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:

[1] R. Cheng, L. Tesfatsion, & Z. Wang (2021), **"A Multiperiod Consensus-Based Transactive Energy System for Unbalanced Distribution Networks,"** WP #21005, Economics Working Paper Series, ISU Digital Repository, Iowa State University, Ames, IA
https://lib.dr.iastate.edu/econ_workingpapers/127

ISU Team 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.

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

TES Design: Key Features

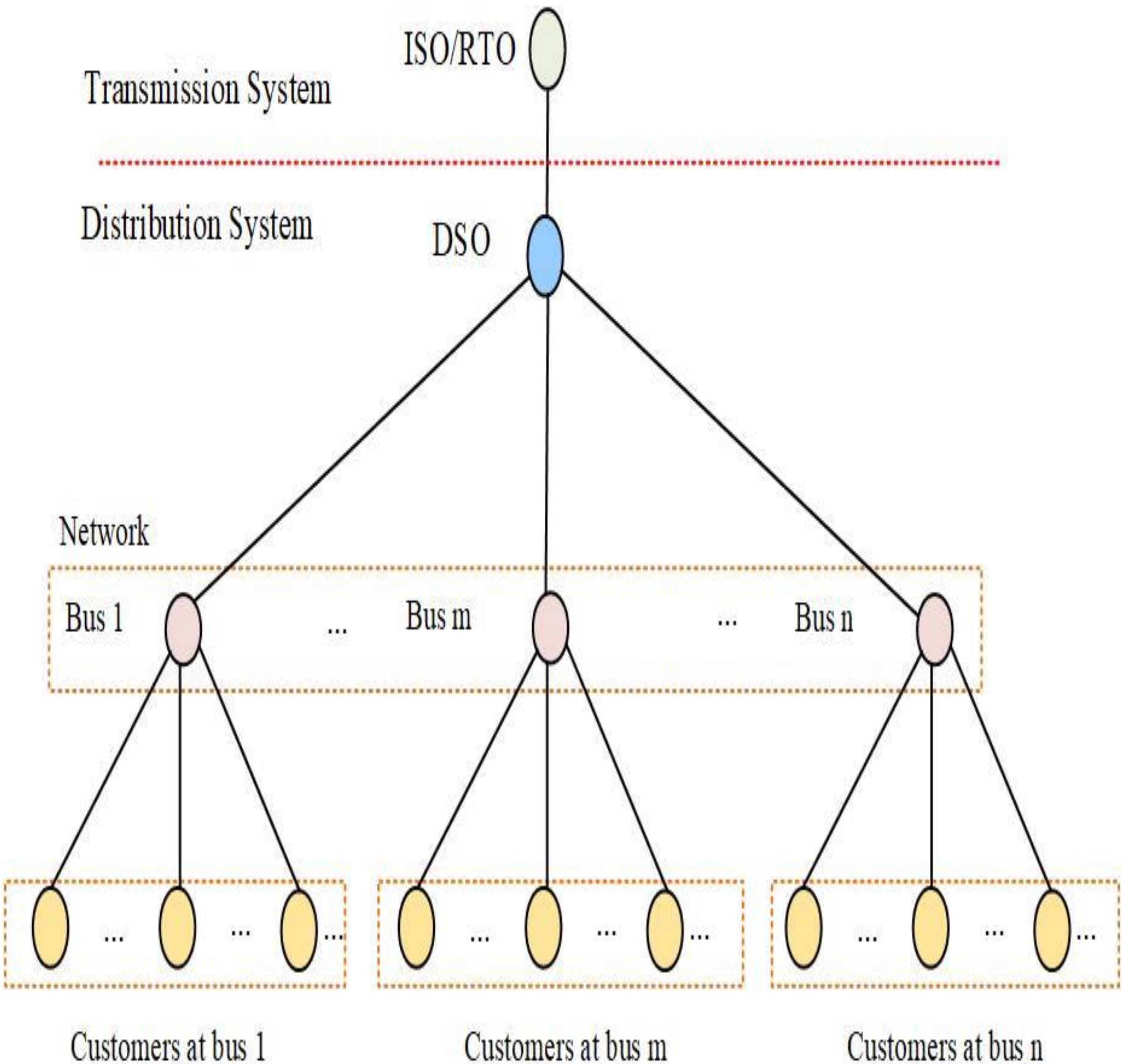

Fig. 1

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.

TES Design: Timing of Negotiation Process N(OP)

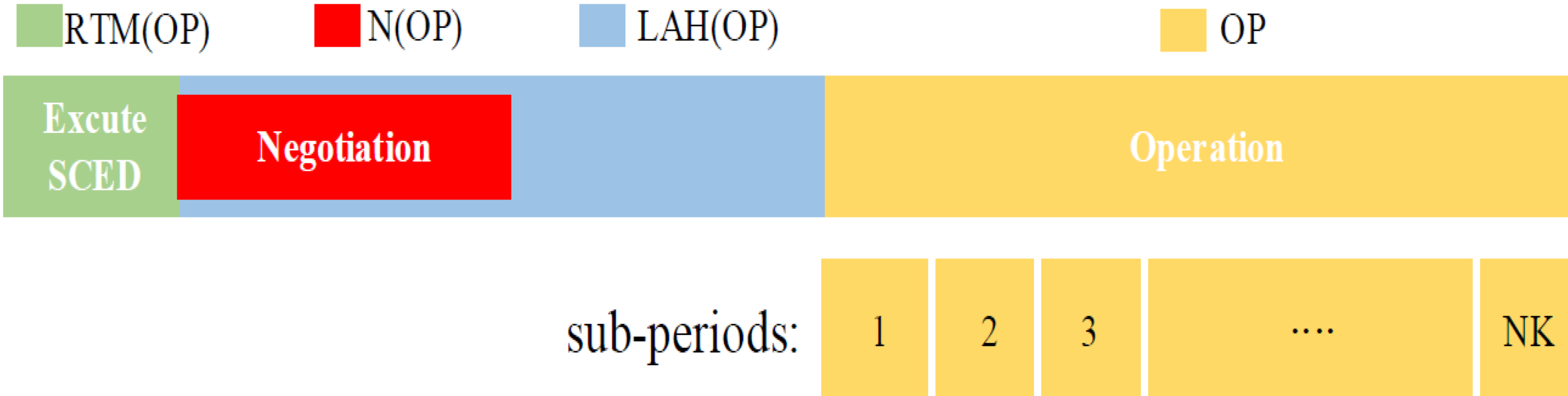

Fig. 2

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.

TES Design Illustration: Household Customers

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.

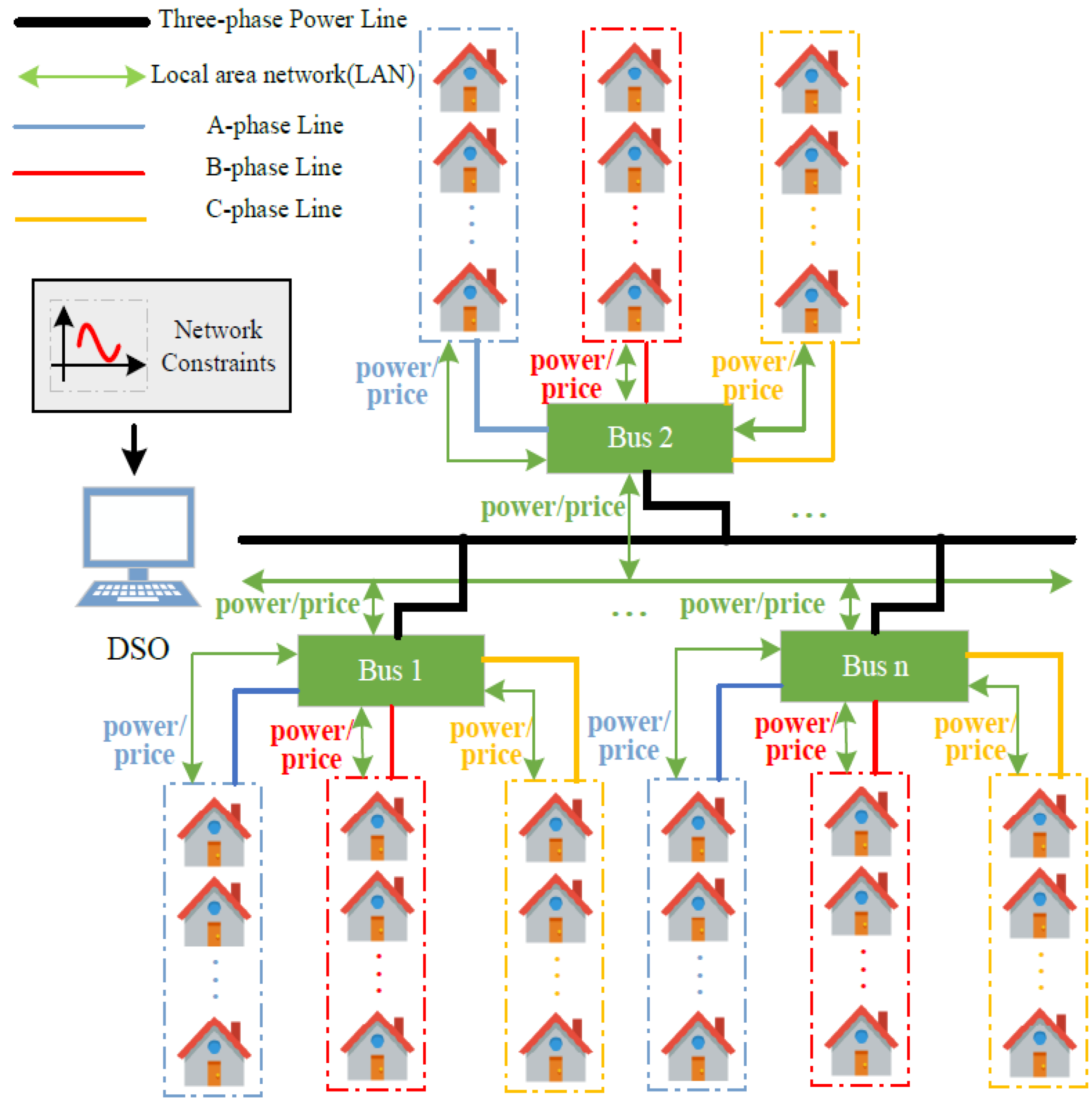

Fig. 3

TES Design Illustration: Household-Level Problem

Goal of each household ψ: *Max net benefit (i.e., benefit - cost)* by feasible choice of TCL power schedule for subperiods t in K = {1,2,…,NK}

Objective:

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

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

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

— Choice variables must satisfy *thermal dynamic equations* determining household ψ'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 ψ's optimization problem takes form:

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

TES Design Illustration: DSO-Level Problem

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:

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

Household Private Information

DSO Choice Variables:

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

DSO Constraints: $X_{\psi}(K), \psi \in \boldsymbol{\psi}$ 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:

$$\max_{x \in X} F(x)$$
$$\text{subject to } g(x) \le c$$

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 $\left(P^*(K), \pi^*(K)\right)$ will be called a ***TES equilibrium for OP***.

Proposition 2: Suppose (x^*, λ^*) 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^*, λ^*) determines a TES equilibrium $\left(P^*(K), \pi^*(K)\right)$ for OP.

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

$\pi_\psi^*(K)$ = Initial retail price-to-go sequence set for ψ by DSO
+ Price-to-go adjustment (if needed) to ensure *peak demand limit*
+ Price-to-go adjustment (if needed) to ensure *voltage magnitude limits*

TES Design Illustration: Propositions … Continued

Dual Decomposition Algorithm (DDA) for a TES equilibrium for OP:
Starting from simple initial conditions, and assuming various regularity conditions hold, algorithm DDA provides iterative solutions for primal and dual variables that converge to a limit point (x^*, λ^*) as the iteration time approaches +∞. **(Props. 4-5, [1])**

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^*, λ^*) as the iteration time approaches +∞ .

Then the DDA limit point (x^*, λ^*) 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].

Case Study: IEEE 123-Bus Network with 345 Households

Minimum squared voltage magnitude profiles (by phase) without TES design

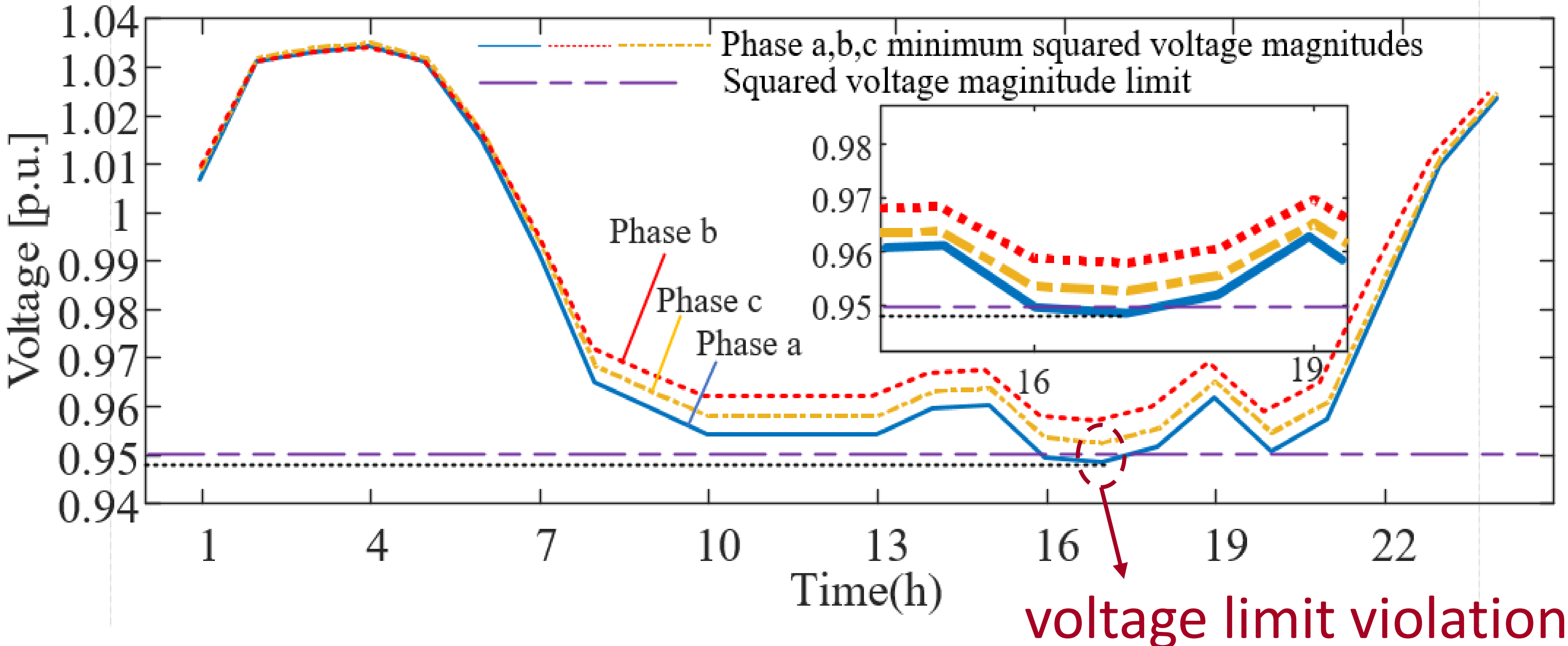

Fig. 4

- **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)**

TES Design Case Study … Continued

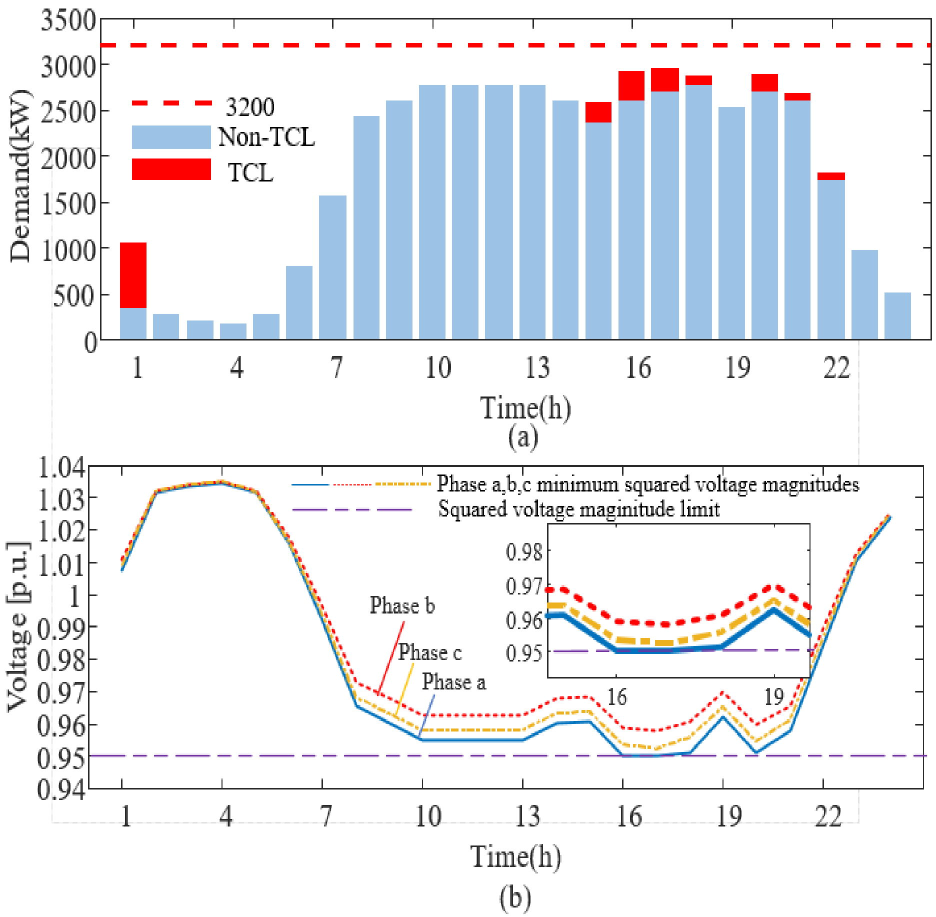

Fig. 5

(a) Day-D power usage & (b) day-D min squared voltage magnitudes by phase, under TES Design

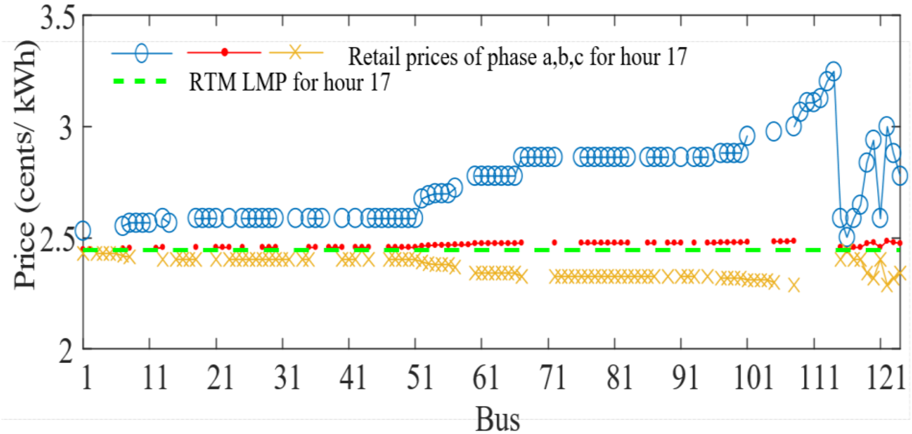

Fig. 6

Hour 17 retail prices by phase across entire network (123 buses) under the TES Design

— 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**

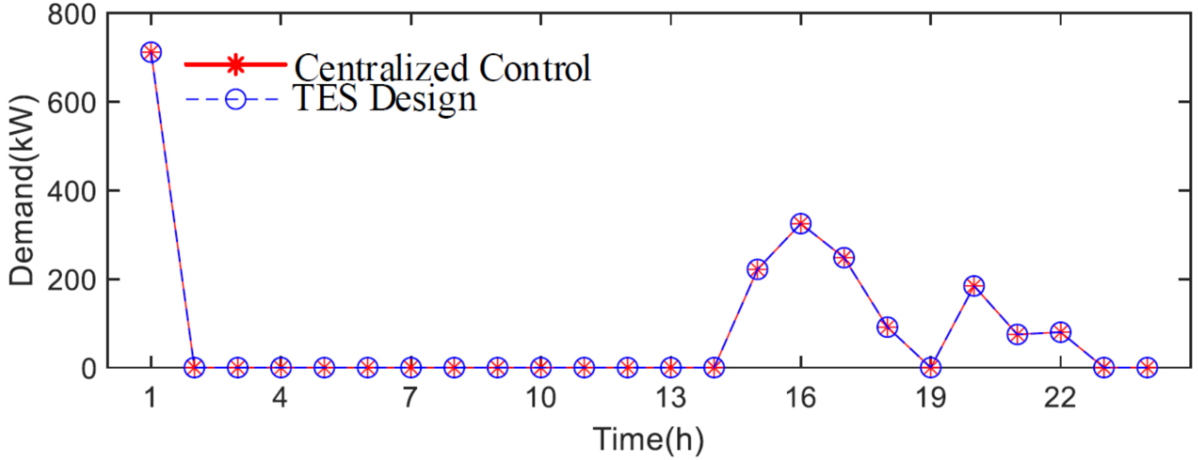

Fig. 8: Centralized control vs. TES outcomes for total TCL demand during day D

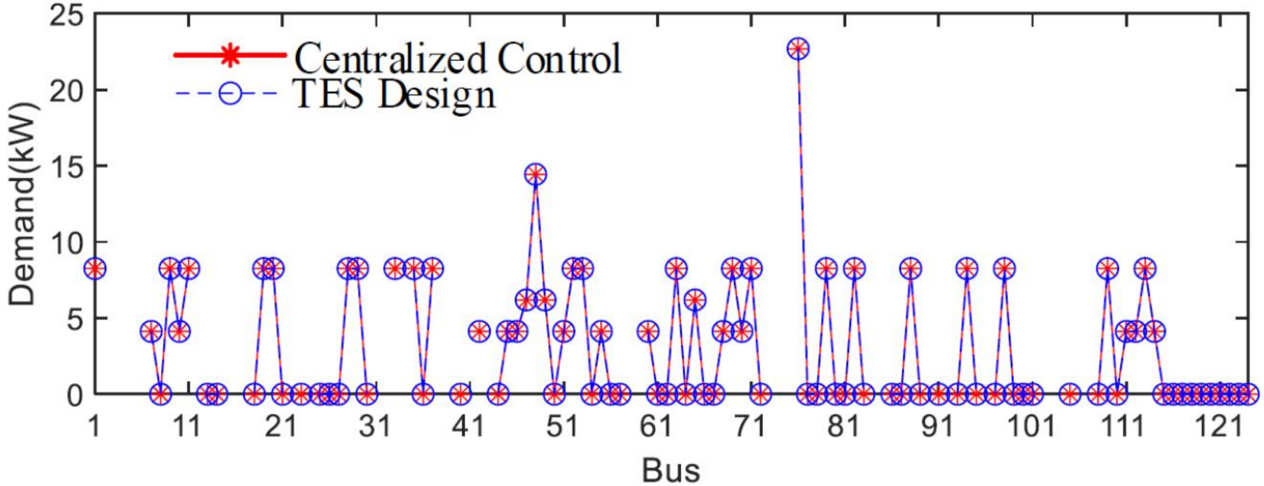

Fig. 9: Centralized control vs. TES outcomes for phase-a TCL demand during hour 17 across the entire network (123 buses)