Optimal Decentralized Protocol for Electrical Vehicle Charging

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Main Reference

Lingwen Gan, Ufuk Topcu, and Steven Low, *"Optimal decentralized protocols for electric vehicle charging"*, IEEE Transactions on Power Systems, to appear, 2012

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OUTLINE

- **Introduction**
  - Smart Charging
  - Different Charging Schemes
  - Contribution
- **Problem Formulation**
  - Global Optimal Charging (OC)Formulation
  - Optimality of OC
- **Optimal Decentralized Scheduling Algorithm (ODC)**
  - Synchronous ODC
  - Asynchronous ODC
- **Case Studies**
- **Extensions and Conclusions**

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Introduction (1)

- **Electrical Vehicles (EV)**
  - Increase energy efficiency
  - Reduce Green house gas emission and reliance on fossil fuels
  - Several types of EVs are already in or about to enter the market

- **Challenges Brought by EVs**
  - Integration with the power grid
  - Increase the electricity load, potentially the peak load
  - Load uncertainties, overload the transformers, increase power losses and lead to voltage regulation violations

- **Smart Charging**
  - Carefully schedule EV charging time and amounts to get less cost and energy waste for users and operators, and to stabilize the grid
  - Energy stored in EVs can be utilized to compensate fluctuating renewable generations

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Introduction (2)

- Smart Charging Strategies
  - Time-of-use price (price is given and cannot be set)
  - Centralized charging control (centralized collecting structure and optimization over all the EVs' charging profiles)
  - Decentralized charging control (potentially enabled by home area networks and advanced EV chargers)

- Contribution
  - Define optimal charging profiles of EVs explicitly by a global optimization problem
  - Propose a decentralized charging algorithm that guarantees optimality in both homogeneous and heterogeneous cases
  - Ameliorate the penalty item in EV's charging objective in [1] making it vanish at convergence
  - Prove that the algorithm can accommodate asynchronous computation
  - Extend algorithm to obey a given load profile and to real-time implementation

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[1] Z. Ma, D. S. Callaway and I. A. Hiskens, "Decentralized charging control of large populations of plug-in electric vehicles," in Proceedings of IEEE Conference on Decision and Control, 2010.

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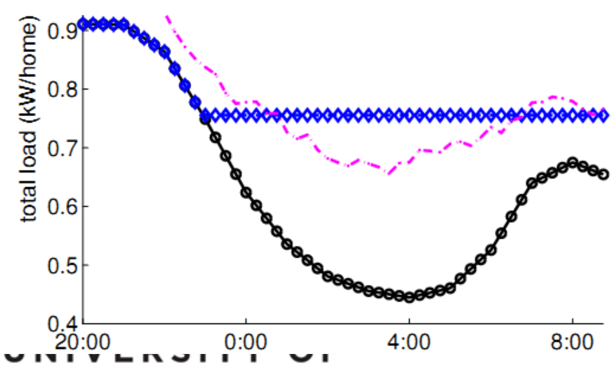
Problem Formulation(1)

- Scenario
  - Electric utility negotiates with N EVs over T time slots of length ΔT. Utility company knows the base load profile (aggregate non-EV load)
- Goal
  - Shape the aggregate charging profile of EVs to flatten the total load (base load plus EV load) profile.
- System Model
  - EV charge after it plugs in and charge a pre-specified amount of electricity by its deadline. In each time slot, the charging rate of an EV is a constant.
  - This optimal control problem formalizes the intent of flattening the total load profile, which is captured by the objective function



Charging rate of EV n at slot t

Base load

$$L(r) = L(r_1, \ldots, r_N) := \sum_{t=1}^{T} U\left(D(t) + \sum_{n=1}^{N} r_n(t)\right)$$

U mapping function R->R, strictly convex

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Problem Formulation(2)

$$L(r) = L(r_1, \ldots, r_N) := \sum_{t=1}^{T} U\left(D(t) + \sum_{n=1}^{N} r_n(t)\right)$$

- $r_n(t)$ is in $[0, \overline{r}_n]$
- In order to impose plug-in time and deadline constraints, $\overline{r}_n$ is considered to be time-dependent with $\overline{r}_n(t) = 0$ for slots t before the plug-in time and after the deadline of EV n.
- It should satisfy:

$$\eta_n \sum_{t \in \mathcal{T}} r_n(t) \Delta T = B_n(s_n(T) - s_n(0)), \; n \in \mathcal{N}.$$

$$R_n := \frac{B_n(s_n(T) - s_n(0))}{\eta_n \Delta T} \longrightarrow \sum_{t=1}^{T} r_n(t) = R_n, \; n \in \mathcal{N}.$$

- Optimization Problem Formulation

$$\textbf{OC} \begin{cases} \min\limits_{r_1, \ldots, r_N} & \sum_{t=1}^{T} U\left(D(t) + \sum_{n=1}^{N} r_n(t)\right) \\ \text{s.t.} & 0 \le r_n(t) \le \overline{r}_n(t), \; t \in \mathcal{T}, n \in \mathcal{N}; \\ & \sum_{t=1}^{T} r_n(t) = R_n, \; n \in \mathcal{N}; \end{cases}$$

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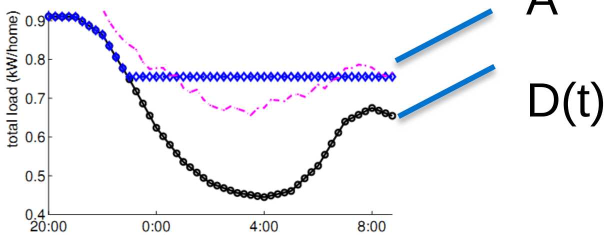
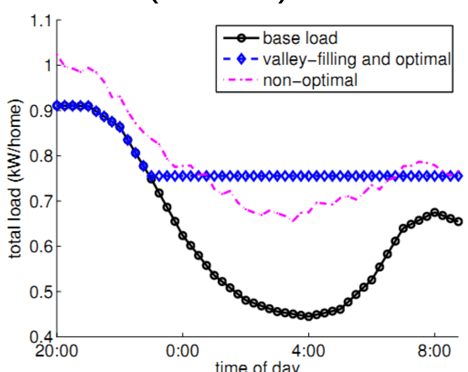
Problem Formulation (3)

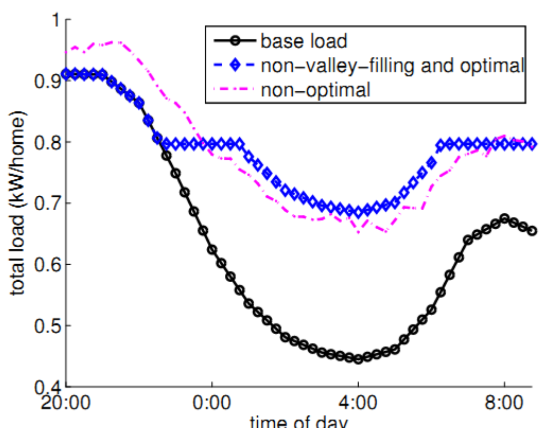
- Valley-Filling
  - If it is feasible, and there exists a constant A such that

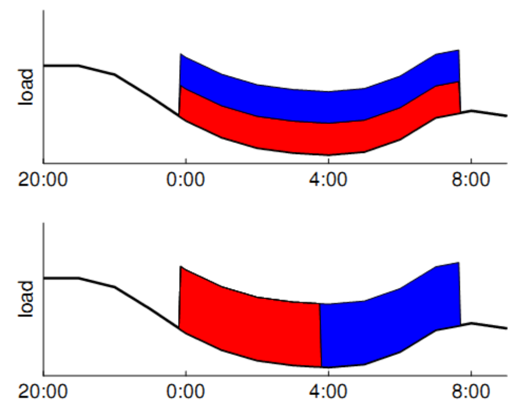
$$\sum_{n \in \mathcal{N}} r_n(t) = [A - D(t)]^+ \, , \; t \in \mathcal{T}.$$



- Optimality Analysis
  - A value-filling charging profile is optimal (Proved)
  - Optimal charging profiles exist if feasible charging profiles exist (Proved)
  - Valley filling is not always achievable (deep valley of D(t), different EV deadlines)
  - There can be a class of optimal charging profiles, independent of the mapping U function (Proved)







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Decentralized Scheduling Algorithm

- Decentralize
  - EVs choose their own charging profiles instead of being instructed by a centralized infrastructure.
  - Utility company only uses control signals (e.g. price) to guide EVs' decision making

- Procedure
  - Decision Phase: EVs and utility company will negotiate and carry out an <u>iterative</u> procedure to determine the charging rates for each slot in the future, at the beginning of the scheduling horizon
  - Execution Phase: All EVs start charging according to the scheduled profile

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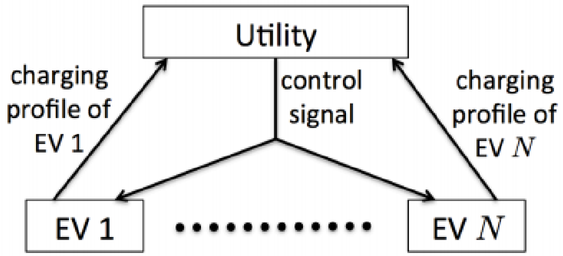
Synchronous Decentralized Algorithm



- Information Exchange
  - Given the control signal broadcast by the utility, each EV chooses it charging profile independently, and reports back to the utility. The utility guides their behavior by altering the control signal.
  - We assume that U' is Lipschitz with the Lipschitz constant β>0

$$|U'(x) - U'(y)| \leq \beta|x - y|$$

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Synchronous Decentralized Algorithm

- Optimal Decentralized Charging (ODC) Algorithm

Given scheduling horizon $\mathcal{T}$, the maximum number K of iterations, error tolerance $\epsilon > 0$, base load profile D, the number N of EVs, charging rate sum R_n and charging rate upper bound $\overline{r}_n$ for EV $n \in \mathcal{N}$, pick a step size γ satisfying

$$0 < \gamma < \frac{1}{N\beta}.$$

1) Initialize the control signal and the charging profiles as

$$p^0(t) := U'(D(t)), \ \ r_n^0(t) := 0$$

for $t \in \mathcal{T}$ and $n \in \mathcal{N}$. Set $k \leftarrow 0$.

2) The utility broadcasts γp^k to all EVs.

3) Each EV $n \in \mathcal{N}$ calculates a new charging profile r_n^{k+1} as the solution to the following optimization problem

$$\begin{aligned} \min_{r_n} \quad & \sum_{t\in\mathcal{T}} \gamma p^k(t) r_n(t) + \frac{1}{2}\left(r_n(t) - r_n^k(t)\right)^2 \qquad (7) \\ \text{s.t.} \quad & 0 \le r_n(t) \le \overline{r}_n(t), \ \ t \in \mathcal{T}; \\ & \sum_{t\in\mathcal{T}} r_n(t) = R_n, \end{aligned}$$

and reports r_n^{k+1} to the utility.

4) The utility collects charging profiles r_n^{k+1} from the EVs, and updates the control signal as

$$p^{k+1}(t) := U'\left(D(t) + \sum_{n=1}^{N} r_n^{k+1}(t)\right) \qquad (8)$$

for $t \in \mathcal{T}$.

If $\|p^{k+1} - p^k\| \le \epsilon$, return p^{k+1}, r_n^{k+1} for all n.

5) If $k < K$, $k \leftarrow k+1$, and go to step (2). Else, return p^K, r_n^K for all n.

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Asynchronous Decentralized Algorithm

- Allow decisions to be made at <u>different times</u> with potentially <u>outdated</u> information, i.e., in each iteration, <u>only some</u> EVs update their charging profiles, using information from <u>earlier</u> iterations (not necessarily the previous iteration).

Given planning horizon $\mathcal{T}$, the maximum number K of iterations, error tolerance $\epsilon > 0$, base load profile D, the number N of EVs, charging rate sum R_n and charging rate upper bound $\overline{r}_n$ for EV $n \in \mathcal{N}$, pick a step size γ satisfying

$$0 < \gamma < \frac{1}{N\beta(3d+1)}.$$

1) Initialize the control signal and the charging profiles as

$$p^0(t) := U'(D(t)), \quad r_n^0(t) := 0$$

for $t \in \mathcal{T}$ and $n \in \mathcal{N}$. Set $k \leftarrow 0$.

2) If $k = 0$ or $k-1 \in K_0$, the utility broadcasts γp^k to all EVs.

3) For each EV $n \in \mathcal{N}$, if $k \in K_n$, it calculates a new charging profile r_n^{k+1} as the solution to the following optimization problem

$$\begin{aligned} \min_{r_n} \quad & \sum_{t\in\mathcal{T}} \gamma p^{k-a_n(k)}(t) r_n(t) + \frac{1}{2}\left(r_n(t) - r_n^k(t)\right)^2 \\ \text{s.t.} \quad & 0 \le r_n(t) \le \overline{r}_n(t), \ t \in \mathcal{T}; \\ & \sum_{t\in\mathcal{T}} r_n(t) = R_n, \end{aligned}$$

and reports r_n^{k+1} to the utility.

4) If $k \in K_0$, the utility updates the price profile p^{k+1} as

$$p^{k+1} := U'\left(D + \sum_{n=1}^{N} r_n^{k+1-b_n(k)}\right).$$

If $\left\|p^{k+1} - p^k\right\| \le \epsilon$, return p^{k+1}, r_n^{k+1} for all n.

5) If $k < K$, $k \leftarrow k+1$, and go to step (2). Else, return p^K, r_n^K for all n.

The authors have proved that for Asynchronous ODC, charging profile also converges to optimal charging profiles.

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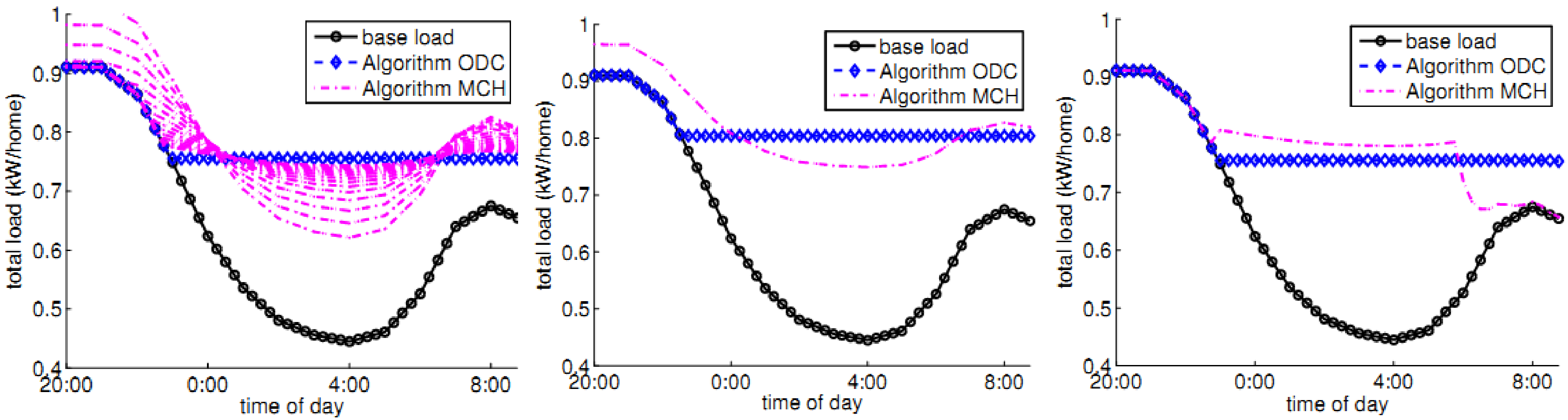
Case Study

- Choose the average residential load profile in the service area of South California Edison from 20:00 to 9:00 next day as the base load per household
- Consider the penetration level of 20 EVs in 100 households



- Algorithm ODC obtains optimal charging profiles irrespective of the specifications of the EVs, i.e., different plug-in times, different deadlines, charge different amounts of electricity, and different maximum charging rates..

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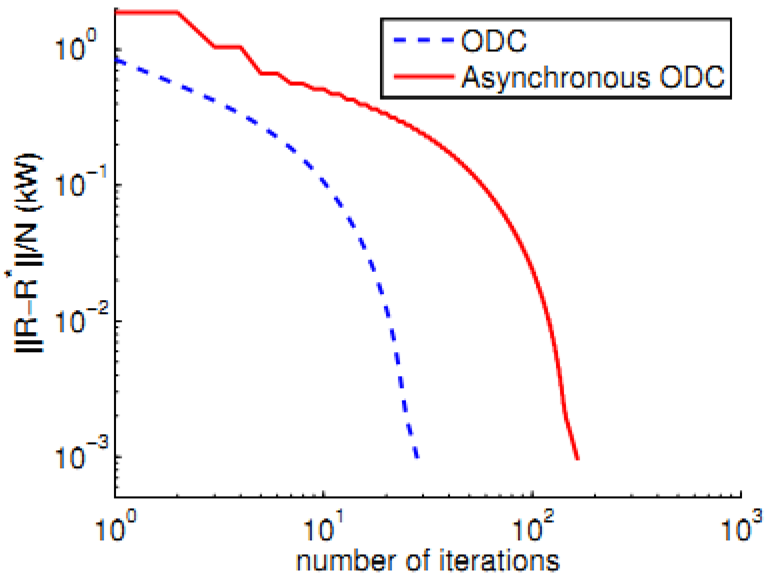
Case Study



- Both Algorithm ODC and Asynchronous ODC obtain optimal charging profiles
- Asynchronous ODC converges slower than ODC, since EV does not necessarily update its charging profile in each iteration and uses potentially outdated information when it does

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Extensions

- Follow a given profile
  - A load aggregator may need to buy electricity in the day-ahead electricity market, and supplies the purchased electricity to EVs in real time. Hence, a load aggregator may want to schedule EV charging to follow the electricity profile G(t) it bought in the day-ahead market.
  - Objective:

$$J(r) = J(r_1, \ldots, r_N) := \sum_{t=1}^{T} \left(\sum_{n=1}^{N} r_n(t) - G(t) \right)^2 .$$

- Real-Time ODC
  - Schedule at the beginning of each time slot
  - Choose a time horizon T that covers the deadlines of all active EVs
  - Repeat the propose ODC

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Conclusions

- The authors have studied decentralized electric vehicle (EV) charging to fill the overnight electricity load valley by:
  - Formulating the EV charging protocol design problem as an optimal control problem
  - Proposing a decentralized algorithm to solve the problem.
  - In each iteration of the algorithm, each EV calculates its own charging profile according to the control signal broadcast by the utility, and the utility guides their decision making by updating the control signal.
- They proved that
  - algorithm converges to optimal charging profiles, irrespective of the specifications of the EVs, even with asynchronous computation.
- Extension
  - Extend the algorithm to follow a given load profile and to real-time implementation.

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