IOWA STATE UNIVERSITY

# Multi-Period Consensus-Based Transactive Energy System for Unbalanced Distribution Networks


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**PSERC Project M-40: ISU Team**


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# PSERC Project M-40: Participants

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|---|---|
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# Presentation Outline

- Research Contribution: Overview
- Our Proposed Transactive Energy System (TES) Design: Key Features
- TES Design Illustration
- TES Design Case Study
- Conclusion

**Reference:**

[1] R. Cheng, L. Tesfatsion, & Z. Wang, “Multi-Period Consensus-Based Transactive Energy System Design for Unbalanced Distribution Networks,” Working Paper, ISU Digital Repository, to appear.

# Research Contribution: Overview

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.

We have developed a new **DSO-managed TES design** with advantages as follows:

- Implementable for an *unbalanced distribution network*.
- *Consensus-based:* Retail prices for each operating period OP are determined by a negotiation process N(OP) between DSO and customers.
- Supports *multi-period decision-making:* N(OP) permits the DSO and customers to plan power usage over operating periods OP consisting of multiple decision periods.
- *System/customer alignment:* DSO goals and constraints are aligned with customer goals and constraints in a manner that preserves customer privacy

# Our TES Design: Key Features

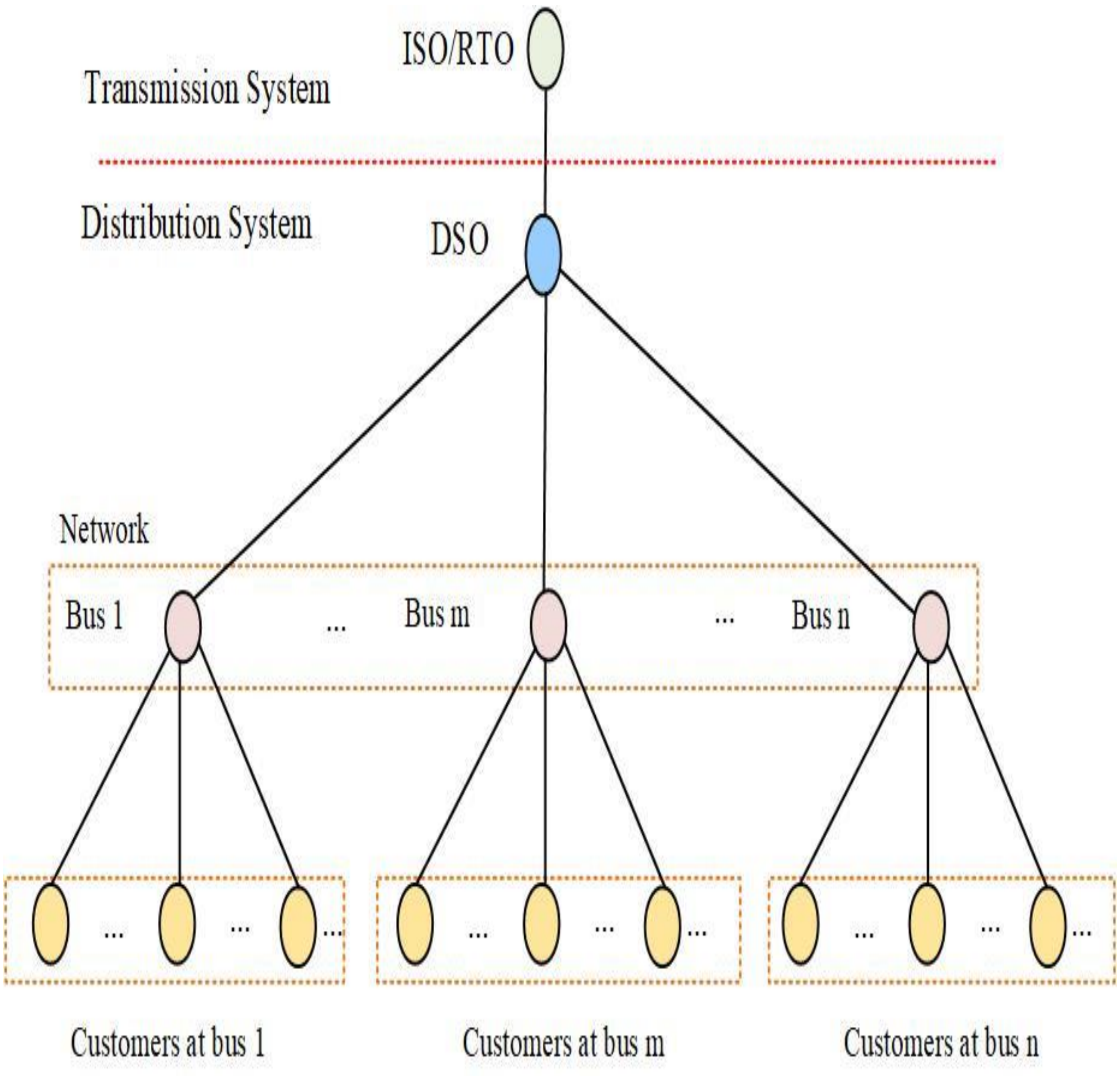


Fig. 1

An **ISO/RTO** manages a wholesale power market operating over a high voltage transmission grid.

A **DSO** manages the power usage of distribution network customers by engaging them in a retail price negotiation process.

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.

# Our TES Design: Timing

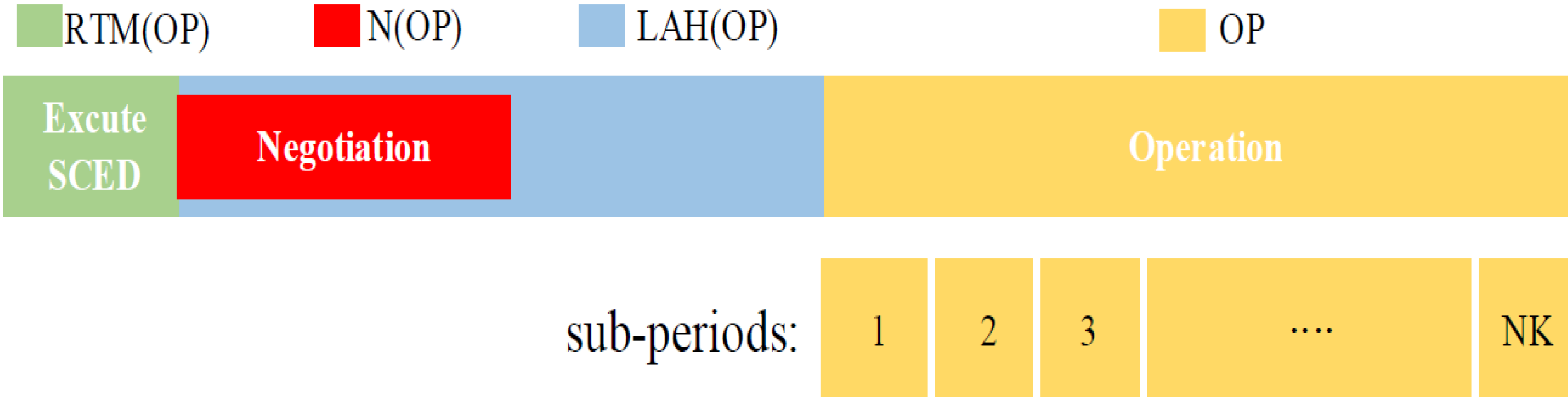


Fig. 2

- **Step 1:** The ISO/RTO executes a SCED optimization for a Real-Time Market RTM(OP) for a future operating period OP, which determines LMPs for OP.
- **Step 2:** At start of the Look-Ahead Horizon LAH(OP), the ISO communicates these RTM LMPs to the DSO
- **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 LAH(OP) each customer determines an optimal NK-dimensional power schedule for OP, conditional on its negotiated retail price-to-go sequence.

# Our TES Design: Negotiation Process N(OP)

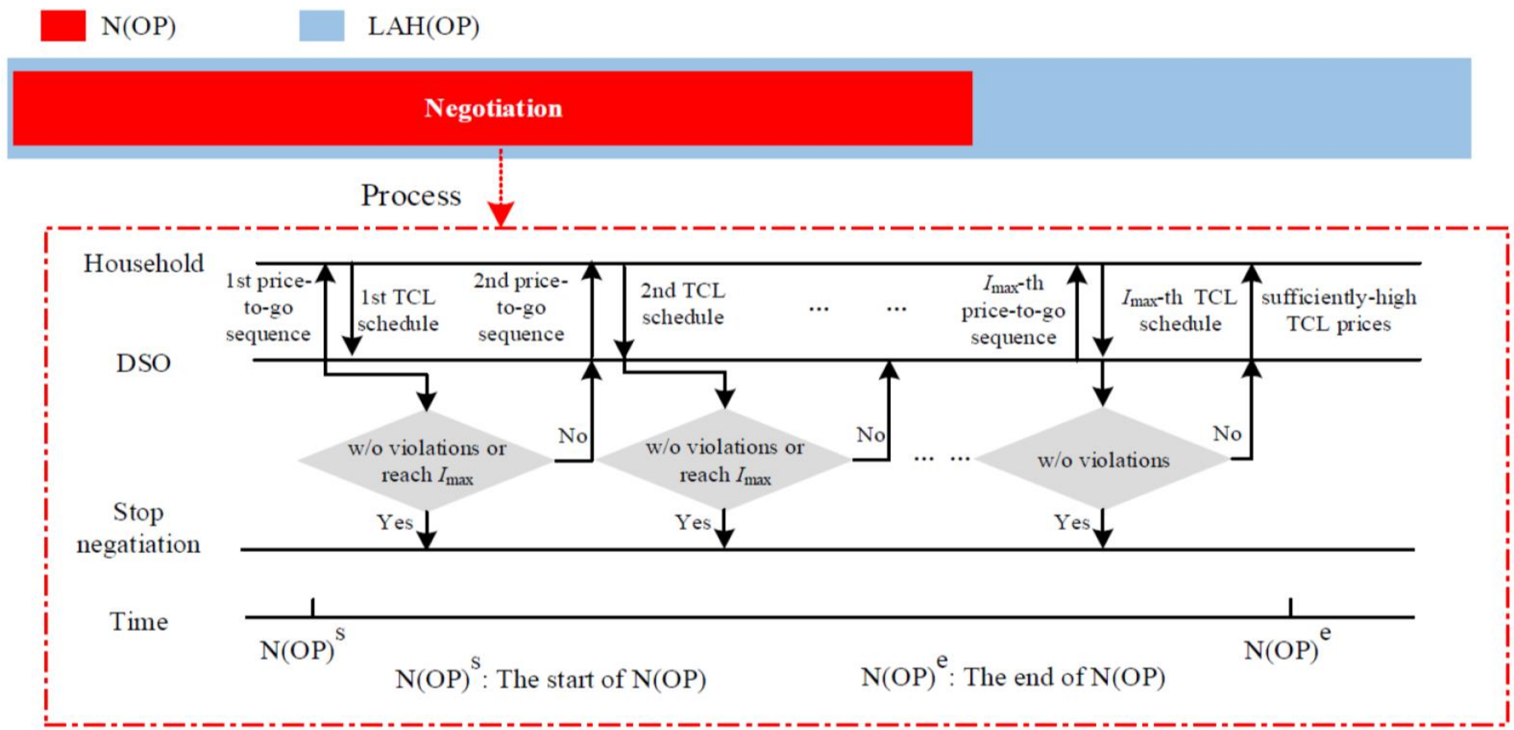


Fig. 3

**Initialization:** DSO receives from each customer: (i) power factor information; and (ii) a thermostat slider-knob setting in (0,1) indicating customer's preferred emphasis on power-usage benefit relative to power-usage cost. The DSO sends initial retail prices to customers.

**Price Adjustment Rule:** If customer power schedules result in system constraint violations, the DSO updates its signaled retail price-to-go sequences.

**Stopping Rule:** N(OP) terminates when no system constraints are violated, or when the number of iterations reaches a pre-specified maximum.

# TES Design Illustration: Household Customers

**Customers:**

Households with price-sensitive thermostatically controlled load (TCL) as well as non-TCL.

**Market Timing:**

As in ERCOT, the durations of RTM(OP), LAH(OP) and OP are set to 1min, 59min, and 60min.

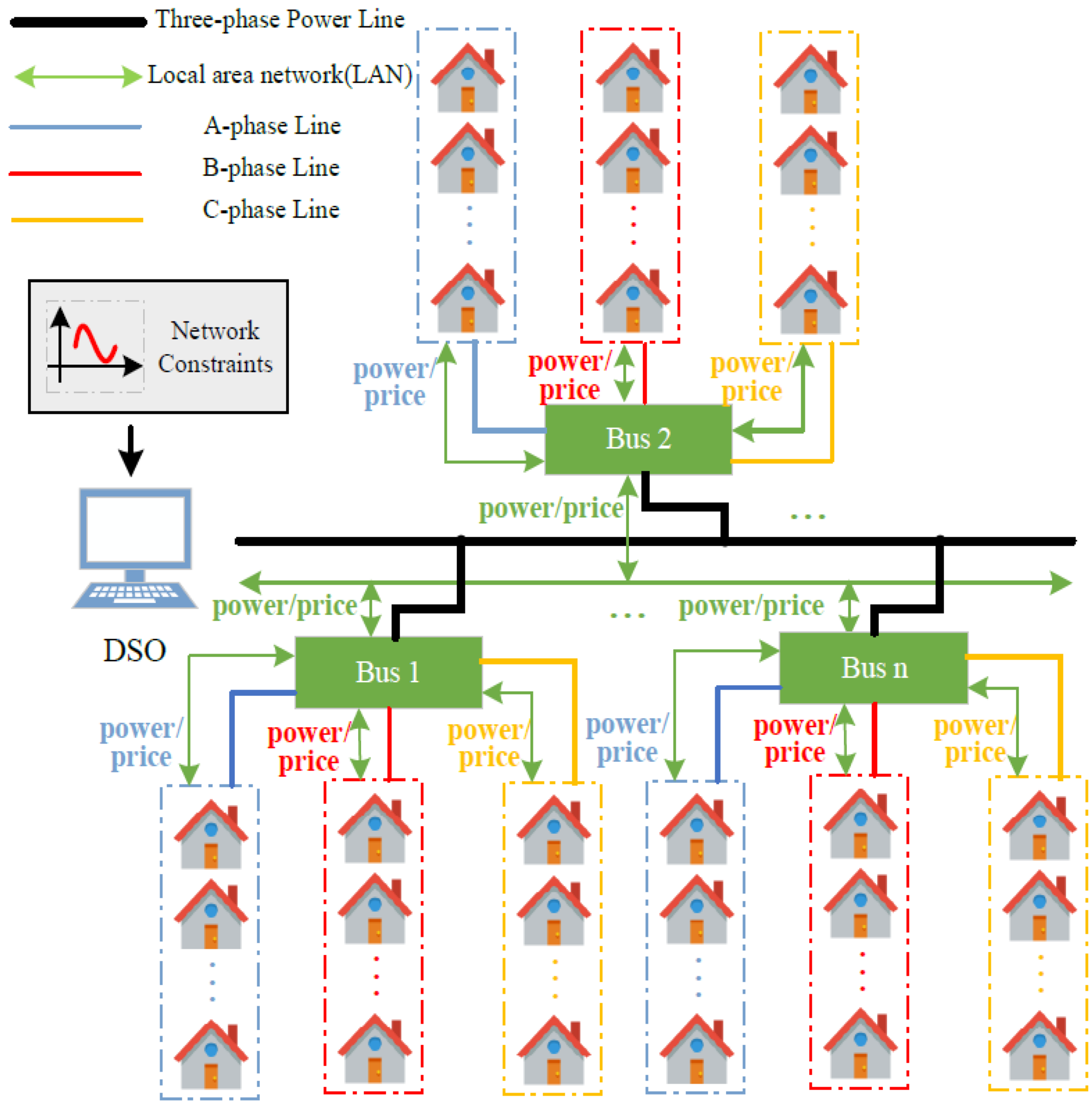


Fig. 4

# TES Design Illustration: Household-Level Problem

**Goal of each household $\psi$**: Maximize net benefit (i.e., benefit – cost) by choice of a TCL power schedule for all subperiods t in $K$={1,2,…,NK}

**Objective:**

$$\max_{P_\psi(K)} \sum_{t \in K} \underbrace{\boxed{U\left(P_\psi(t)\right)}}_{\text{Benefit obtained from power usage}} - \underbrace{\boxed{\mu_\psi \pi_\psi(K) P_\psi(K) * P_{base} \Delta t}}_{\text{TCL power usage cost}}$$

**Control Variables:**

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

**Constraints $X_\psi(K)$:**

- Thermal dynamic system determining household $\psi$'s inside air temperature over time as a function of appliance attributes, initial state conditions, external forcing terms, and control variables

**Hence, the solution takes the form:**

$$P_\psi\left(\pi_\psi(K)\right) = \underset{P_\psi(K) \in X_\psi(K)}{argmax} \left[U\left(P_\psi(K)\right) - \mu_\psi \pi_\psi(K) P_\psi(K) * P_{base} \Delta t\right]$$

# TES Design Illustration: DSO-Level Problem

**Goal of DSO:** Maximize the expected net benefit of distribution system customers subject to household constraints **and network constraints**.

**Objective:**

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

**Household Private Information**

**Control Variables:**

All the household TCL power schedules $P(K) = \{P_\psi(K) | \forall\psi \in \boldsymbol{\psi}\}$

**Constraints:** $\boxed{X_\psi(K), \psi \in \boldsymbol{\psi}}$ and network constraints:

DSO cannot solve this problem directly, as a centralized control problem, because the DSO does not have the required household private info.

# TC Design Illustration: Retail Price-To-Go Sequence

The best the DSO can do is ***control the price-to-go sequence*** $\pi_{\psi}(K)$ for each household $\psi$ ***in order to induce changes*** in $P_{\psi}(\pi_{\psi}(K))$ in a way that is consistent with the DSO's goals and constraints.

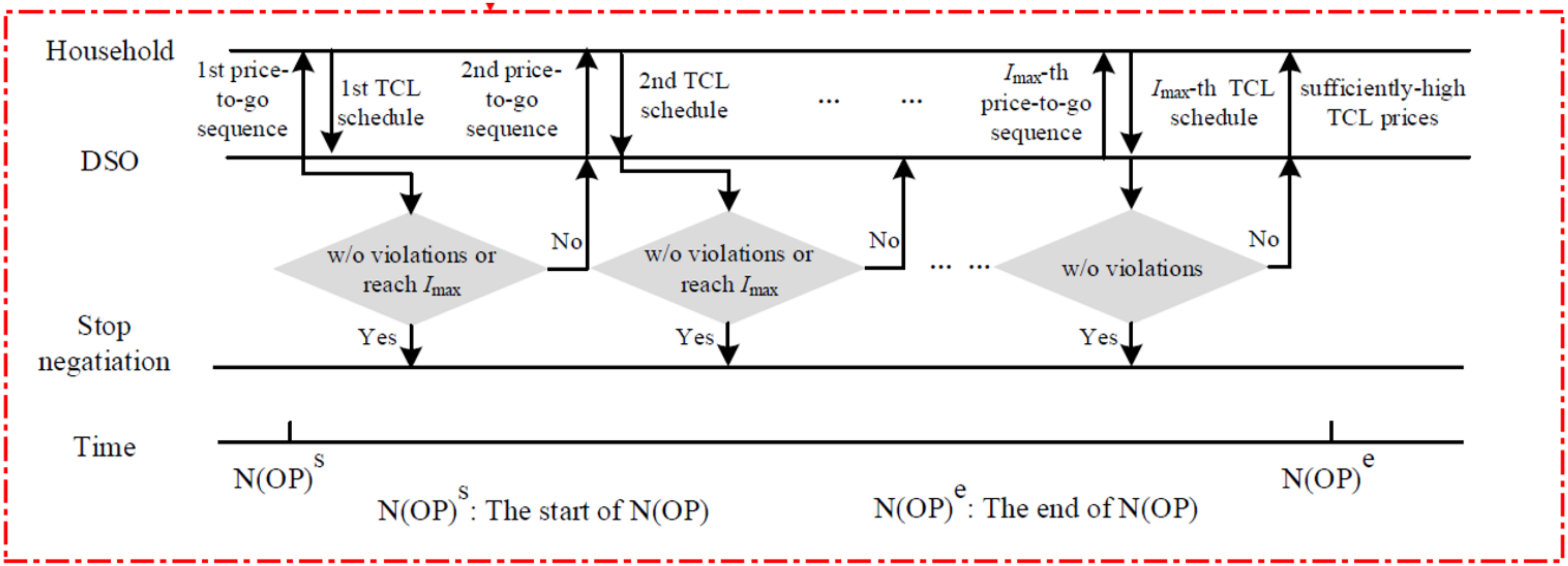


Fig. 5

$$\psi \in \boldsymbol{\psi}, \pi_{\psi}(K) \rightarrow \pi_{\psi}^{*}(K)$$

# TES Design Illustration: Propositions

The three propositions, below, give the theoretical basis for ***alignment of DSO goals & constraints with customer goals & constraints***.

The centralized DSO problem can be expressed as a standard nonlinear programming problem as follows:

$$\max_{x \in X} F(x)$$

$$\text{subject to } g(x) \leq c$$

The Lagrangian Function is:

$$L(x, \lambda) = F(x) + \lambda[c - g(x)]$$

**Proposition 1 （Classical）：** A point $(x^*, \lambda^*)$ in $X \times R_+^m$ is a saddle point for the Lagrangian Function $L(x, \lambda)$ if and only if :

[P1.A] $x^*$ is a solution for the primal problem.

[P1.B] $\lambda^*$ is a solution for the dual problem.

[P1.C] Strong duality holds.

# TC Design Illustration: Propositions … Continued

**Definition:** Suppose an optimal solution $x^* = P^*(K)$ for the DSO's centralized problem equals $P(\pi^*(K))$ for some collection $\pi^*(K)$ of household retail price-to-go sequences for OP. Then the pairing $\left(P^*(K), \pi^*(K)\right)$ 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 $\left(P^*(K), \pi^*(K)\right)$ for OP.

**NOTE:** The retail price-to-go sequences $\pi^*(K)$ in Prop. 2 depend on *customer preferences*, *physical attributes*, *and phase and bus locations*, as well as on the *extent to which network constraints are violated*.

# TES Design Illustration: Propositions … Continued

***Dual Decomposition Algorithm (DDA) for a TES equilibrium for OP***:
Starting from simple initial conditions, and given certain regularity conditions, this algorithm provides iterative solutions for primal and dual variables that converge to a limit point $(x^*, \lambda^*)$ as the iteration time approaches +∞ .

**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 +∞ .

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

**NOTE:** Complete proofs for Propositions 1-3 are provided in Ref. [1].

# TES Design Case Study: Modified IEEE 123-Bus Feeder

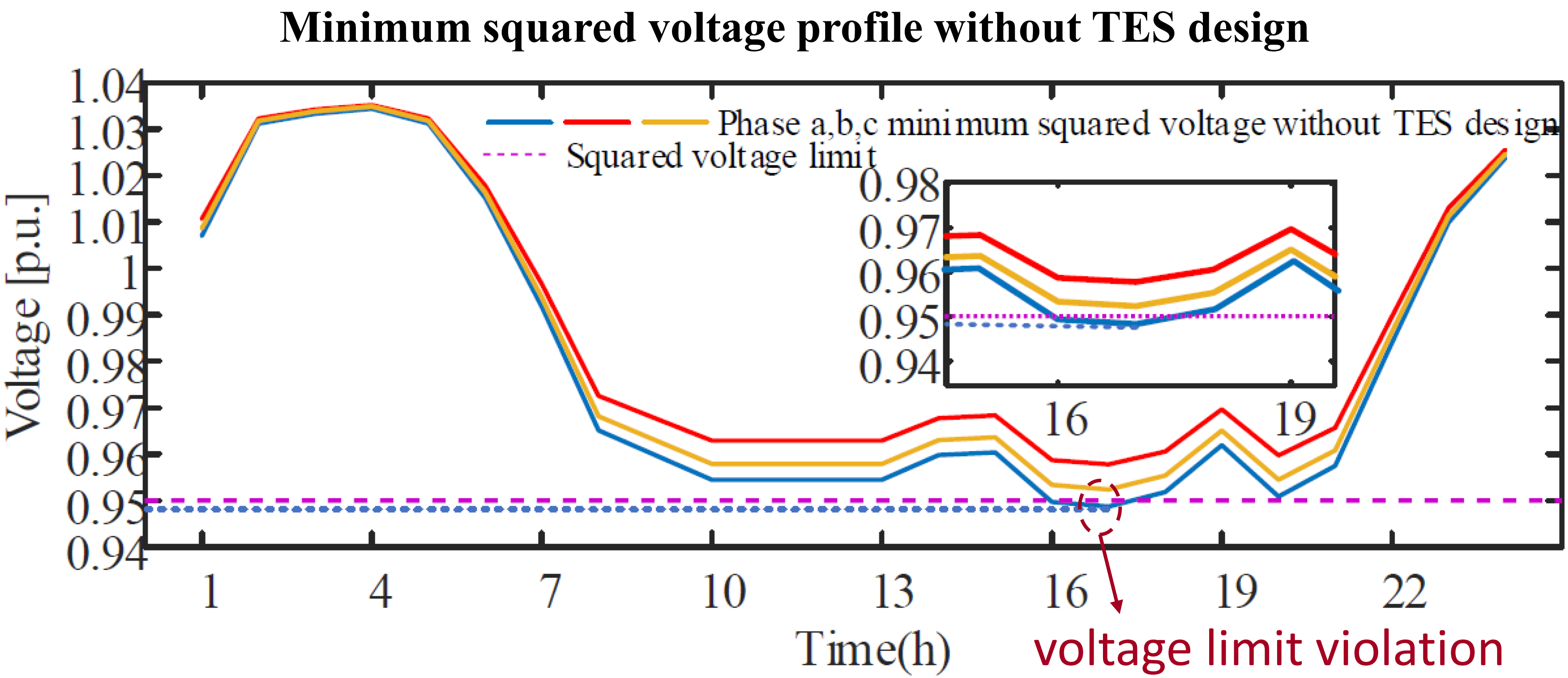


Fig. 6

- **DSO network constraints include power demand & voltage limits**
  - Peak demand limit is 3200kW & min squared voltage limit is 0.95
  - Without TES Design, the peak demand is 2962 kW < 3200kW
  - **Without TES Design, there is a voltage limit violation (0.9485 < 0.95)**

# TES Design Case Study … Continued

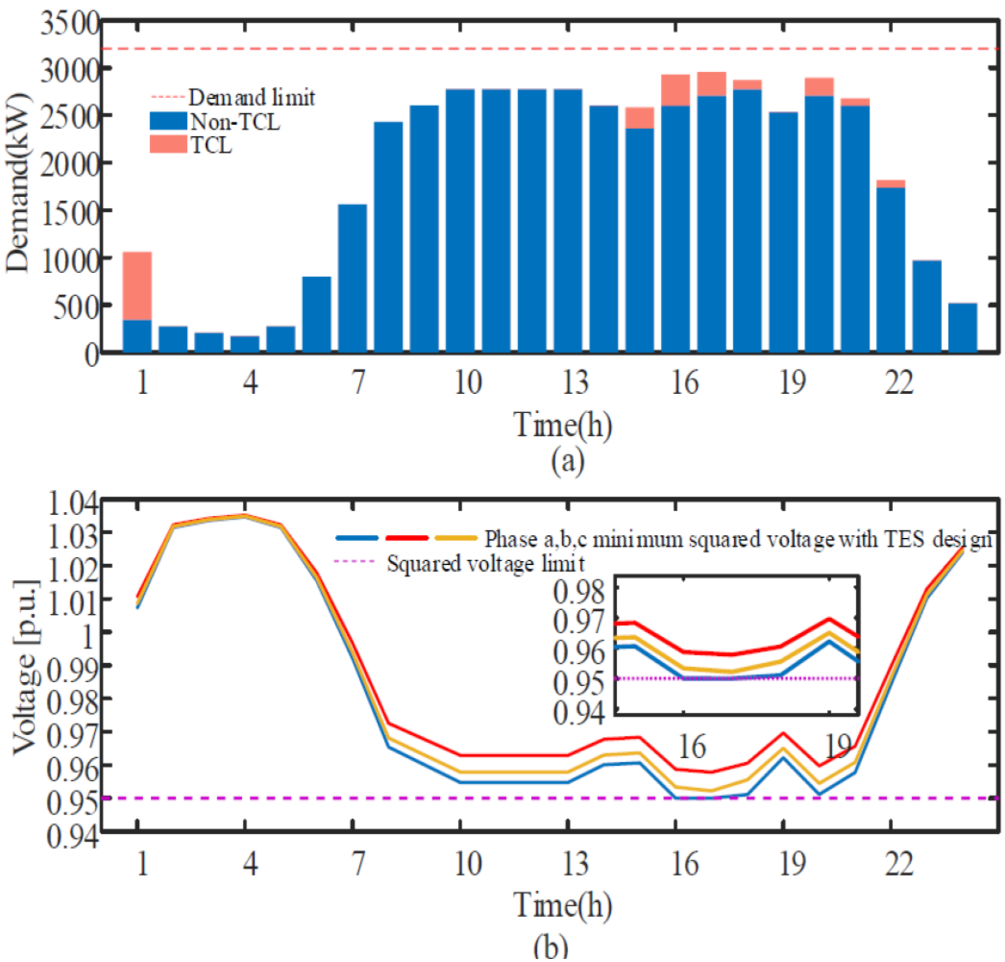


Fig. 7

**Minimum squared voltage profile and power usage demand under TES Design**

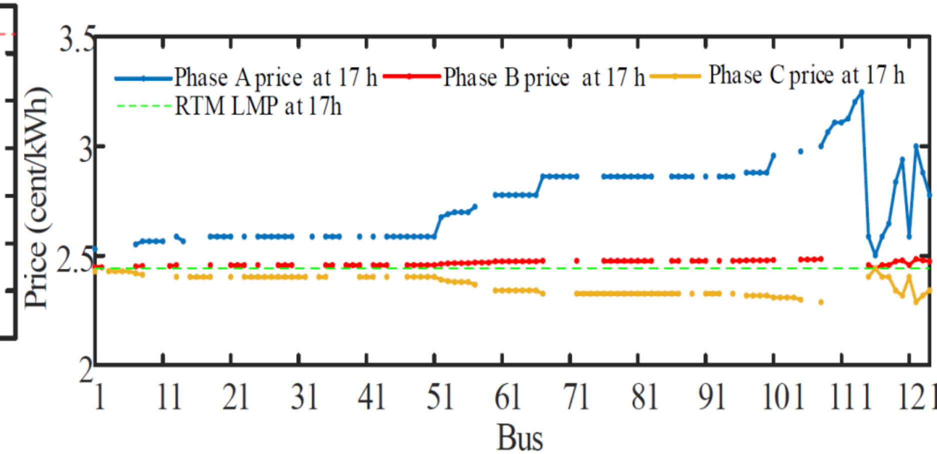


Fig. 8

**Retail price profile at 17h under TES Design**

- Under TES design, there is no violation of either network (demand limit & voltage) constraints or household constraints.
- The retail price at time 17h differs from bus to bus and from phase to phase.

# TC Design Case Study … Continued

- ❑ **TES design outcomes closely track centralized DSO control outcomes**

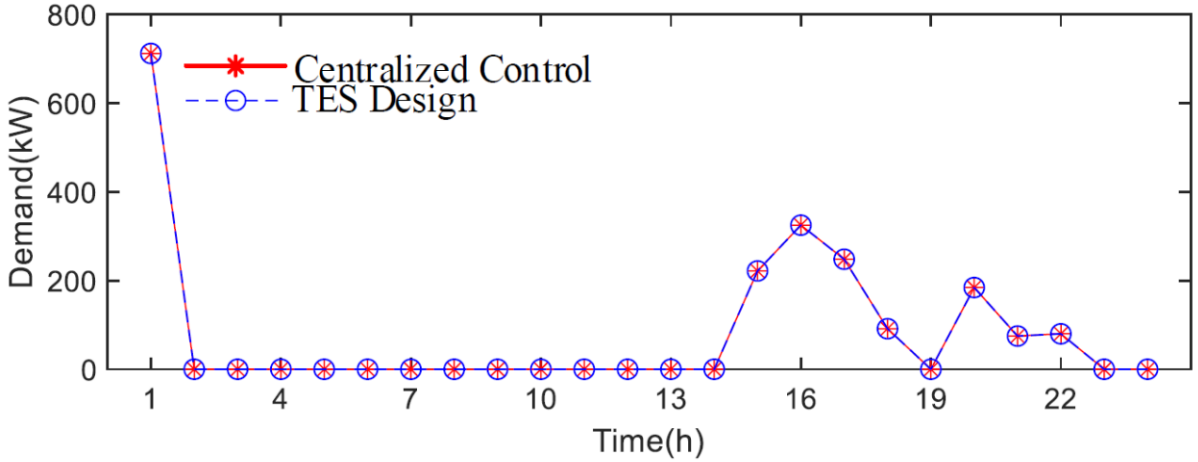


Fig. 9

**TCL Profile**

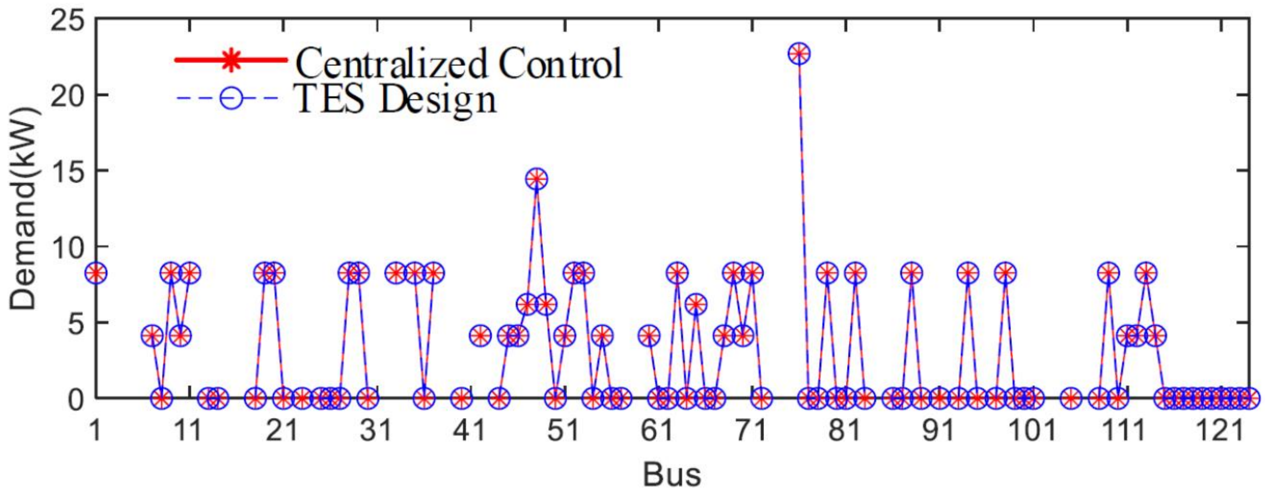


Fig. 10

**TCL across the 123 buses for phase A at hour 17**

# Conclusion

✓ Our proposed TES design:

- can be implemented for unbalanced distribution networks with operating periods OP consisting of multiple decision periods.
- can align DSO goals and constraints with local customer goals and constraints without violating household privacy.
- permits the DSO to protect against network constraint violations by engaging in a retail price negotiation process with customers.

✓ In future studies, distributed energy resources will be incorporated into our TES design.

# Thank you!

# Q&A