Consensus-based Transactive Design for Unbalanced Distribution Networks

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Presentation Outline

1. Proposed Transactive Energy System (TES) Design
2. Analytical Illustration
3. Numerical Case Study
4. Conclusion

1. What is a TES design?

- 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 [2].

1. Our Proposed Consensus-Based TES Design

- **RTO/ISO**: Manages a wholesale power market.

- **Independent DSO (IDSO)**: Manages the power usage of distribution network customers.

- **Bus**: A physical location where customers connect to the distribution network.

- **Customers**: Maximize own net-benefit (i.e., benefit minus cost), subject to own local constraints.

Fig. 1
1. Consensus-Based TES Design: Timing

Step 1: The RTO/ISO runs a 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 RTO/ISO conveys RTM LMPs to the IDSO, which uses them to set initial retail price-profiles for negotiation with its managed customers.

Step 3: During LAH(OP), the IDSO conducts a Negotiation Process N(OP) with its customers to determine for each of these customers a NK-dimensional retail price-profile for OP.

Step 4: During OP, each customer implements its NK-dimensional optimal power-profile for OP, conditional on its negotiated retail price-profile for OP.
1. Consensus-Based TES Design: Negotiation Process

Three-Step Negotiation Process $N(\text{OP})$ for each Operating Period $\text{OP}$:

- **Initialization:** The IDSO receives from each customer $J$ a thermostat slider-knob setting in $(0,1)$ indicating $J$’s preferred emphasis on power-usage benefit relative to power-usage cost. The IDSO then communicates to each customer a customer-specific initial retail price-profile for operating period $\text{OP} = (1,2,...,NK)$.

- **Iterated Price-Adjustment Process:** Each customer determines its optimal power-profile, taking its received retail price-profile as given. If these customer-determined optimal power-profiles result in distribution network constraint violations, the IDSO communicates adjusted customer-specific retail price-profiles to these customers.

- **Stopping Rule:** $N(\text{OP})$ halts either when no distribution network constraints are violated or when the number of negotiation rounds reaches a pre-specified maximum.
2. Analytical Illustration: Basic Features

Unbalanced Distribution Network:
(1) Multi-phase;
(2) Radial;
(3) Relatively small compared to the transmission network size.

Households:
(1) Price-sensitive thermostatically controlled load (TCL);
(2) Non-TCL not sensitive to price.
2. Analytical Illustration: Household Optimization

Household-level Optimization Problem for Operating Period OP:

Goal of each household $\psi$: **Maximize net benefit (i.e., benefit - cost) for OP**, where OP is partitioned into $NK$ household decision sub-periods $t \in K = (1,2,...,NK)$.

Optimization Problem for $\psi$:

\[
\max_{P_\psi(K) \in X_\psi(K)} \left[ U(P_\psi(K)) - \mu_\psi \pi_\psi(K) P_\psi(K) * S_{base} \Delta t \right]
\]

**Benefit** obtained from TCL power-profile $P_\psi(K)$

**Cost** of TCL power-profile $P_\psi(K)$, given the TCL retail price-profile $\pi_\psi(K)$

Choice Variables: Household $\psi$’s TCL power-profile $P_\psi(K) = [p_\psi(1), ..., p_\psi(NK)]^T$

Feasible Choice Set: Household $\psi$’s constraint set $X_\psi(K)$

**NOTE**: A solution for household $\psi$’s optimization problem for operating period OP has the price-dependent form

\[
P_\psi(\pi_\psi(K)) = \arg\max_{P_\psi(K) \in X_\psi(K)} \left[ U(P_\psi(K)) - \mu_\psi \pi_\psi(K) P_\psi(K) * S_{base} \Delta t \right]
\]
Centralized IDSO Optimization Problem for Operating Period OP:

**Goal of IDSO:** Max total net benefit of households *subject to household constraints and network constraints.*

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

**Constraints:** Household constraints \( X_{\psi}(K) \), \( \psi \in \Psi \), plus following network constraints: For each sub-period \( t \in K \),
\[
\sum_{\psi \in \Psi} [p_{\psi}(t) + p_{\psi}^{non}(t)] \leq \bar{P}
\]

Min/max voltage magnitude limits at each bus

**Control Variables:** The set of all household TCL power-profiles \( P(K) = \{P_{\psi}(K) | \psi \in \Psi\} \)

**Problem:** This is private household information

Note: The linearized multi-phase distribution system *power-flow modeling* used in the above network constraint formulation is adapted from:

Centralized IDSO Optimization Problem in Standard NP Form:

\[
(*) \quad \max_{x \in X} F(x)
\]

subject to: \(g(x) \leq c\)

where: \(x = \{x_{\psi} | \psi \in \Psi\}; \ x_{\psi} = \{x_{\psi}(t) | t \in K\} = P_{\psi}(K)\).

Lagrangian Function for (*)&: \[
L(x, \lambda) = F(x) + \lambda[c - g(x)]
\]

Key Issue: How to solve (*)& while maintaining household privacy and network reliability?

- We solve a **distributed** form of (*)& by means of our TES design negotiation process N(OP).
  - We prove N(OP) converges to an **optimal** solution for (*)& given regularity conditions; see [1, Props. 1-5].
  - Thus, the final N(OP)-determined vector of optimal household power-profiles **satisfies all network constraints as well as all household constraints while maintaining household privacy.**
2. Analytical Illustration: Summary of Key Findings

Given regularity conditions, our TES design negotiation process N(OP) ensures:

1. Convergence to an optimal solution for the centralized IDSO optimization problem (*);
2. Household privacy is maintained;
3. All distribution network constraints are satisfied;
4. Each household $\psi$ is maximizing its net benefit subject to its local constraints, given its ultimate N(OP)-determined retail price-profile $\pi^*_\psi(K)$;
5. The price-profile $\pi^*_\psi(K)$ for each household $\psi$ has an informative additive structure:

$$\text{[initial IDSO-set price-profile]} + \text{[(possibly zero) adjustment } A_1(\psi) \text{ for distribution network reliability constraint 1]} + \ldots + \text{[(possibly zero) adjustment } A_M(\psi) \text{ for distribution network reliability constraint M]}$$
2. Analytical Illustration: Price Additive Structure Details

The N(OP)-determined retail price-profile \( \pi^*_\psi(K) \) for each household \( \psi \in \Psi \) has the following informative form:

\[
\pi^*_\psi(K) = \left[ \text{Initial commonly set retail price-profile} \right] + \frac{1}{\mu_\psi S_{\text{base}} \Delta t} \lambda^*_\psi(K) - \frac{2 r_D \left( j_\psi, N^h_\psi \right)^T}{\mu_\psi S_{\text{base}} \Delta t} \left[ \Lambda^*_{v_{\text{max}}}(K) - \Lambda^*_{v_{\text{min}}}(K) \right]^T - \frac{2 x_D \left( j_\psi, N^h_\psi \right)^T}{\mu_\psi S_{\text{base}} \Delta t} \left[ \Lambda^*_{v_{\text{max}}}(K) - \Lambda^*_{v_{\text{min}}}(K) \right]^T H_\psi(K)
\]

Vector \( P(\pi^*(K)) = \{P_\psi(\pi^*_\psi(K))|\psi \in \Psi\} \) of optimal household power-profiles, given the vector \( \pi^*(K) = \{\pi^*_\psi(K)|\psi \in \Psi\} \) of N(OP)-negotiated price-profiles (**), is an optimal solution for the centralized IDSO optimization (*). See [1, Prop. 2].

For each household \( \psi = (\mu_\psi, H_\psi(K), \phi_\psi, j_\psi) \), the additive structural form (***) depends on:

- Household \( \psi \)'s preference and structural attributes: \( \mu_\psi, H_\psi(K) \)
- Household \( \psi \)'s phase and location attributes: \( \phi_\psi, j_\psi \)
- The extent of network constraint violation given initial IDSO-set retail price-profile \( \text{LMP}(K) \), as measured by: \( \lambda^*_\psi(K), \Lambda^*_{v_{\text{max}}}(K), \Lambda^*_{v_{\text{min}}}(K) \)

Adjustment to \( \psi \)'s price-profile (if needed) to ensure peak demand limit

Adjustment to \( \psi \)'s price-profile (if needed) to ensure \textit{min/max voltage mag. limits}
3. Numerical Case Study

Network constraints = Peak demand limit & min/max bus voltage magnitude limits
- Peak demand limit is set to 3200kW & minimum voltage magnitude limit is set to 0.95 p.u.
- Without TES design, the peak demand is 2962kW < 3200kW (no violation)
- Without TES design, there is a phase-a voltage magnitude violation (0.9485 p.u. < 0.95 p.u.)
Under TES design, there is no violation either of network constraints (peak demand & bus voltage magnitude limits) or of household constraints.

- The retail price for hour 17 differs from bus to bus and from phase to phase.
Fig. 7: Centralized IDSO optimization vs. TES design outcomes for total TCL demand during day D

Fig. 8: Centralized IDSO optimization vs. TES design outcomes for phase-a TCL demand during hour 17 across the entire network (123 buses)
4. Conclusion

- Our IDSO-managed Consensus-Based TES Design:
  - can be implemented for unbalanced distribution networks;
  - permits each operating period OP to be partitioned into arbitrarily many customer decision sub-periods;
  - permits an IDSO to protect against distribution network constraint violations by engaging in a negotiation process $N(\text{OP})$ with customers in advance of each OP that determines customer-specific retail price-profiles for OP and price-conditional optimal customer power-profiles for OP;
  - permits IDSO goals and constraints to be aligned with customer goals and constraints while respecting customer privacy.
Thank you!

Q&A