Boolean Microgrid

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The ISO Problem

Research Objective

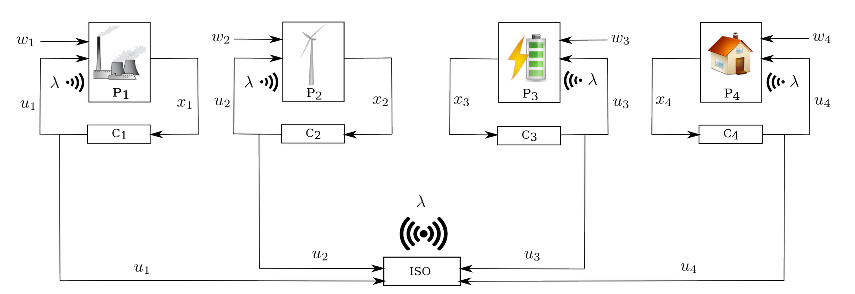
A theory for operation of the Independent System Operator (ISO) in smart grid with stochastic renewables, demand response, and storage.

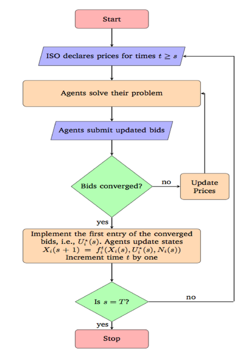
Research Challenges

1. How to price the power so as to regulate demand as well as allocating the generation from multiple fossil fuel and renewable sources?
2. Generators, storages and loads are all dynamical systems with constraints, e.g. ramping rate constraints for generators, capacity and rate constraints for storages, comfort range constraints for thermal inertial loads like air conditioners.
3. Renewable generation is stochastic. So is the future demand.
4. Generators (for business reasons) and loads (for privacy reasons) do not want to disclose their own utility functions, dynamics, and states.

Key Question: How should the ISO price power, so as to maximize the social welfare of generators, loads, and storages?

Proposed Architechture: Iterative Bidding Scheme





Formulation

minimize $\mathbb{E}\left[\sum_{t=0}^{T}\sum_{i=1}^{N} c_i\left(x_i(t), u_i(t)\right)\right]$ subject to (1) $\sum_{i=1}^{N} u_i(t) = 0,\ \forall\, t = 0, 1, 2, \ldots, T$, (2) $x_i(t+1) = f_i\left(x_i(t), u_i(t), w_i(t)\right)$. Assumption: the cost function is convex in the vector $\{u_i(t)\}_{i=0}^{T}$, for each realization of noise sequence.

Results: Algorithm for Iterative Bidding Scheme

for bidding times $s = 0$ to T, **do**

$k = 0$

repeat

each agent i solves $\underbrace{\operatorname{argmin}_{u_i(t)} \mathbb{E}\left[\sum_{t\geq s} c_i\left(x_i(t), u_i(t)\right) + \lambda_k(t) u_i(t)\right]}_{\{u_{i,k}(t)\}_{t=s}^{T}}$

and submits the bidding sequence $\{u_{i,k}(t)\}_{t=s}^{T}$ to the ISO.

ISO then declares new price sequence via subgradient iteration

$$\lambda_{k+1}(t) = \lambda_k(t)(1-\alpha_k) + \alpha_k \sum_{i=1}^{N} u_{i,k}(t), \forall t \in [s, T].$$

$k \to k+1$

until $u_{i,k}(t)$ converges a.s. to optimal bidding sequence $\{u_i^*(t)\}_{t=s}^{T}$.

ISO implements $u_i^*(s)$.

end for

References

[1] R. Singh, P.R. Kumar, and L. Xie, “The ISO Problem: Decentralized Stochastic Control Via Bidding Schemes”. *53rd Annual Allerton Conference on Communication, Control, and Computing*, Monticello, Illinois, Sept. 29–Oct. 2, 2015.

[2] R. Singh, K. Ma, A. Thatte, P.R. Kumar, and L. Xie, “A Theory for the Economic Operation of a Smart Grid with Stochastic Renewables, Demand Response and Storage”. *54th IEEE Conference on Decision and Control*, Osaka, Japan, Dec. 15–18, 2015.

The LSE Problem

Research Objective

A theory for operation of the Load Serving Entity (LSE) to enable demand response by controlling the aggregate power consumption for a population of thermostatically controlled loads (TCLs) such as residential air conditioners.

Research Challenges

1. How to design the *reference* total power trajectory as a function of the forecasted price of energy?
2. The room temperature, setpoint, and ON/OFF binary state of any individual TCL cannot be measured for privacy reasons.
3. The LSE may have different contractual obligations for different TCLs in terms of their comfort ranges.

Key Question: What is the *optimal* plan for the LSE to schedule the purchase of power? Also, how to control the TCLs in real-time to track the reference total power, while respecting privacy and comfort range constraints?

Idea: Adjust setpoints to meet the optimized target consumption.

Proposed Architecture: A Two Layer Approach

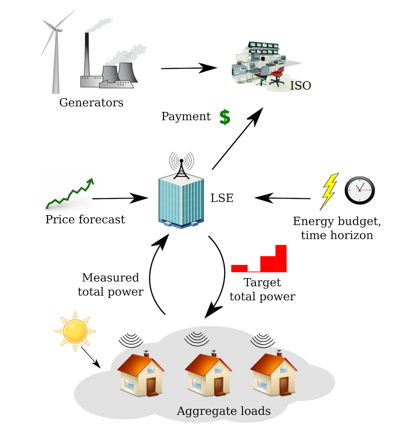


Fig. 1. Architecture of the proposed demand response system.

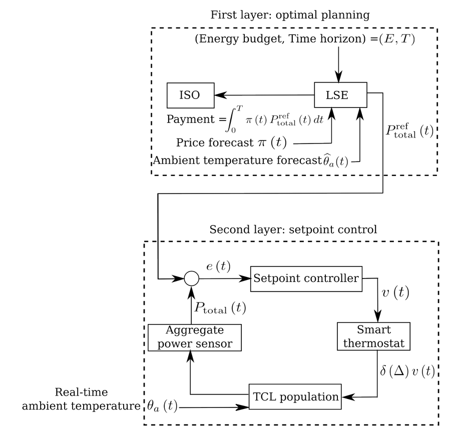


Fig. 2. Block diagram for the two layer control framework.

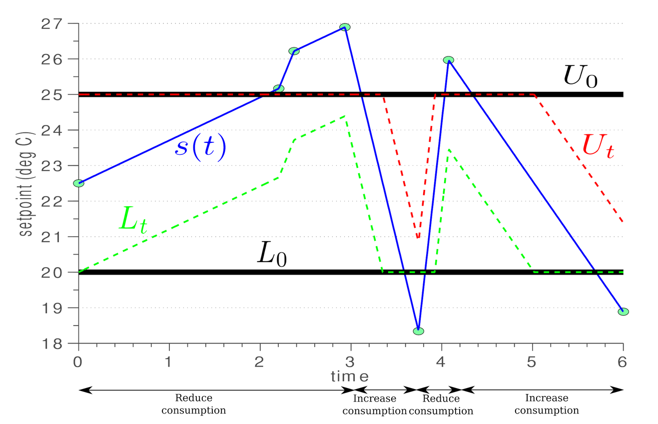


Fig. 3. Setpoint control with comfort range constraint to track optimal reference power trajectory.

Formulation

First layer: optimal planning of target consumption

$$\underset{\{u_1(t),\ldots,u_N(t)\}\in\{0,1\}^N}{\text{minimize}} \int_0^T P\pi(t)\left(u_1(t)+u_2(t)+\ldots+u_N(t)\right) \quad \mathrm{d}t,$$

subject to

(1) $\dot{\theta}_i = -\alpha\left(\theta_i(t) - \widehat{\theta}_a(t)\right) - \beta P u_i(t) \qquad \forall\, i = 1, \ldots, N,$

(2) $\int_0^T \left(u_1(t)+u_2(t)+\ldots+u_N(t)\right)\,\mathrm{d}t = \tau \doteq \dfrac{E}{P}(< T, \text{given})$

(3) $L_0^{(i)} \leq \theta_i(t) \leq U_0^{(i)} \qquad \forall\, i = 1, \ldots, N.$

Second layer: setpoint control

$$P^*_{\text{ref}}(t) = P\sum_{i=1}^{N} u_i^*(t), \qquad e(t) = P^*_{\text{ref}}(t) - P(t),$$

$$v(t) = k_p e(t) + k_i \int_0^t e(\tau)\mathrm{d}\tau + k_d \frac{\mathrm{d}}{\mathrm{d}t} e(t), \qquad \frac{\mathrm{d}s_i}{\mathrm{d}t} = \Delta_i v(t),$$

$$L_t^{(i)} = L_0^{(i)} \vee \left(s_i(t) - \Delta_i\right), \qquad U_t^{(i)} = U_0^{(i)} \wedge \left(s_i(t) + \Delta_i\right).$$

Results

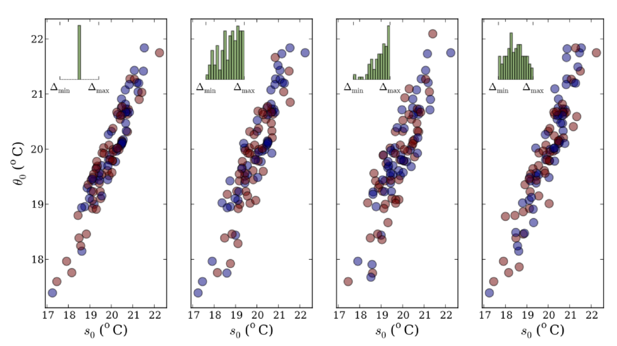


Fig. 4. 100 initial conditions $(s_0, \theta_0) \sim \mathcal{N}\left([20, 20]^\top, \begin{bmatrix} 1 & 0.5 \\ 0.5 & 3 \end{bmatrix}\right)$ where *red* denotes ON, and *blue* denotes OFF TCL. Four columns correspond to four different contract distributions (*inset histogram*). $\Delta_{\min} = 0.1^o\text{C}, \Delta_{\max} = 1.1^o\text{C}$.

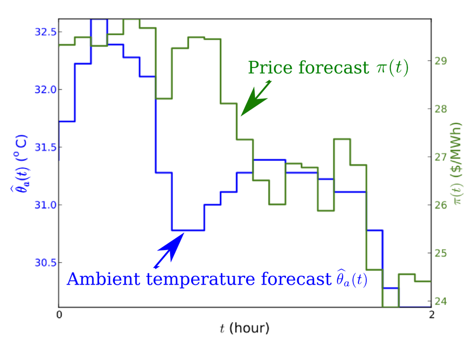


Fig. 5. Price and ambient temperature forecast for Houston on May 20, 2015, 4--6 pm.

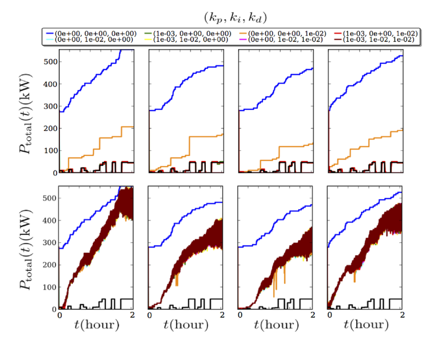


Fig. 6. PID controller tracks the total power consumption to the optimal reference consumption, with (*bottom row*) and without (*top row*) comfort constraints. Four columns are for four contract distributions, as in Fig. 4.

References

[1] A. Halder, X. Geng, G. Sharma, L. Xie, and P.R. Kumar, “A Control System Framework for Privacy Preserving Demand Response of Thermal Inertial Loads”. *6th IEEE International Conference on Smart Grid Communications*, Miami, Florida, Nov. 2–5, 2015.