Market and Control Mechanisms Enabling Flexible Service Provision by Grid-Edge Resources Within End-to-End Power Systems

PROJECT #M-40

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ISU TEAM: Presentation Outline

• Research Contribution: Overview
• Our Proposed Transactive Energy System Design
• Analytical Illustration
• Numerical Case Study
• Conclusion

Key Reference:

https://lib.dr.iastate.edu/econ_workingpapers/127
A **Transactive Energy System (TES) design** is a collection of economic and control mechanisms that supports the dynamic balancing of power supply and demand across an entire electrical infrastructure, using value as the key operational parameter.

Our proposed **DSO-managed TES design** has the following advantages:

- Implementable for an *unbalanced distribution network*.
- **Consensus-based**: Retail prices for each operating period OP are determined by a negotiation process N(OP) between the DSO and its customers.
- Supports *multiperiod decision-making*: N(OP) permits the DSO and its customers to plan power usage over operating periods OP consisting of multiple decision periods.
- **System/customer alignment**: DSO goals and network constraints are aligned with customer goals and local constraints in a manner that respects customer privacy.
An ISO/RTO manages a wholesale power market operating over a high-voltage transmission grid.

A DSO manages distribution network reliability & power usage of distribution network customers by engaging in a retail price negotiation process with customers.

A bus is a physical location where customers connect to the distribution network.

Each customer chooses a power schedule to maximize its net benefit subject to local constraints, given negotiated retail power prices.
**Step 1:** ISO/RTO runs SCED optimization for a Real-Time Market RTM(OP) for a future Operating Period OP, resulting in RTM Locational Marginal Prices (LMPs) for OP.

**Step 2:** At start of the Look-Ahead Horizon LAH(OP), the ISO conveys RTM LMPs to the DSO, which uses them to set initial retail prices for negotiation with customers.

**Step 3:** During LAH(OP) the DSO conducts a Negotiation Process N(OP) with customers to determine an NK-dimensional retail price-to-go sequence for OP.

**Step 4:** During OP each customer implements its optimal NK-dimensional power schedule for OP, conditional on its negotiated retail price-to-go sequence for OP.
**Customers:**
Households with appliance mixes consisting of:
(i) price-sensitive thermostatically controlled load (TCL)
(ii) non-TCL whose usage is not sensitive to price.

**Market Timing:**
The durations of RTM(OP), LAH(OP), and OP are set to 1min, 59min, and 60min.
Goal of each household $\psi$: *Max net benefit (i.e., benefit - cost) by feasible choice of TCL power schedule for subperiods $t$ in $K = \{1, 2, ..., NK\}$*

**Objective:**

$$\max_{P_\psi(K)} \sum_{t \in K} u(p_\psi(t), t) - \mu_\psi \pi_\psi(K) P_\psi(K) * S_{base} \Delta t$$

*Benefit* obtained from TCL power schedule

*Cost* of TCL power schedule, given the retail price-to-go sequence $\pi_\psi(K)$

**Choice Variables:**

— TCL power schedule $P_\psi(K) = [p_\psi(1), ..., p_\psi(NK)]^T$

**Feasible Choice Set $X_\psi(K)$:**

— Choice variables must satisfy *thermal dynamic equations* determining household $\psi$’s inside air temperature over time as a function of appliance attributes, initial state conditions, external forcing terms, & appliance TCL/non-TCL power usage.

**Hence, solution for household $\psi$’s optimization problem takes form:**

$$P_\psi(\pi_\psi(K)) = \arg \max_{P_\psi(K) \in X_\psi(K)} [U(P_\psi(K)) - \mu_\psi \pi_\psi(K) P_\psi(K) * S_{base} \Delta t]$$
**Goal of DSO:** Max household net social benefit subject to household constraints and network constraints (i.e., a peak demand limit and lower/upper bounds on voltage magnitudes).

**DSO Objective:**

$$\max_{P(K) \in X(K)} \sum_{\psi \in \Psi} \left[ U(P_{\psi}(K)) - \mu_{\psi} LMP(K) P_{\psi}(K) \right] - \mu LMP(K) P_{\psi}(K) * S_{base} \Delta t$$

**DSO Choice Variables:**

Set of all household TCL power schedules: $P(K) = \{P_{\psi}(K) | \psi \in \Psi\}$

**DSO Constraints:** $X_{\psi}(K), \psi \in \Psi$ plus network constraints

**NOTE:** The DSO cannot directly solve this centralized control problem because the DSO does not have the required household private info.
TC Design Illustration: Negotiation Process N(OP)

DSO uses N(OP) to set household retail price-to-go sequences

\[ \pi(K) = \{ \pi_{\psi}(K) \} \]

such that the resulting household-chosen TCL power schedules

\[ P(K) = \{ P_{\psi}(\pi_{\psi}(K)) \} \]

satisfy all household and network constraints.

Propositions 1-5 in ref. [1] give the theoretical basis for alignment of DSO goals & constraints with household goals & constraints.

The centralized DSO control problem (previous slide) can be expressed as a standard nonlinear programming problem:

\[
\max_{x \in X} F(x) \\
\text{subject to } g(x) \leq c
\]

The Lagrangian Function is:

\[
L(x, \lambda) = F(x) + \lambda[c - g(x)]
\]
TC Design Illustration: Propositions from Ref. [1]

**Definition:** Suppose an optimal solution \( P^*(K) \) for the DSO centralized control problem equals \( P(\pi^*(K)) \) for a collection \( \pi^*(K) \) of household retail price-to-go sequences for OP. Then \( (P^*(K), \pi^*(K)) \) will be called a **TES equilibrium for OP**.

**Proposition 2:** Suppose \( (x^*, \lambda^*) \) is a saddle point for the Lagrangian Function \( L(x, \lambda) \), where \( x^* = P^*(K) \). Suppose, also, that \( x^* \) uniquely maximizes \( L(x, \lambda^*) \) with respect to \( x \) in \( X \). Then \( (x^*, \lambda^*) \) determines a TES equilibrium \( (P^*(K), \pi^*(K)) \) for OP.

**NOTE:** The equilibrium price-to-go sequence \( \pi^*_\psi(K) \) for household \( \psi \) in Prop. 2 has the following separable structure:

\[
\pi^*_\psi(K) = \text{Initial retail price-to-go sequence set for } \psi \text{ by DSO} \\
+ \text{Price-to-go adjustment (if needed) to ensure } \text{peak demand limit} \\
+ \text{Price-to-go adjustment (if needed) to ensure } \text{voltage magnitude limits}
\]
Proposition 3: Suppose the following three conditions hold

[P3.A] \( X \) is compact, and the objective function \( F(x) \) and constraint function \( g(x) \) are continuous over \( X \).

[P3.B] For every \( \lambda \in R_+^m \), the Lagrangian Function \( L(x, \lambda) \) achieves a finite maximum at a unique point \( x(\lambda) \in X \).

[P3.C] The primal and dual variable iterates in the DDA converge to a limit point \( (x^*, \lambda^*) \) as the iteration time approaches +\( \infty \).

Then the DDA limit point \( (x^*, \lambda^*) \) is a saddle point for the Lagrangian Function that determines a TES equilibrium for OP.

NOTE: Complete proofs for Propositions 1-5 are provided in Ref. [1].
Network constraints = Peak demand & voltage magnitude limits
- Peak demand limit is 3200kW & min squared voltage mag limit is 0.95
- Without TES, peak demand is 2962kW < 3200kW (no violation)
- Without TES design, voltage mag limit violation occurs (0.9485 < 0.95)
Under TES design, there is no violation either of network constraints (peak demand & voltage magnitude limits) or of household constraints.

The retail price for hour 17 differs from bus to bus and from phase to phase.
TC Design Case Study ... Continued

- TES outcomes closely track centralized DSO control solution

Fig. 8: Centralized control vs. TES outcomes for total TCL demand during day D

Fig. 9: Centralized control vs. TES outcomes for phase-a TCL demand during hour 17 across the entire network (123 buses)
UI Team Presentation: Market efficiency impacts of aggregated distributed energy resources (DERs)

Prosumer participation through profit-motivated retail aggregator

Stackelberg Game

Wholesale Market

Retail Aggregator (price-arbitrageur)

Prosumers

Price and quantity \((\lambda, q_A)\)

Capacity \(X(\rho)\)

Direct prosumer participation in wholesale markets (ideal but impractical benchmark)

Inverse Supply Offers

Price of aggregation


Retail market design

Design supply offers/demand bids

- Must be a two-sided market mechanism
- The offer and bid format must be succinct
- Should support an efficient competitive equilibrium with price-taking market participants
- Must limit impacts of strategic behavior with price-anticipating market participants

Our work: A scalar parameterized mechanism for two-sided markets


Design and analyze price formation

- Prices should be nodally uniform
- Should support an efficient competitive equilibrium
- Payment mechanism must be revenue adequate under reasonable assumptions

Our work: Convex relaxation-based (distribution) locational marginal prices

...ignores bid/offer mechanism and the multi-phase unbalanced nature of distribution grids

“Convex Relaxation based Locational Marginal Prices for Electricity Markets,” A. Winnicki, M. Ndrio, and S. Bose.
What should the bid/offer format be in a two-sided retail market?

Generalizes one-sided scalar-parameterized supply functions
Kelly ‘03, Johari ‘04 & ‘11, Hajek ‘02, Maheswaran ‘04

What a demander provides
Scalar-parameterized demand bid with elastic and inelastic component
\[ d_i = D(\theta_d^i, p) := d_0 + \frac{\theta_d^i}{p}, \quad \theta_d^i \geq 0. \]

What a supplier provides
Scalar-parameterized supply offer with capacity constraints
\[ s_i = S(\theta_s^i, p) := \kappa_0 - \frac{\theta_s^i}{p}, \quad \theta_s^i \geq 0. \]

Market is cleared at a price at which total supply equals total demand
\[ \sum_{i=1}^{M} D(\theta_d^i, p) = \sum_{i=1}^{N} S(\theta_s^i, p). \]
Properties of the market mechanism

- The mechanism supports an efficient competitive equilibrium with price-taking market participants.

- With price-anticipating participants, Nash equilibrium does not exist when a pivotal supplier exists in the market.

- When pivotal suppliers do not exist, a unique Nash equilibrium exists. Moreover, this equilibrium can be computed as the solution of a convex optimization problem with modified utilities and costs.

- The efficiency loss at this equilibrium is bounded below as

\[
\sum_{i=1}^{M} U_i(d_i^{\text{Nash}}) - \sum_{i=1}^{N} C_i(s_i^{\text{Nash}}) \geq \frac{3}{4} \sum_{i=1}^{N} U_i(d_i^\ast) - \frac{4}{3} \sum_{i=1}^{N} C_i(s_i^\ast).
\]
The Dispatch Problem

minimize \( \sum_{k=1}^{n} c_k(p^G_k, q^G_k) \),

subject to \( p^G_k - p^D_k = \sum_{e \rightarrow e'} P_{ke} - \sum_{e \rightarrow e'} (P_{ke} - r_{ke} J_{ke}) \),
\( q^G_k - q^D_k = \sum_{e \rightarrow e'} Q_{ke} - \sum_{e \rightarrow e'} (Q_{ke} - x_{ke} J_{ke}) \),
\( P_{ke} \leq f_{ke}, \ r_{ke} J_{ke} - P_{ke} \leq f_{ke}, \)
\( p_k \leq p^G_k \leq \bar{p}_k, \ q_k \leq q^G_k \leq \bar{q}_k, \ \bar{v}_k^2 \leq w_k \leq \bar{v}_k^2, \)
\( w_e = w_k - 2(P_{ke} r_{ke} + Q_{ke} x_{ke}) + (r_{ke}^2 + x_{ke}^2) J_{ke} \),
\( P_{ke}^2 + Q_{ke}^2 = J_{ke} w_k \)
for \( k \in \mathbb{N}, \ k \rightarrow \ell \in \mathbb{E} \)

The Pricing Problem

minimize \( \sum_{k=1}^{n} c_k(p^G_k, q^G_k) \),

subject to \( p^G_k - p^D_k = \sum_{e \rightarrow e'} P_{ke} - \sum_{e \rightarrow e'} (P_{ke} - r_{ke} J_{ke}) \),
\( q^G_k - q^D_k = \sum_{e \rightarrow e'} Q_{ke} - \sum_{e \rightarrow e'} (Q_{ke} - x_{ke} J_{ke}) \),
\( P_{ke} \leq f_{ke}, \ r_{ke} J_{ke} - P_{ke} \leq f_{ke}, \)
\( p_k \leq p^G_k \leq \bar{p}_k, \ q_k \leq q^G_k \leq \bar{q}_k, \ \bar{v}_k^2 \leq w_k \leq \bar{v}_k^2, \)
\( w_e = w_k - 2(P_{ke} r_{ke} + Q_{ke} x_{ke}) + (r_{ke}^2 + x_{ke}^2) J_{ke} \),
\( P_{ke}^2 + Q_{ke}^2 \leq J_{ke} w_k \)
for \( k \in \mathbb{N}, \ k \rightarrow \ell \in \mathbb{E} \)

Relaxation-based Locational Marginal Prices (DLMP) \( \lambda^p_k, \lambda^q_k \)

Dispatch and prices are derived from two different problems (both derived with branch-flow model for distribution networks)
Properties of relaxation-based DLMPs

When relaxation is exact, the dispatch and prices support an efficient competitive equilibrium. On radial distribution networks, relaxation is often exact.

Non-binding voltage lower bounds are sufficient, but not necessary, for revenue adequacy.

Due to the nature of the power flow equations, real power prices are sensitive to real power demand & line limits and reactive power prices are sensitive to limits on voltage magnitudes.

These prices minimize a form of side payments that comprises lost opportunity cost and product revenue shortfall. Such a property is more relevant for its generalization to a semidefinite relaxation-based locational marginal prices.

Real power prices

Reactive power prices