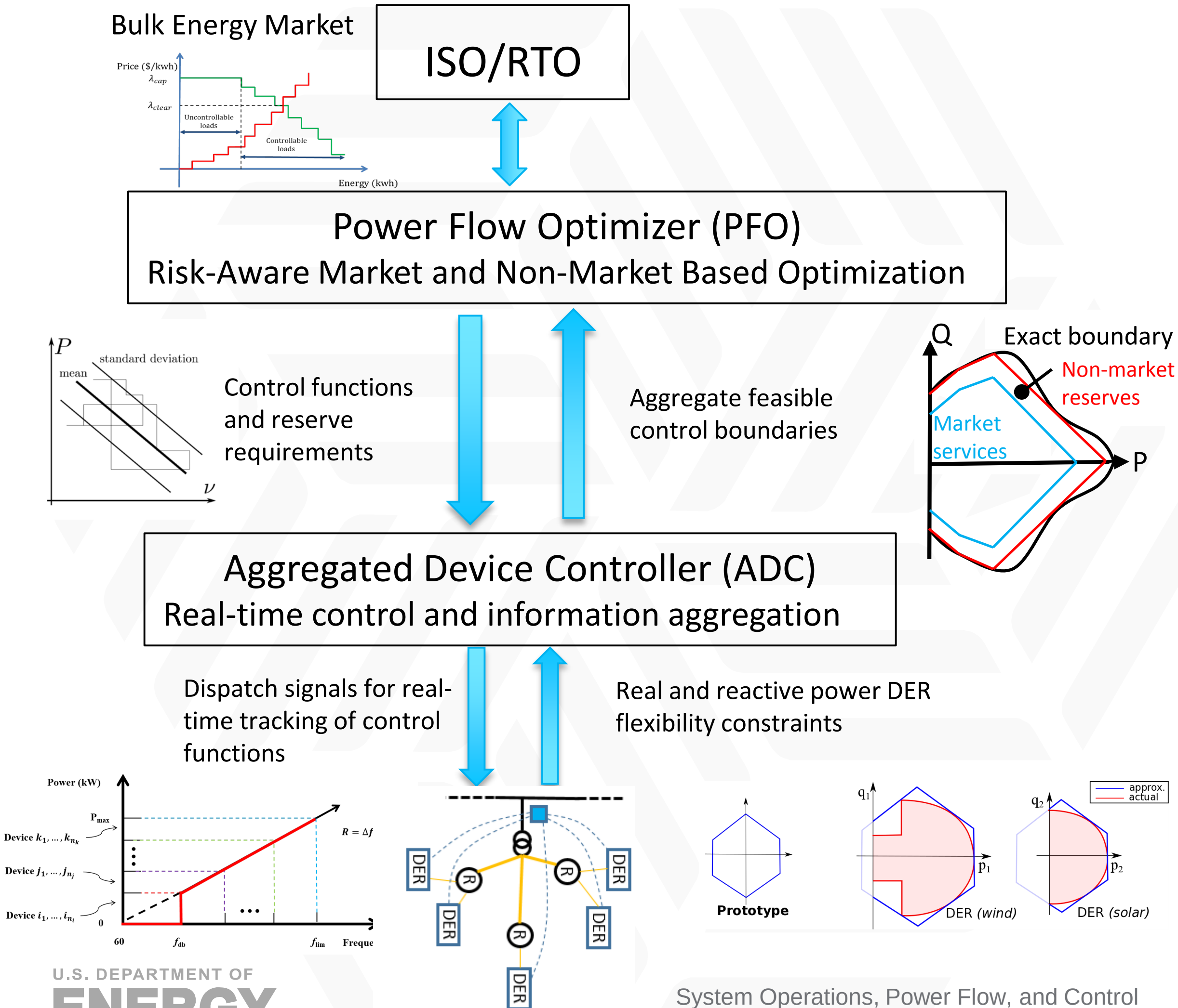
Control Theory

Key Project Milestones

Milestone (FY16-FY18)	Status	Due Date
Task 1.1: Documented architectural reference models with extensions to include market/control interactions, multi-structure architecture diagrams and detailed data.	**Completed.** High-level architecture package. Extension. Publication on detailed mathematical formulation of market integration in progress	**4/1/17**
Task 2.1: Aggregated energy and ancillary service bids and flexibility constraints formulated.	**Completed.** Initial formulation. **Revision.** Initial formulation required revision to enable all ancillary services anticipated in Task 1 and 2.3.	**4/1/17**
Task 2.4: Documented final specifications for the hierarchical control framework for each of the architectural reference models including topologies, communications, data exchange, and time scales.	**Completed.** Details presented in later slides.	**4/1/17**
Task 3: Documented numerical simulation test bed requirements and down select (adapt existing vs develop new).	**In Progress.** Completed initial test plan for addressing distribution level optimization and control of DERs.	**10/1/17**

Control Theory

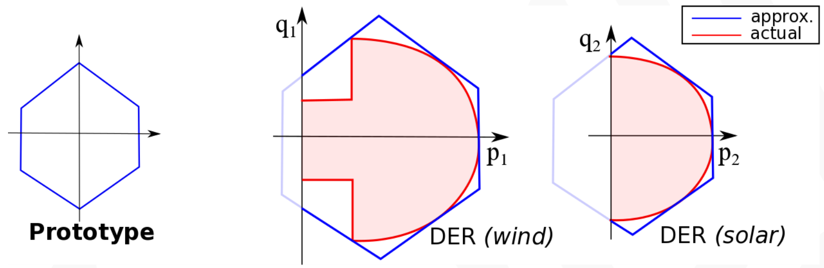
Accomplishments to Date—Project Wide



Major accomplishments:

- ✓ Developed interfaces for PFO-bulk system, PFO-ADC and ADC-DER
- ✓ Completed initial mathematical formulations for each interface
- ✓ Submitted 5 conference papers and 2 journal papers

Algorithm for determining aggregate feasible control boundaries



Step 1: Choose a prototype domain (convex polygon)

$$\mathcal{Y} = \{(p,q) \mid F_1\, p + F_2\, q \le d\} \xrightarrow{\mathcal{H}} \begin{cases} (p_1, q_1) \in \mathcal{Y}_1 \subseteq \alpha_1\, \mathcal{Y} + \beta_1 \\ (p_2, q_2) \in \mathcal{Y}_2 \subseteq \alpha_2\, \mathcal{Y} + \beta_2 \end{cases}$$

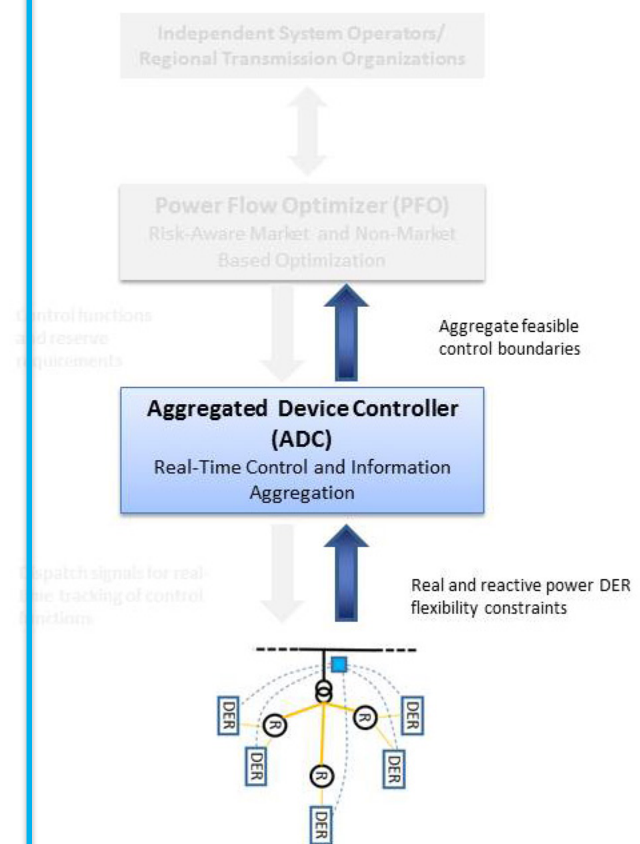
Step 2: Apply homothetic transformation (scaling and translation) to approximate (homogenize) DER flexibility

$$(p_1 + p_2\,,\ q_1 + q_2) \in \mathcal{Y}_1 \uplus \mathcal{Y}_2 \subseteq (\alpha_1 + \alpha_2)\, \mathcal{Y} + (\beta_1 + \beta_2)$$

Step 3: Compute algebraic calculations to approximate the aggregate flexibility (no Minkowski)

Key technical challenges

- Define and measure quality/tightness of approximation
- Capturing the (stochastic) uncertainties in DER flexibility



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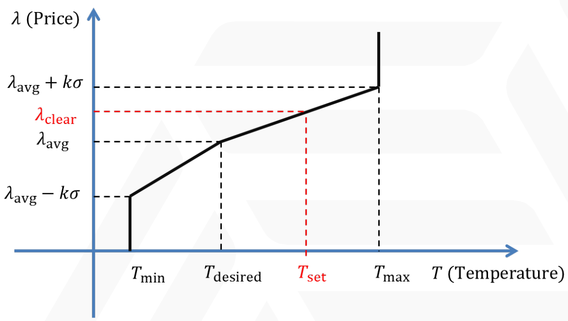
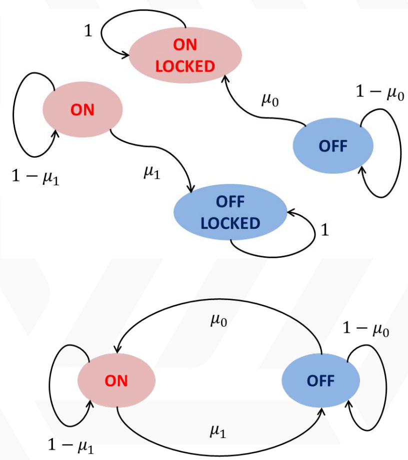
Real-time tracking of power set points and ancillary service control functions

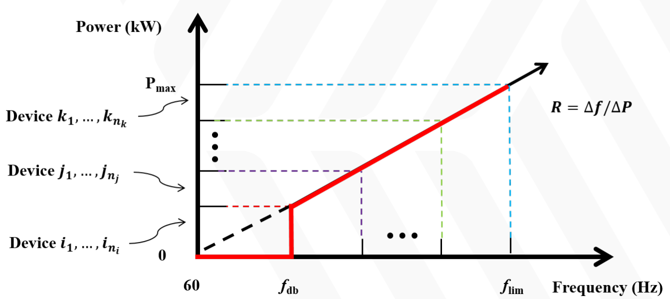
Energy Set point

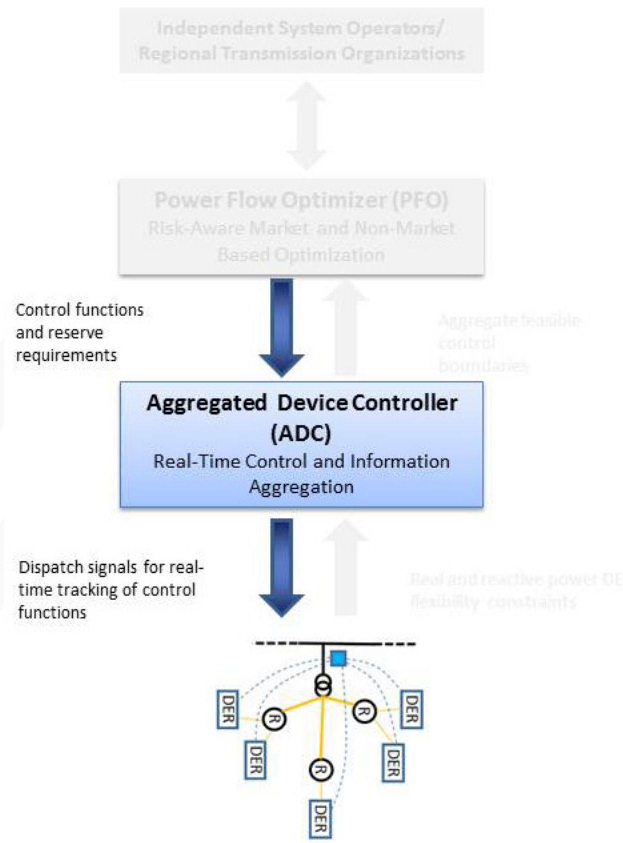


Frequency Regulation



Primary Frequency Control





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Risk-aware power flow optimization

Power flow

$$\min_{p,v,\alpha,r^+,r^-} \sum_{i\in\mathcal{G}} c_i p_i + \sum_{j\in\mathcal{W}} c_j v_j + \sum_{i\in\mathcal{W},\mathcal{G}} (c_i^+ r_i^+ + c_i^- r_i^-)$$

$$P_{ij} = P_j + \sum_{k:(j,k)\in\mathcal{L}} (P_{jk} + R_{ij}\ell_{ij})$$

$$Q_{ij} = Q_j + \sum_{k:(j,k)\in\mathcal{L}} (Q_{jk} + X_{ij}\ell_{ij})$$

$$|V_j|^2 - |V_i|^2 = -2\left(R_{ij}P_{ij} + X_{ij}Q_{ij}\right) + \left(R_{ij}^2 + X_{ij}^2\right)\ell_{ij}$$

$$\ell_{ij}\,|V_i|^2 = P_{ij}^2 + Q_{ij}^2$$

Risk-aware ADC constraints

$$p + r^+ \leq p_G^{max} \;,$$

$$p - r^- \geq p_G^{min} \;,$$

$$WCC\left(-\alpha_i\tilde{\Omega} > r_i^+\right) \leq \epsilon_i \;, \quad \forall_{i\in\mathcal{G}} \;,$$

$$WCC\left(-\alpha_i\tilde{\Omega} < r_i^-\right) \leq \epsilon_i \;, \quad \forall_{i\in\mathcal{G}} \;,$$

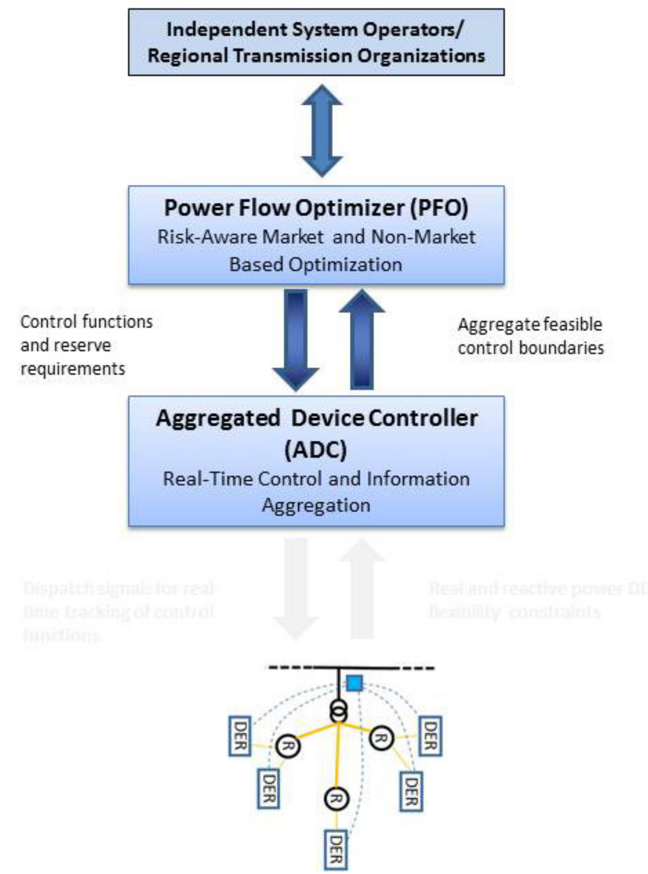
Risk-aware network constraints

$$WCC\left(\mathbf{M}_{(ij,\cdot)}(p - \alpha\tilde{\Omega} + \tilde{v} - d) > p_{ij}^{max}\right) \leq \epsilon_{ij} \;, \quad \forall_{ij\in\mathcal{E}} \;,$$

$$WCC\left(\mathbf{M}_{(ij,\cdot)}(p - \alpha\tilde{\Omega} + \tilde{v} - d) < -p_{ij}^{max}\right) \leq \epsilon_{ij} \;, \quad \forall_{ij\in\mathcal{E}}$$

Key technical challenges

- Nonlinear power flow equations
- Non-convex ADC control functions
- General probability distributions for uncertainty



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Response to December 2016 Program Review

Recommendation	Response
Please make sure there is "congruence" between the use cases/test cases in the TDC design and planning tools project with this Control Theory project	PNNL lead for HELICS (TDC) development (Jason Fuller) has written test plan to ensure proper use case crossover.
Realizing that this project covers difficult subject matter, better articulate the value and benefit of these activities as part of the Annual Peer Review in April. Please be mindful of the level of understanding of the audience.	Attempted to provide additional clarity through block diagram descriptions of approach.

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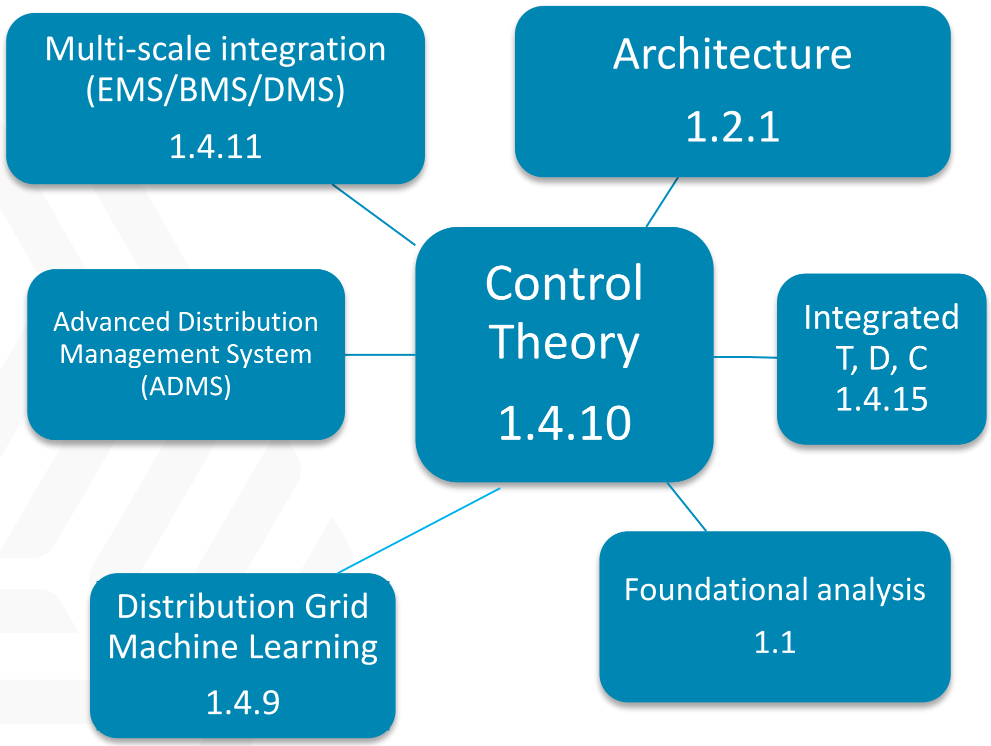
Project Integration and Collaboration

- ✓ **1.2.1:** Architectural views developed used to inform control theory.
- ✓ **1.4.11 & ADMS:** Prototype systems developed will ensure compatibly of control solutions to ensure near-term adoption.
- ✓ **1.4.9:** Data-driven methods to characterize uncertainty at ADC/PFO interface.
- ✓ **1.4.15:** Co-simulation platform will enable control solution testing at scale.
- ✓ **1.1:** Adopt and adapt the system control metrics and extend them where needed to make the metrics useful for assessing advances in control theory and architecture.



Control Theory

Next Steps and Future Plans

- ✓ **Extend control theory roadmap and developments** to distributed computational settings.
- ✓ **Small-scale field demonstration** to vet/test architecture in a real-world environment.
- ✓ **Workshop** with range of OE and EERE offices and industry representatives to further describe ADC functionality and PFO interaction across many DERs and create roadmap for coordinated controls development.

<Project Title>

Technical Details

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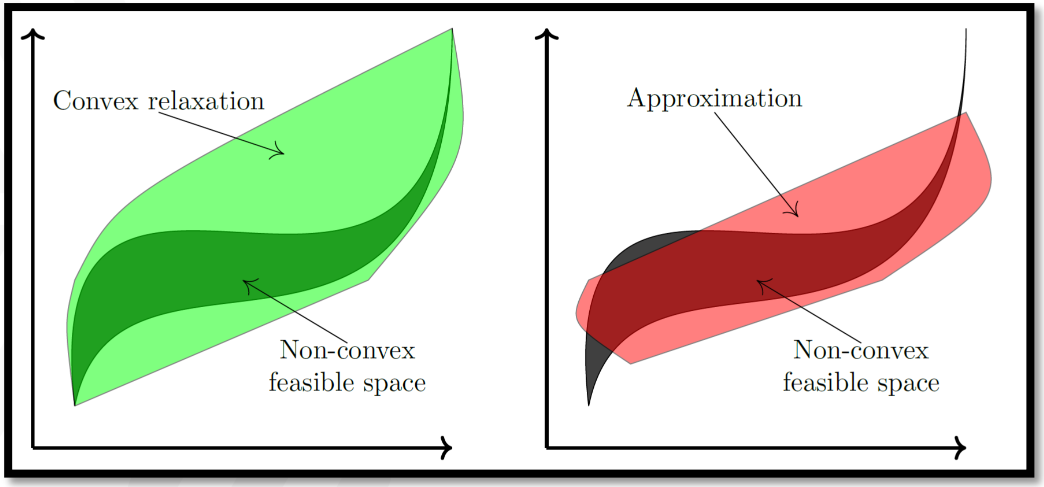
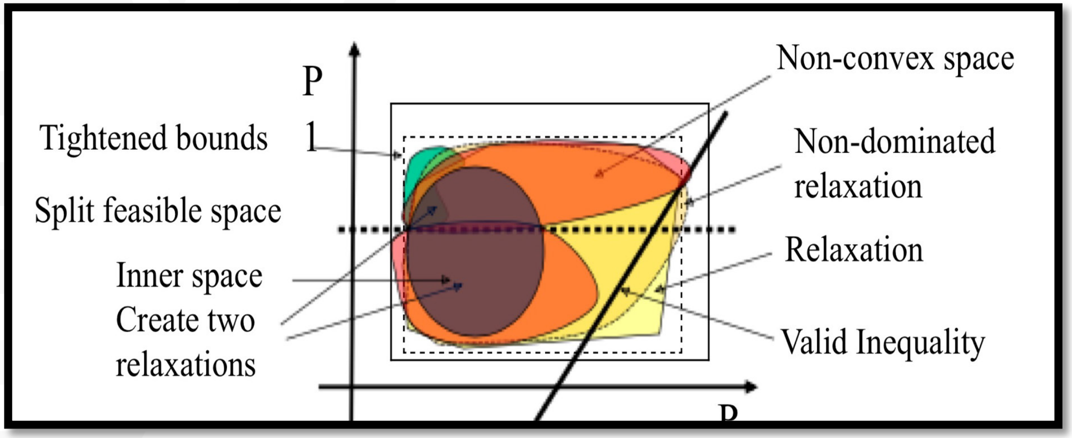
- Include technical backup here – no more than 5 slides

Power flow relaxations and approximations

- IEEE Review Article characterizing power flow formulations, relaxations, and approximations in final revisions for submission
- Developing metrics and methods for evaluation of accuracy and computational speed of each approach
- Testing will explore improvements in solution quality through simultaneous application of multiple methods
- Testing of computational efficiency and solution quality over next two quarters
- Down selecting based on qualitative assessments—probabilistic injections and power flows, discrete optimization variables



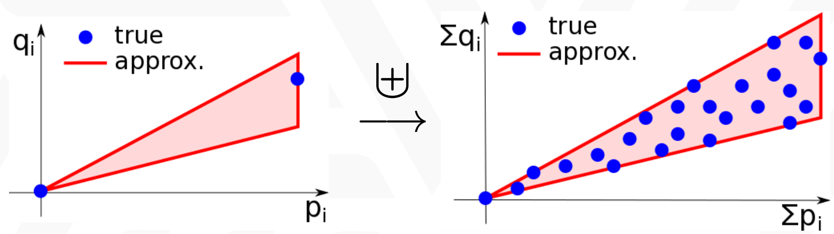


Algorithm for aggregating devices with discrete operating states

- Feasible set is a collection discrete points:
  - Switching devices (e.g. ACs, water heaters)

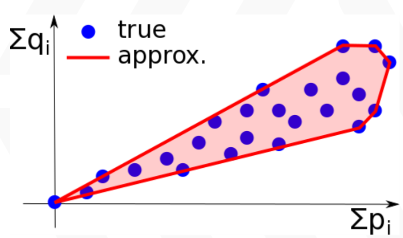
$$p_i \in \{0,\, p_i^{on}\}, \quad q_i = \gamma_i\, p_i$$

- **Method 1: Relax and aggregate** (using prototype)

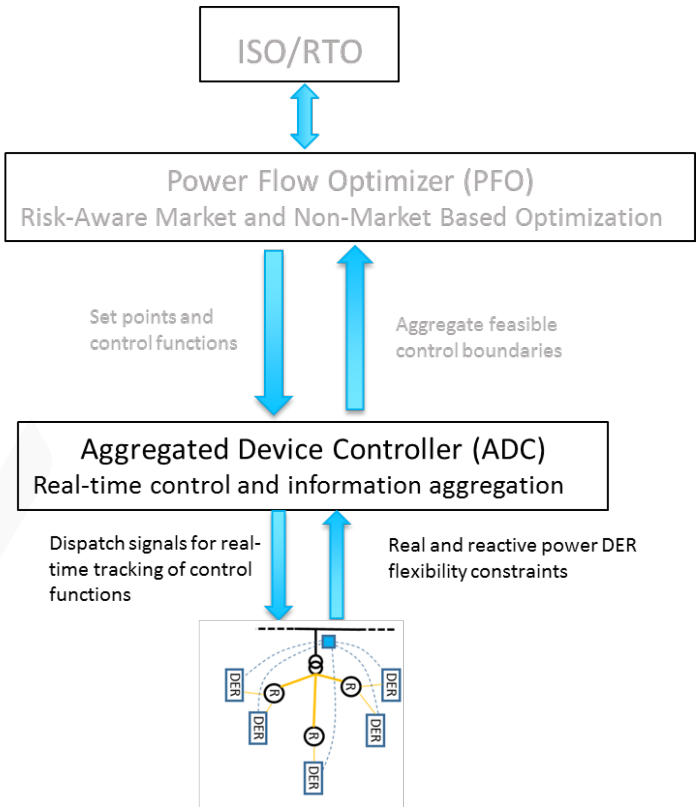


$$\mathcal{Y}_i^{\text{relax}} = \left\{ (p,q) \,\middle|\, p \in [0, p_i^{on}] \;,\; q \in \left[\underline{\gamma}\, p \,,\, \overline{\gamma}\, p \right] \right\}$$

- **Method 2: Aggregate and approximate**



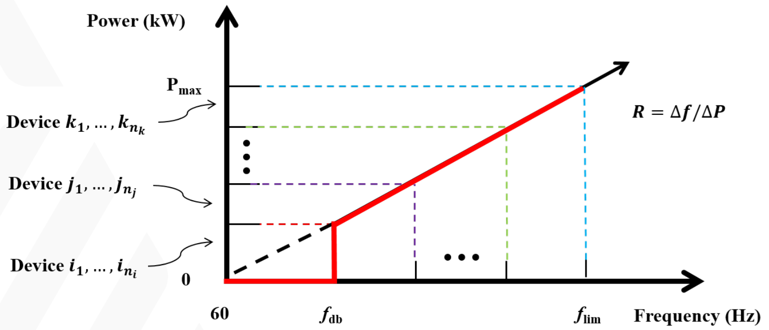
Q: Can we trace (or, approximate) the boundary of the convex hull directly?



ADC level real-time controls

- Design appropriate control strategies for aggregations of heterogeneous DERs to deliver ancillary services
  - Primary frequency response
  - Secondary frequency regulation
  - Flexible ramping
- Ensure real and reactive power control requirements met simultaneously

Primary frequency response



Secondary frequency regulation