Exploiting Flexible Loads in Buildings for Renewable Integration

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November 4, 2015
IEEE conference on Smart Grid Communications
Miami, USA

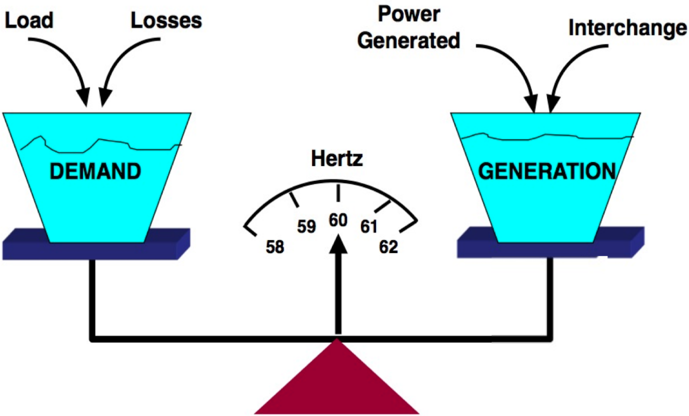
Environmental Concerns

Future 2050?

Now 2015!

A sustainable energy future needs the help from clean renewable energies

Challenge in Power Balance with Renewables



Power balance must be maintained at a second-to-second basis

A Paradigm Shift

- Today: tailor generation to meet uncertain net load
  - decrease generator efficiency
  - diminish net carbon benefit from renewables
  - increase electricity price
- Tomorrow: tailor load to meet uncertain generation
  - reduce generation reserves
  - clean, environmentally friendly
  - fast response
- Enabling ingredient: flexible loads
  - thermostacally controlled loads, energy storages
  - pool pumps, plugin electric vehicles
  - commercial HVAC, refrigeration systems, data centers
- One of the Key Questions:
  - How to characterize their aggregate flexibility in a unified way

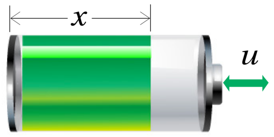
Virtual Battery Model

Definition

A *Virtual Battery Model* $\mathbb{B}$ is a set of signals $u(t)$ that satisfy

$$-N^- \leq u(t) \leq N^+, \quad \forall\ t > 0,$$

$$\dot{x}(t) = -ax(t) + u(t),\ x(0) = 0\ \Rightarrow C^- \leq x(t) \leq C^+, \quad \forall\ t > 0.$$



- $u(t)$ as the power input or output
- $x(t)$ as its state-of-charge

The model is specified by the non-negative parameters $\phi = (C^-, C^+, N^-, N^+, a)$, and we write this compactly as $Batt(\phi)$.

- Interpretation of parameters ϕ

parameter	meaning
N^-, N^+	discharge/charge power limits
C^-, C^+	lower/upper energy capacity
a	dissipation rate

Aggregate Flexibility of Flexible Loads

Theorem (Hao, *et. al.*, CDC,'14; Hao, *et. al.*, SmartGridComm, '15)

Consider a collection of **homogeneous** *electric vehicles parameterized by* $T = (a, d, E, p_m)$*. The aggregate flexibility* $\mathbb{U}$ *of the collection satisfies*

$$\mathbb{U} = Batt(\phi_t)$$

where the parameters ϕ_t *of the virtual battery model are given by*

$$C_t^- = \sum_{i:d^i<t} E^i + \sum_{i:a^i\leq t<d^i} \max\{E^i - (d^i - t)p_m^i\delta, 0\},$$

$$C_t^+ = \sum_{i:d^i<t} E^i + \sum_{i:a^i\leq t<d^i} \min\{E^i, (t - a^i)p_m^i\delta\},$$

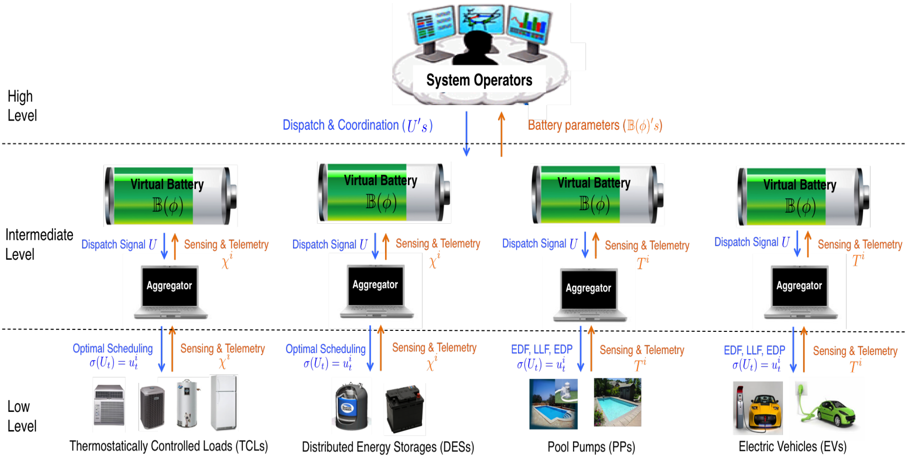
$$N_t^- = 0, \qquad N_t^+ = \sum_{i\in\mathbb{A}_t} p_m^i, \qquad a_t = 1,$$

where $t \in \{0, 1, \cdots, T\}$.

For **heterogeneous** EVs, and other loads, please refer to:

Hao, *et. al.*, CDC,'14; Hao, *et. al.*, tech report,'15, Hao, *et. al.*, TPS, '15;

A Generalized Aggregate and Coordination Architecture



Conclusions & Future Work

Conclusions

- We developed a virtual battery model to aggregate the flexibility of various classes of loads
- We proposed a unified aggregation and coordination framework for flexible loads

Future Work

- Design attractive incentives to engage customers for demand response
- Quantify the value of virtual battery (flexible loads) and compare it with real battery

References

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Thank you very much for your time!