An Integrated Transmission and Distribution Test System for Evaluation of Transactive Energy Designs☆

Hieu Trung Nguyen[a], Swathi Battula[a], Rohit Reddy Takkala[a], Zhaoyu Wang[a], and Leigh Tesfatsion[b]

[a]*Department of Electrical and Computer Engineering, and* [b]*Department of Economics,*
Iowa State University, Ames, IA 50011, USA.

Abstract

This study presents an open-source software platform specifically tailored to permit careful dynamic performance evaluation of transactive energy designs for end-to-end electric power systems. The platform models a centrally-managed wholesale power market operating over a transmission grid linked to one or more distribution systems, where each distribution system consists of a collection of grid-edge resources operating over a distribution grid. Test case findings are presented to illustrate the capabilities of the platform. The test cases implement a transmission system linked to a distribution system populated by households that have smart price-responsive appliances as well as conventional loads. Transactions at the distribution level are conducted in accordance with a well-known bid-based transactive energy design known as the PowerMatcher.

Keywords: Software platform, integrated transmission and distribution system, grid-edge resources, transactive energy system design

---

☆This work was supported by contract #339051 with the Pacific Northwest National Laboratory operated for the U.S. DOE under contract DE-AC65-76RLO1830, and by contract DE-OE 0000839 with the U.S. DOE Office of Electricity Delivery and Energy Reliability. The current paper is a substantially revised version of an unpublished working paper [1]. Corresponding author: Leigh Tesfatsion (tesfatsi@iastate.edu), Department of Economics, Iowa State University, Heady Hall 260, Ames, IA 50011-1054, USA.

	Acronyms and Generic symbols
b	Generic symbol for a distribution grid bus
B	Generic symbol for a transmission grid bus
D	Generic symbol for a day
DAM	Day-Ahead Market (wholesale)
DSO	Distribution System Operator
GER	Grid-Edge Resource
GERA	Grid-Edge Resource Aggregator
H	Generic symbol for an hour
h	Generic symbol for a household
ISO	Independent System Operator (wholesale)
LMP	Locational Marginal Price (\$/MWh)
RTM	Real-Time Market (wholesale)
RTO	Regional Transmission Organization (wholesale)
t	Time point (at a granularity of seconds)
	Parameters
β	Household comfort parameter (Utils/hr-[^{o}F]^2)
NH	Total number of households
TB	A household's bliss inside air temperature (^oF)
TMax	A household's maximum acceptable inside air temperature (^oF)
TMin	A household's minimum acceptable inside air temperature (^oF)
U(TB)	A household's maximum attainable hourly comfort (Utils/hr)
θ^s	Scale factor (cents/kWh) for a household's ancillary service supply offer
θ^u	Scale factor (cents/kWh) for a household's power usage demand bid
	Variables and Functions
$\mathrm{A}^{\mathsf{AvD}}$	Average household DSO-allocation (\$/day)
$\mathrm{CM}^{\mathsf{AvH}}$	Average household comfort (Utils/hr)
$\mathrm{NEP}^{\mathsf{AvH}}$	Average household net energy payment (\$/hr)
p^{DA}	Power dispatch (MW) scheduled in the day-ahead market
p^{RT}	Power dispatch (MW) determined in the real-time market
p^{RET}	Retail power usage (kW)
π^{DA}	Locational marginal price (\$/MWh) determined in the day-ahead market
π^{RT}	Locational marginal price (\$/MWh) determined in the real-time market
π^{RET}	Retail power price (cents/kWh)
$\pi^s(\mathrm{T}_a)$	A household's min acceptable compensation (cents/kWh) for ancillary service
$\pi^u(\mathrm{T}_a)$	A household's max willingness to pay (cents/kWh) for power usage
$\mathrm{T}_a(t)$	A household's inside air temperature (^oF) at t
$\mathrm{T}_m(t)$	A household's inside mass temperature (^oF) at t
$V_{b,p}^{\mathsf{lo}}$	Lower voltage magnitude limit violation (pu)
$V_{b,p}^{\mathsf{hi}}$	Upper voltage magnitude limit violation (pu)
%VIB$_b$	Voltage Imbalance Metric (%)

Table 1: Nomenclature

1. Introduction

This study reports on the development of an open-source software platform permitting comprehensive performance evaluation of economic and control mechanisms for electric power systems in advance of implementation. The platform models a centrally-managed wholesale power market operating over a high-voltage transmission grid linked to one or more distribution systems. Each distribution system consists of a lower-voltage distribution grid supporting the operations of a collection of grid-edge resources, i.e., resources with a direct point of connection to the distribution grid.

A primary envisioned use of this platform is the study of *Transactive Energy System (TES)* designs. A TES design is a collection of economic and control mechanisms permitting the dynamic balancing of power demands and supplies across an entire electrical infrastructure, using buyer and seller reservation values[1] as key operational parameters [2].

The validation of TES designs for power systems prior to real-world implementation requires test platforms permitting the high-fidelity modeling of physical attributes, institutional arrangements, and decision-maker behaviors and methods. In keeping with these needs, our platform permits: (i) modeling of power systems as open-ended dynamic systems operating over successive days; (ii) detailed modeling of economic and control operations at both the transmission and distribution levels; (iii) careful modeling of *Integrated Transmission and Distribution (ITD)* system operations; (iv) physically-based modeling of grid-edge resources; (v) modeling of TES designs for the bid-based trading of power and ancillary services within ITD systems; (vi) modeling of ITD decision-makers as strategic agents with learning capabilities; (vii) evaluation of ITD system reliability and efficiency; and (viii) evaluation of economic viability for individual ITD system participants, taking local goals and constraints into account.

Our platform, hereafter referred to as the *ITD TES Platform*, relies on the following key software components to realize these eight features. At the transmission level, the agent-based AMES Wholesale Power Market Test

---

[1] A *buyer's reservation value* for a good or service at a particular point in time is defined to be the buyer's maximum willingness to pay for the purchase of an additional unit of this good or service at that time. A *seller's reservation value* for a good or service at a particular point in time is defined to be the minimum payment that the seller is willing to receive for the sale of an additional unit of this good or service at that time.

Bed [3] is used to model core institutional and operational aspects of U.S. centrally-managed wholesale power markets, with transmission grid congestion handled by locational marginal pricing. Modeled agents include an independent system operator, non-dispatchable generation (e.g., wind power), generation companies, and grid-edge resource aggregators that manage power usage and ancillary service provision for collections of grid-edge resources. A learning module included within the AMES package permits any transmission system decision-maker to be equipped with learning capabilities.

At a T-D interface, an agent referred to as a distribution system operator participates in the distribution system as a grid-edge resource aggregator and in the transmission system as an ancillary service provider and/or a power procurer. At the distribution level, GridLAB-D [4] together with newly developed household, appliance, and controller agents are used to model the local physical and operational aspects of grid-edge resources. Finally, data exchange among these components is handled by the *Framework for Network Co-simulation (FNCS)* [5], a TCP/IP-based middleware developed by the *Pacific Northwest National Laboratory (PNNL)*.

Illustrative test cases are used to demonstrate the capabilities of our ITD TES Platform for the evaluation of TES designs in terms of carefully constructed reliability and welfare metrics. These test cases incorporate a well-known 5-bus transmission test system developed by Lally [6] for ISO New England and an IEEE 13-bus distribution test system [7] populated by households with both price-sensitive and conventional loads. Transactions at the distribution level are conducted in accordance with an extended version of the PowerMatcher [8, 9], a well-known TES design originally developed by Koen Kok [10].

The remainder of this study is organized as follows. Section 2 provides more detailed background motivation for our work, together with a review of related existing literature. Section 3 presents a summary overview of daily U.S. ISO/RTO-managed wholesale power market operations. Section 4 explains the basic features of our ITD TES Platform, including software components, modeling of transmission and distribution systems, and formulation of a generic TES design. Illustrative test cases are formulated in Section 5, and reliability and welfare test-case outcomes are reported in Sections 6–7. Section 8 concludes. Code and data for the ITD TES Platform and test cases can be accessed at a code/data repository [11].

2. Motivation and Related Literature Review

2.1. Background Motivation for the ITD TES Platform

A *Grid-Edge Resource (GER)* is defined to be any resource with a direct point of connection to a distribution grid. Common examples of GERs include households, commercial businesses, and industrial plants. However, individual devices (e.g., appliances, wind turbines, solar PV arrays, and storage devices) also constitute GERs if they are directly connected to a distribution grid. A *GER Aggregator* is any entity that manages power usage and/or ancillary service provision for a collection of GERs.

As noted in Section 1, TES designs are hybrid economic-control mechanisms that permit a balancing of power demands and supplies across an entire electrical infrastructure via value-based transactions [12–14]. A key hallmark of TES designs is a stress on the active participation of GERs as a counter-weight to the traditional activism of transmission-system participants [15, 16].

Interest in TES designs has been growing rapidly in response to technological developments, such as smart metering and intelligent devices, that facilitate the participation of retail customers in power system transactions through two-way communication channels [17]. This interest has also been encouraged by the demonstrated cost-effectiveness of TES designs in field studies [10, 18] and in some wholesale energy markets such as the Nord Pool Spot Market [8].

Nevertheless, the conceptual formulation and implementation of TES designs poses difficulties that have not yet been fully resolved. Participants in TES designs are permitted to make proactive bids for power usage and proactive offers of ancillary services in advance of real-time transactions. These bids and offers can reflect local goals and structural constraints. In addition, however, these bids and offers can reflect variable local state conditions, such as financial and operating conditions, that in turn depend on previously communicated and cleared bids and offers. Moreover, GERs with some flexibility in their power usage needs can function as *prosumers*, i.e., as entities that can either provide power or use power depending on their local state conditions.

In consequence, as depicted in Fig. 1, TES implementations within ITD systems can induce tight two-way feedback linkages between transmission and distribution level operations through market processes, two-way data and signal flows, and two-way power flows. The dynamics of ITD systems operating under TES designs thus tend to be extremely complex.

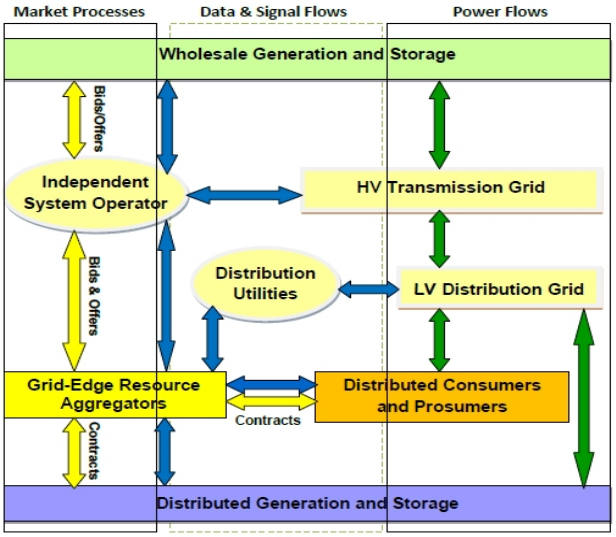


Figure 1: TES designs can induce tight two-way T-D linkages.

The difficulties facing ITD TES designers can be summarized in the form of five critical challenges, as follows:

- The validation of ITD TES designs prior to real-world implementation requires an ITD test system permitting the high-fidelity modeling and simulation of physical attributes, institutional arrangements, and decision-maker behaviors and methods.
- This ITD test system should model ITD systems as open-ended dynamic systems in order to permit performance evaluation for proposed TES designs over successive days of operation.
- This ITD test system should permit careful modeling of linkages between transmission and distribution systems.
- This ITD test system should permit careful evaluation of the physical viability of grid operations and the economic viability of all participants taking their local goals and constraints into account.
- This ITD test system should easily scale to permit consideration of TES designs encouraging active participation by grid-edge resources as these resources continue to increase in number and diversity.

Fortunately, *Agent-Based Modeling (ABM)* is well suited for the study of ITD systems operating under TES designs. As detailed in [19, 20], TES researchers are increasingly turning to ABM tools in an attempt to bridge the gap between conceptual TES design proposals and validated real-world TES implementations. In particular, as will be demonstrated in subsequent sections, the ITD TES Platform developed and implemented in this study is an agent-based platform that permits each of the above five challenges to be carefully addressed.

2.2. Review of Related Literature

Our ITD TES Platform incorporating co-simulation technology permits researchers to model the economic and control operations of an end-to-end power system encompassing both transmission and distribution levels. The open source release of the ITD TES Platform makes it suitable for research, teaching, and training purposes.

In this section we compare our ITD TES Platform to other existing open-source power system platforms. Comparisons are made on the basis of two important criteria. First, what operational levels are considered? Second, what types of studies are facilitated?

To date, open source test systems developed by individual electric power researchers have largely been designed for reliability studies at a single level of operation. For example, in 2005 Xia et al. [21] developed 9-bus and 179-bus transmission test systems that were then used by Chatterjee and Ghosh [22] (among others) to conduct transient stability studies. Gegner et al. [23] propose a new method for the construction of transmission test systems. Efforts to develop open-source distribution test systems are discussed in [24].

Similarly, IEEE test systems released as open source have also been designed primarily for reliability studies at a single level of operation. IEEE test systems for transmission networks can be found at [25], and IEEE test systems for distribution networks can be found at [26].

However, the importance of test systems permitting the evaluation of market arrangements in electric power systems has also been recognized. For example, John Lally [6] in 2002 developed a 5-bus test system for ISO New England that is still used in training manuals for ISO/RTO-managed energy regions to explain locational marginal price determination. In 2010 Li and Bo [27] proposed modifications to an IEEE 30-bus transmission test system to make it suitable for market studies. More recently, Krishnamurthy et al. [28] report on the development of an 8-bus transmission test system based on data and market arrangements for ISO New England.

Transmission test systems incorporating wholesale power market arrangements rely on software packages such as MATPOWER [29] and the AMES Wholesale Power Market Test Bed [3]. These packages permit the derivation of day-ahead and real-time market solutions for *Security-Constrained Unit Commitment (SCUC)* and *Security-Constrained Economic Dispatch (SCED)* as optimal power flow (OPF) problems. SCUC/SCED are the core types of optimizations undertaken in centrally-managed wholesale power markets.

MATPOWER contains a set of MATLAB files that can be used to solve both power flow and OPF problems for the transmission test systems in the IEEE repository [25]. Although MATPOWER is distributed under a GNU General Public License (GPL), this license includes exceptions to protect MATPOWER's proprietary MATLAB code. In addition, MATPOWER models single market optimizations rather than market processes. It is primarily designed to support stability studies at small time scales.

In contrast, AMES (*A*gent-based *M*odeling of *E*lectricity *S*ystems) is an open-source agent-based platform that incorporates key structural and institutional features of U.S. ISO/RTO-managed wholesale power systems operating as two-settlement systems, with grid congestion handled by locational marginal pricing. Developed entirely in Java/Python, AMES is easily integrated with third-party software packages. For example, the AMES package includes a *Java Reinforcement Learning Module (JRELM)* that permits decision-makers to be equipped with learning capabilities. As demonstrated in the AMES study [30], JRELM can be used to implement a wide variety of reinforcement learning methods for market participants, such as generation companies bidding into a day-ahead market.

Distribution test systems often rely on GridLAB-D [4], an agent-based platform developed by PNNL. GridLAB-D can accurately simulate the state dynamics for numerous independent appliances and devices at time scales ranging from sub-seconds to years. Similar to AMES, GridLAB-D is open source and easy to integrate with third-party software packages. A highly useful feature of GridLAB-D is that it contains *glm* files representing the distribution test systems in the IEEE repository [26]. Also, a transactive control module has recently been integrated into GridLAB-D based on the TES design adopted for the distribution system in the Olympic Peninsular demonstration project [18, 31]. However, this module is not necessarily applicable for other forms of TES designs.

As noted in Section 2.1, the coordination of transmission and distribution operations via TES designs has become a major research topic over the past several years. This, in turn, has highlighted the need for ITD test systems.

In response to this need, several software platforms for ITD simulation have recently been developed [32–35]. Aristidou et al. [32] propose a platform for the specific purpose of analyzing the voltage stability of transmission and distribution system interactions. Pilatte et al. [33] report on the development of an open-source ITD platform referred to as ITDNetGen. This platform, based on MATPOWER, permits the solution of power flow and OPF problems in ITD systems. Thus, ITDNetGen is effectively an extension of MATPOWER to an ITD formulation.

Auswin and Tesfatsion [34] construct an agent-based platform for the study of integrated retail and wholesale power system operations. The wholesale sector is simulated using AMES [3]. However, the retail sector is modeled in relatively simple fashion as a collection of households with price-responsive air-conditioning systems.

Huang et al. [35] present an open-source *Transactive Energy Simulation Platform (TESP)* [36] whose purpose is to permit the performance evaluation of TES designs for distribution systems. TESP integrates transmission (PyPower), distribution (GridLAB-D), and building (EnergyPlus) simulators, as well as plug-in double-auction and thermostat controller agents. TESP uses PNNL's *Framework for Network Co-Simulation (FNCS)* [5] to handle data exchange and coordination among its various components. FNCS is an open source middleware based on TCP/IP protocol.

As indicated by TESP, an increasing number of power system simulation platforms now incorporate co-simulation technology permitting the integration of different tools and simulation components. As detailed in Li et al. [37], co-simulation methods currently take three basic forms:

1. **Master-Slave:** During the co-simulation, a master simulator with highest priority coordinates the operations of all other simulators. Examples include MAPNET and POWERNET.
2. **Time-Stepped:** The individual simulators run their simulations independently but halt at fixed synchronization points to permit information to be exchanged between simulators. This approach requires a communication middleware to permit synchronization and data exchange. Examples include FNCS, VPNET, and EPOCHS.
3. **Global Event:** A global event list is prepared that schedules simulator

events according to their time-stamps. An example is GECO.

Our ITD TES Platform uses the time-stepped co-simulation technology FNCS to integrate AMES [3] and GridLAB-D [4] into a framework enabling the evaluation of TES designs for *integrated* transmission and distribution systems. By employing AMES rather than MATPOWER or PyPower, we can incorporate a detailed dynamic modeling of economic and control processes at both the transmission and distribution levels. In addition, the AMES learning module JRELM permits decision-making participants to be equipped with learning capabilities for determining over time how best to formulate their decisions in accordance with their local goals and constraints.

Among previously developed power system platforms, the TESP proposed in [35] is closest in formulation to our ITD TES Platform. However, the primary purpose of TESP is to permit the performance evaluation of TES designs for distribution systems, not ITD systems. In particular, the PyPower package used in TESP to implement transmission system operations is not specifically designed for the modeling of wholesale market operations.

In summary, to our knowledge, the ITD TES Platform is currently the only open-source co-simulation framework that permits careful performance evaluation of ITD systems operating under variously configured TES designs. Another novel feature of this platform is that private TES participants can be modeled as strategic decision-makers with learning capabilities who pursue local goals subject to local constraints.

3. U.S. ISO/RTO-Managed Wholesale Power Market Operations

This section describes daily market operations in current U.S. wholesale power markets that are centrally-managed either by an *Independent System Operator (ISO)* or a *Regional Transmission Organization (RTO)*.[2] These operations are based on the two-settlement system design formulated by the U.S. Federal Energy Regulatory Commission in a 2003 White Paper [38]. As will be seen in Section 4, these daily market operations are modeled by AMES [3], the computational platform used to implement transmission operations in our ITD TES Platform.

---

[2] The key difference between an ISO and an RTO is that RTOs have larger regional scope.

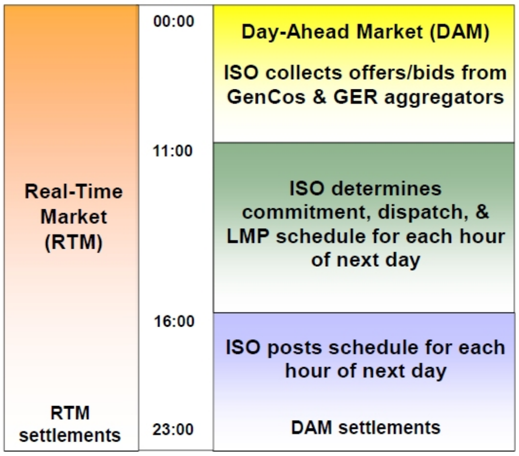


Figure 2: Simplified depiction of daily ISO market operations

For ease of exposition, an ISO/RTO-managed wholesale power market will henceforth simply be referred to as an *ISO market*. Also, the system operator for such a market will simply be referred to as an ISO.

Figure 2 depicts, in simplified form, an ISO market operating over an AC transmission grid on a typical day D. This ISO market is organized as a two-settlement system consisting of a *Day-Ahead Market (DAM)* operating in tandem with a *Real-Time Market (RTM)*. The power dispatch solutions determined in the DAM and RTM are separately settled in accordance with DAM-determined and RTM-determined *Locational Marginal Prices (LMPs)*.[3]

The participants in this ISO market include an ISO together with a collection of traders consisting of *Load-Serving Entities (LSEs)*[4] and *Generation*

---

[3] Roughly defined, locational marginal pricing is the pricing of power in accordance with the timing and location of its injection into, or withdrawal from, a physical grid. More formally, an LMP determined for a particular time at a particular grid bus is the dual variable of the power balance constraint for this time and bus. By construction, it measures the change in the ISO-optimized objective function with respect to a change in the constraint constant for this power balance constraint. This constraint constant is typically taken to be the possibly-zero amount of fixed (must service) load appearing in the power balance constraint.

[4] As will be clarified below, LSEs in current ISO markets are GER aggregators that service the power usage demands of downstream retail customers by aggregating these demands into demand bids for submission into the DAM.

Companies (GenCos) distributed across the buses of the transmission grid. The ISO's goal is to ensure over time the reliable and efficient operation of the ISO market. The goal of each LSE is to secure for itself over time the highest possible *net earnings* (i.e., earnings net of costs) through the daily purchase of electric power in the ISO market and the resale of this electric power to its downstream retail customers. The goal of each GenCo is to secure for itself over time the highest possible net earnings through the daily sale of electric power in the ISO market.

A more detailed description of the daily ISO market operations depicted in Fig. 2 is as follows:

- During the morning of each day D, each LSE chooses a *demand bid* to submit to the day-D DAM based on its forecasted loads for day D+1. Each demand bid consists of two parts: a *fixed demand bid* (i.e., a 24-hour price-insensitive load profile); and 24 *price-sensitive demand bids* (one for each hour), each consisting of a demand function defined over a purchase capacity interval.

- During the morning of each day D, each GenCo chooses a *supply offer* to submit to the ISO for use in all 24 hours of the day-D DAM. Each supply offer consists of a reported marginal cost function defined over a reported operating capacity interval.

- After receiving LSE demand bids and GenCo supply offers during the morning of day D, the ISO conducts the day-D DAM to determine hourly unit commitment, scheduled dispatch, and LMP values for day D+1. These values are found as solutions to a bid/offer-based Optimal Power Flow (OPF) problem that determines a *Security-Constrained Unit Commitment (SCUC)* and a *Security-Constrained Economic Dispatch (SCED)* for day D+1.[5] Transmission grid congestion is managed by the inclusion of congestion cost components in LMPs.

- The ISO attempts to resolve any differences that arise during day D between actual day-D power usage and the power supply offers cleared

---

[5] The precise SCUC/SCED optimization formulations currently in use by U.S. ISO markets are proprietary. However, summary descriptions of these formulations can be found in ISO business practice manuals, training manuals, technical reports, conference papers, and journal articles. See, for example, [39] and [40].

during the day-(D-1) DAM by solving appropriate SCED optimizations in the day-D RTM, a balancing mechanism conducted every five minutes during day D based on 5-minute-ahead ISO load forecasts.

- The day-D RTM dispatch solutions are communicated as dispatch set points to *Automatic Generation Control (AGC)*, which in turn signals these set points to GenCos as day-D real-time dispatch instructions.
- The ISO uses the LMPs determined in the day-D DAM to settle all power demands and supplies cleared in the day-D DAM for day D+1.
- The ISO uses the LMPs determined in the day-D RTM to settle five-minute-ahead forecasted adjustments to the day-D power dispatch levels scheduled in the day-(D-1) DAM for day D.
- The ISO uses ex-post LMPs (based on actual day-D loads) and other administratively determined charges to settle any additional needed adjustments in power injections and withdrawals on day D to ensure the real-time balancing of net load on day D. Make-whole ("uplift") payments for unit commitment costs might also be made.

The above simplified description of daily ISO market operations omits consideration of reserve procurement. As detailed in [41], reserve is procured in current U.S. ISO markets either through separate reserve markets or through DAM/RTM co-optimization of energy and reserve. In a DAM/RTM co-optimization the procurement of reserve (unencumbered generation capacity) is undertaken by incorporating ISO-specified demand bids for reserve into the objective function and/or ISO-specified zonal and system-wide reserve requirements into the constraints. AMES [3] models DAM/RTM co-optimization with ISO-specified zonal and system-wide reserve requirement constraints.

4. The ITD TES Platform: Components and Capabilities

4.1. Overview

The ITD TES Platform is an agent-based platform that permits the modeling of transmission and distribution systems linked by market processes, two-way data and signal flows, and two-way power flows. A partial agent taxonomy for this platform is depicted in Fig. 3. Down-pointing arrows indicate "has a" relations, and up-pointing arrows indicate "is a" relations.

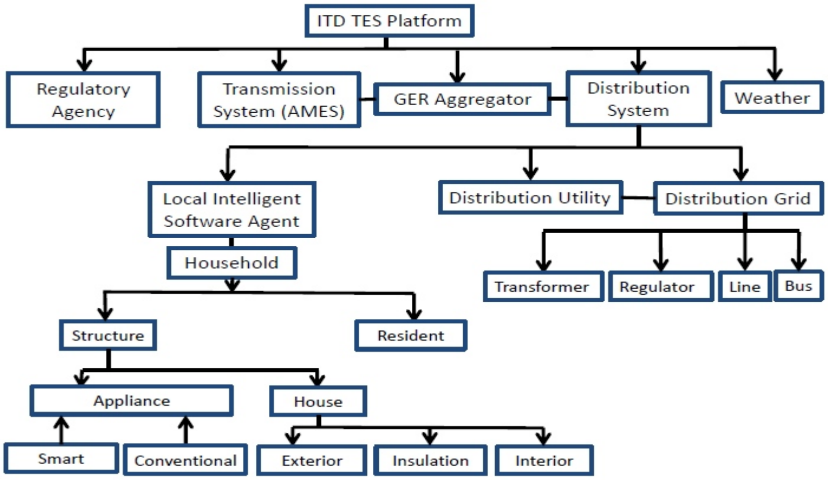


Figure 3: Partial agent taxonomy for the ITD TES Platform.

Fig. 4 depicts more carefully the agent taxonomy for the transmission sector component of the ITD Platform, implemented by means of AMES [3]. The daily interactions of these agents in accordance with a two-settlement DAM/RTM market design are discussed in the preceding Section 3. The two-way feedback between transmission and distribution systems modeled by the ITD TES Platform is depicted in Fig. 5

4.2. Key Software Components

As depicted in Fig. 6, the four principal software components comprising the ITD TES Platform are as follows:

- *C1:* A transmission system, implemented by the AMES Wholesale Power Market Test Bed [3];
- *C2:* A distribution system, implemented by GridLAB-D [4] and by plug-in resident, appliance, and controller agents implemented in Python;
- *C3:* A DSO agent, implemented in Python, with both economic and control methods;
- *C4:* TCP/IP middleware to handle communication among C1-C3, implemented by FNCS [5].

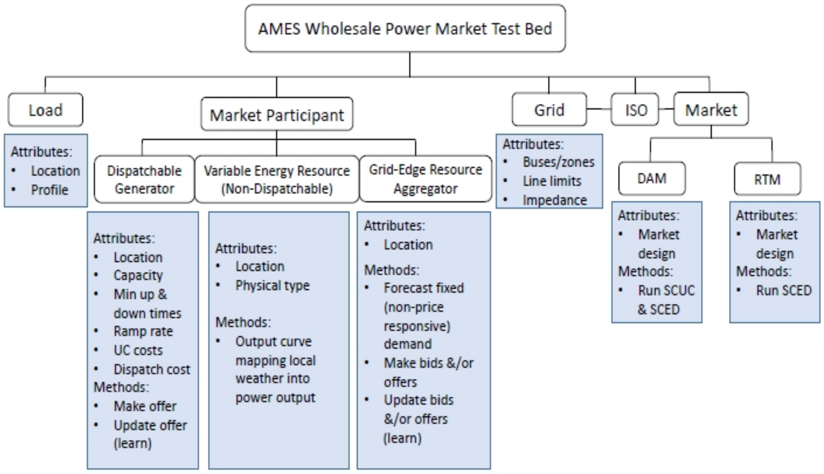


Figure 4: Partial agent taxonomy for the transmission sector of the ITD TES Platform, implemented via AMES.

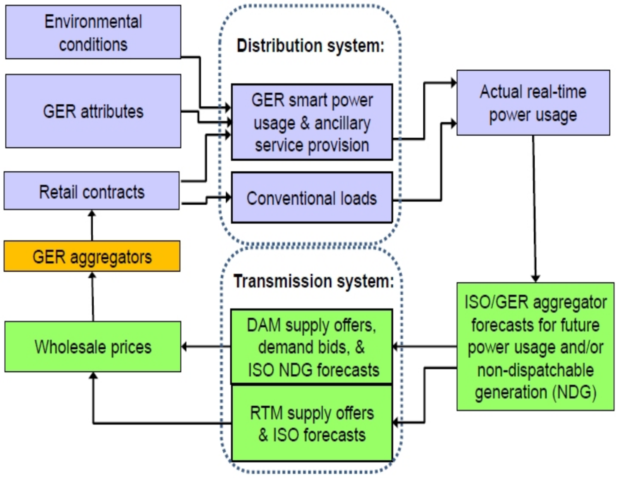


Figure 5: Flow diagram depicting T-D feedback in the ITD TES Platform.

With regard to C1, AMES [3] is used to implement a wholesale power market operating in accordance with the two-settlement system design characterizing actual U.S. ISO/RTO-managed wholesale power markets, as described in Section 3. In particular, AMES implements an ISO-managed DAM and RTM operating in tandem over a high-voltage transmission grid, with congestion handled by LMP.

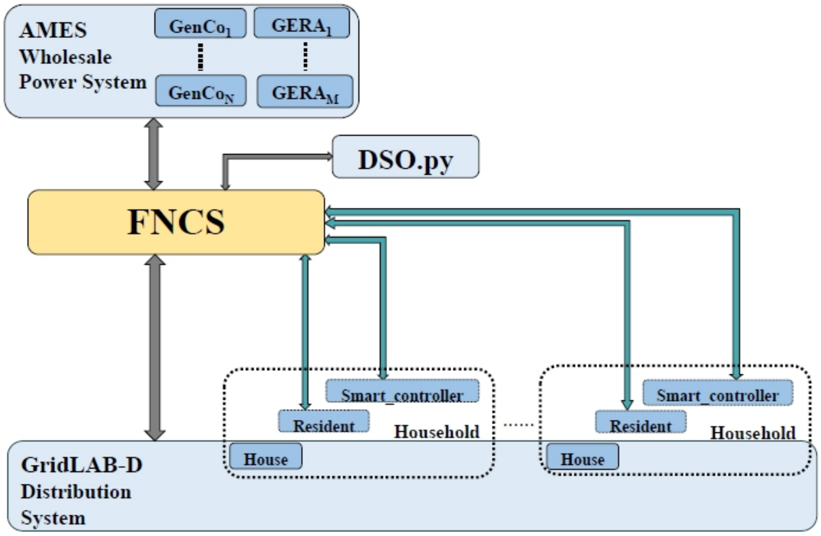


Figure 6: Key software components for the ITD TES Platform.

With regard to C2, GridLAB-D [4] is used to model a distribution grid supporting multiple households dispersed across its buses. More precisely, we use GridLAB-D's household ETP model [42, 43], augmented with plug-in resident and controller agents implemented in Python, to implement household thermal dynamics in dynamic state-space control model form. GridLAB-D is also used to specify physical house, appliance, and grid attributes.

Each household has a collection of appliances divided into two types: conventional (non-price-responsive) load; and smart appliances (e.g., HVAC system, water heater, refrigerator) whose power usage is managed by a smart (price-responsive) controller. Each smart controller maintains a state-conditioned bid function[6] for its appliance that determines the appliance's power settings in response to DSO-communicated price signals.

In addition, each household has a *Local Intelligent Software Agent (LISA)* that manages the power usage of the household's smart appliances as a collective whole. The LISA also manages the communication of bids/signals to

---

[6] In auction theory it is standard to use "bid" for a demand (buy) request and "offer" for a supply (sell) request. However, there is no standard term to describe the trading activities of hybrid prosumer agents that act as buyers or sellers depending on local conditions. In the remainder of this study we use *bid function* to refer to any transactional (buy or sell) request submitted in a functional price-conditioned form.

and from the DSO. The exact nature of the LISA's management activities depends on the particular TES design that is being implemented.

With regard to C3, the distribution system is managed by a *Distribution System Operator (DSO)*. This DSO is assumed to be an independent[7] entity operating at a T-D interface that functions in the distribution system as a GER aggregator and in the transmission system as a power procurer and/or provider of ancillary services. The DSO has three primary goals: (G1) Ensure the short-run efficiency of distribution system operations, which requires non-wastage of existing distribution system resources and the pricing of power-related goods and services in accordance with true production and distribution costs; (G2) maintain the short-run reliability of distribution system operations (e.g., ensure voltage magnitude limits are not violated); and (G3) maintain the DSO's independent status by ensuring that incoming revenues cover all incurred costs and that any revenues in excess of incurred costs are distributed back to households.

The DSO's economic methods allow the DSO to receive household bid functions, aggregate these household bid functions, and use these aggregate household bid functions to determine which price signals are to be sent back to the households in accordance with the DSO's goals. The DSO's economic methods also permit the DSO to submit ancillary service supply offers and/or power demand bids into the wholesale power market.

The DSO's control methods, implemented by the volt/var control object in GridLAB-D, allow the DSO to regulate voltage and reactive power in the distribution system. In particular, the DSO can monitor bus voltages and line currents to check for limit violations and to adjust tap settings and/or exert direct load control if violations are either observed or anticipated.

4.3. A Generic TES Design

To date, TES designs have taken two main forms: peer-to-peer and centrally-managed. In a peer-to-peer TES design, GERs directly engage with each other in bilateral negotiations to determine terms of trade (e.g., prices) as well as amounts traded; see, for example, [44]. In a centrally-managed

---

[7] More precisely, the DSO is assumed to be an entity that manages distribution system operations on behalf of its participants but that is "independent" of this system in the sense that it has no ownership interest in distribution system facilities and no private financial arrangements with distribution system participants.

TES design, some form of aggregator uses bids collected from GERs to determine terms of trade which, when announced, result in purchases and sales by inframarginal GER buyers and sellers.[8]

Centrally-managed TES designs can in turn be divided into two basic types, direct and iterative. In direct forms, referred to in [8] as *one-time information exchange-based designs*, an aggregator sets the terms of trade in each market period directly following the receipt of bids from GERs; see, for example, [48]. In iterative forms, referred to in [8] as *iterative information exchange-based designs*, an aggregator sets the terms of trade in each market period only after multiple information exchanges have taken place between the aggregator and GER participants.[9]

As reviewed in [12, 13], direct centrally-managed TES designs have already been tested in field studies, such as the PowerMatcher TES design in Power City [10] and a PNNL-developed TES design in the Olympic Peninsular Project [31]. In contrast, iterative centrally-managed TES designs are still at a conceptual formulation stage since their communication burden does not currently permit practical implementation.

The ITD TES Platform permits the implementation of direct centrally-managed TES designs generically characterized by the following five steps:

- **Step 1:** For each GER R, the price-responsive controller for each smart device j(R) that belongs to R collects data on the state of R and j(R) at a *data check rate* that it uses to form a state-conditioned bid function bj(R) for power usage and/or ancillary service provision.

- **Step 2:** The LISA for each GER R combines the device bid functions bj(R) into a state-conditioned aggregate bid function b(R) that it communicates to the DSO at a *bid refresh rate.*

- **Step 3:** The DSO combines the received GER bid functions b(R) into an aggregate bid function b at an *aggregate bid refresh rate.*

---

[8] A buyer is *inframarginal* for a market at a particular point in time if the price the buyer would have to pay to procure an additional unit of good or service does not exceed the buyer's reservation value (i.e., the maximum price the buyer is willing to pay). A seller is *inframarginal* for a market at a particular point in time if the price the seller would receive for the provision of an additional unit of good or service does not fall below the seller's reservation value (i.e., the minimum price the seller is willing to be paid).

[9] One possible reason for this iteration could be to allow the aggregator to test potential trade outcomes in advance of actual trading in order to ensure system reliability.

- **Step 4:** The DSO uses the aggregate bid function b to determine price signals in accordance with its goals that it communicates back down to the GER LISAs at a *price signal rate*.

- **Step 5:** The LISA for each GER R inserts its latest received price signal into its latest refreshed state-conditioned bid function bj(R) for each device j(R) at a *power control rate*, which triggers a power response from j(R).

4.4. Performance Metric Construction

The ITD TES Platform can record outputs important for reliability evaluations, such as phase-to-ground and phase-to-phase voltages, currents, reactive power, and active power in both *json* and *csv* formats. These outputs can be in complex or real-number form as appropriate. The time step for sampling and recording of outputs can also be flexibly chosen.

In addition, the ITD TES Platform can record welfare (benefit minus cost) outcomes for each ITD system participant. At the transmission level, these participants can include an ISO, dispatchable and non-dispatchable generation resources, and GER aggregators (e.g., LSEs) that manage ancillary service provision and/or power procurement on behalf of collections of GERs. At the distribution level, these participants can include a DSO, households, and other forms of GERs.

Consequently, platform users can construct and employ a wide variety of performance metrics for the evaluation of TES designs.

5. ITD Test Cases: Basic Formulation

5.1. Overview

This section describes the basic formulation of the ITD test cases reported below in Sections 6–7. The purpose of these ITD test cases is to illustrate how the ITD TES Platform can facilitate the careful performance evaluation of ITD TES designs.

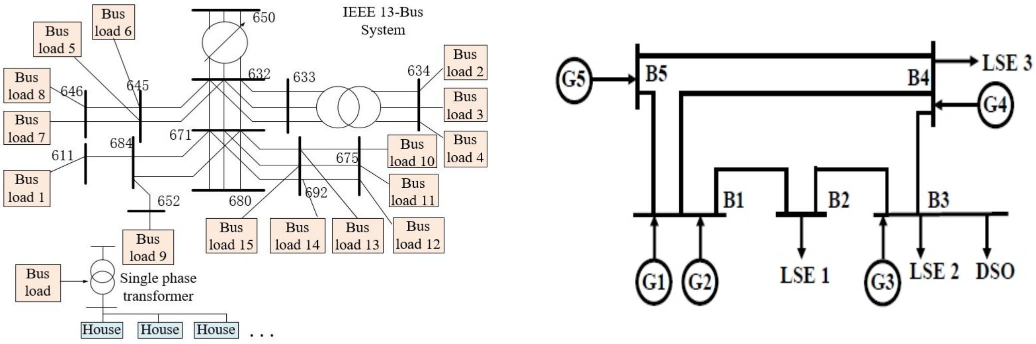
In keeping with this purpose, the ITD test cases implement a variant of the well-known PowerMatcher TES design [9] that has been successfully implemented in numerous field studies in the Netherlands, Germany, and

Denmark. As will be seen, PowerMatcher implements relatively simple types of household bid functions for thermostatically controlled loads.[10]

We start by describing how the ITD test cases model linked transmission and distribution systems, and how these test cases implement a PowerMatcher TES design. We next explain our construction of "house quality types," a key treatment factor for these test cases. Finally, we describe the reliability, welfare, and DSO break-even metrics used to evaluate performance for these test cases.

5.2. ITD Test Case Transmission and Distribution Systems

Each ITD test case models a DSO-managed distribution system linked to an ISO-managed transmission system. Distribution system transactions are conducted in accordance with a PowerMatcher TES design. Transmission system transactions are conducted in accordance with the two-settlement DAM/RTM system described in Section 3.



(a)

(b)

Figure 7: ITD test case grids: (a) A DSO-managed 13-bus distribution system; and (b) an ISO-managed 5-bus transmission system with participation by the DSO at transmission bus B3, the T-D interface.

As depicted in Fig. 7a, the distribution system consists of a 13-bus distribution grid populated by households dispersed across 15 bus loads. Each

---

[10] Although a careful investigation of bid function formulation in relation to TES design performance is outside the scope of this study, we note that much work on this important topic is currently under way [45–48]. As discussed in our concluding Section 8, we intend to use the ITD TES Platform to pursue this topic in future studies.

household has two types of appliances: (i) conventional (non-price-responsive) appliances; and (ii) a smart electric HVAC system with a price-responsive bang-bang (ON/OFF) controller. As depicted in Fig. 7b, the transmission system consists of a 5-bus transmission grid populated by five GenCos G1-G5 and three LSEs 1-3. The DSO operates at the T-D interface between the transmission and distribution systems; this T-D interface is assumed to be located at transmission bus B3.[11]

The state of each household is measured by its inside air temperature, T_a, determined by weather, house structural attributes, and past appliance control settings. Each household strives to ensure T_a is maintained between a lower level TMin and an upper level TMax. Within this interval, each household balances comfort against energy cost (or ancillary service compensation), where comfort is measured by nearness of T_a to a bliss (most desired) inside air temperature TB satisfying TMin < TB < TMax.

Specifically, the comfort level (Utils/hr) attained by any household h during any hour H of any day D is measured as a non-increasing function of the deviation of its inside air temperature T_a from its bliss temperature TB, as follows:

$$\mathrm{Comfort}^h(\mathrm{H,D}) \;=\; U(\mathrm{TB}) - \beta\big[\mathrm{T}_a^h(\mathrm{H,D}) - \mathrm{TB}\big]^2 \qquad (1)$$

In (1), the non-negative factor β (Utils/hr-$[^o\mathrm{F}]^2$) determines the sensitivity of household-h residents to deviations of T_a from TB.

5.3. ITD Test Case Implementation of a PowerMatcher TES Design

The PowerMatcher TES design implemented by the ITD test cases sets each household's bid period equal to 5 minutes (300s) and sets all five TES design rates in Section 4.3 equal to 1/300s. Only summer-day scenarios are considered, hence HVAC systems operate only in a "cooling mode".

A household's bid function conveys the intended power usage (or ancillary service provision) by its HVAC system as a function of price, conditional on current inside air temperature T_a. The exact form of this bid function depends on the relationship of T_a to the household's minimum acceptable inside air temperature TMin, bliss inside air temperature TB, and maximum

---

[11] Apart from the appearance of the DSO at transmission bus B3, this 5-bus transmission system is the well-known 5-bus test case developed by Lally [6] for ISO New England.

acceptable inside air temperature TMax. This state-conditioning results in four possible bid forms, as follows:[12]

F1: **Must Be OFF ($\mathrm{T}_a \leq$ TMin)** The house is too cold. The HVAC system must stay (or be switched) OFF, regardless of price; hence, the HVAC system has no power usage flexibility.

F2: **May Run as Service (TMin $< \mathrm{T}_a \leq$ TB)** The internal air temperature T_a is somewhat cooler than (or at) the household's bliss temperature TB. The HVAC system stays (or is switched) ON if and only if the price π^s *paid to* the household for *ancillary service (power absorption)* equals or exceeds the household's *service offer price* $\pi^s(\mathrm{T}_a)$, the minimum price the household is willing to receive as compensation for running its HVAC system at its ON power-usage level P^*. The cut-off price $\pi^s(\mathrm{T}_a)$ is a non-negative *decreasing* function of T_a.

F3: **May Run for Usage (TB $< \mathrm{T}_a <$ TMax)** The internal air temperature T_a is somewhat hotter than the household's bliss temperature TB. The HVAC system stays (or is switched) ON if and only if the price π^u *charged to* the household for *power usage (cooling)* does not exceed the household's *usage bid price* $\pi^u(\mathrm{T}_a)$, the maximum price that the household is willing to pay for its ON power-usage level P^*. The cut-off price $\pi^u(\mathrm{T}_a)$ is a non-negative *increasing* function of T_a.

F4: **Must Be ON (TMax $\leq \mathrm{T}_a$)** The house is too hot. The HVAC system must stay (or be switched) ON, regardless of price; hence, the HVAC system has no power usage flexibility.

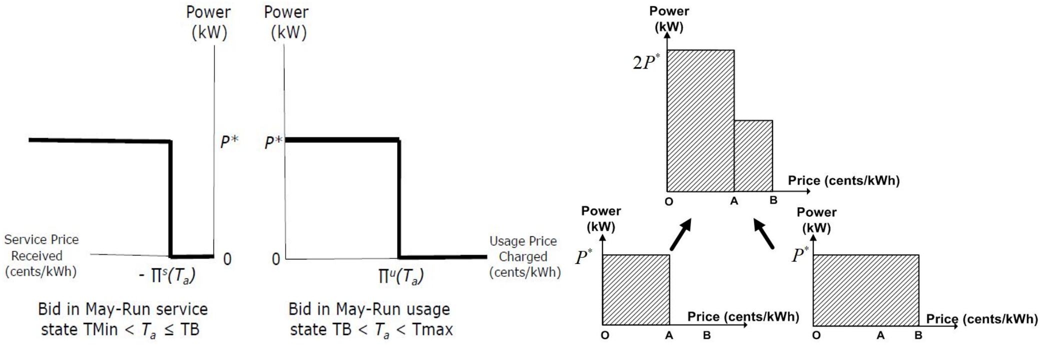
The functional forms used for each household's minimum acceptable service price $\pi^s(\mathrm{T}_a)$ and maximum acceptable usage price $\pi^u(\mathrm{T}_a)$ are as follows:

$$\pi^s(\mathrm{T}_a) = \theta^s\Big[\frac{\mathrm{TB} - \mathrm{T}_a}{\mathrm{TB} - \mathrm{TMin}}\Big] \quad \text{for} \quad \mathrm{TMin} < \mathrm{T}_a \leq \mathrm{TB} \ ; \tag{2}$$

$$\pi^u(\mathrm{T}_a) = \theta^u\Big[\frac{\mathrm{T}_a - \mathrm{TB}}{\mathrm{TMax} - \mathrm{TB}}\Big] \quad \text{for} \quad \mathrm{TB} < \mathrm{T}_a < \mathrm{TMax} \ , \tag{3}$$

---

[12] This four-part bid function for an HVAC system operating in cooling mode is a generalization of the three-part bid function proposed by Koen Kok [10, Section 8.1.2] for the power usage of a freezer. As clarified below, given the four-part formulation, a household can offer ancillary services (power absorption) as well as express demands for power usage.



(a) (b)

Figure 8: (a) A household's two possible "May Run" bid forms, dependent on inside air temperature T_a; and (b) the DSO's bid aggregation method.

where θ^s and θ^u are positively-valued scaling parameters. Illustrative depictions of a household's may-run bid functions in service and usage states are provided in Fig. 8a, where a negative price indicates a price received and a positive price indicates a price charged.

The method used by the DSO to aggregate household bid functions at any given time is illustrated in Fig. 8b for two households, each in a "May Run for Usage" state ($\mathrm{TB} < \mathrm{T}_a < \mathrm{TMax}$). Household one has a lower inside air temperature T_a than household two; hence, the value of (3) for household one (labelled A) is less than the value of (3) for household two (labelled B).

5.4. ITD Test Case Construction of House Quality Types

Structural house attributes strongly affect house thermal dynamics, which in turn can affect the reliability and efficiency of distribution grid operations. Consequently, the structural quality of the houses populating the distribution grid is taken to be a key treatment factor in our ITD test cases.

This section briefly summarizes how we constructed three distinct House Quality Types (Low, Medium, High) for use in these test cases. A detailed explanation of this construction can be found in our working paper [1, App. B, Tables VI-VIII].

In each of our test cases, all household are assumed to have the same appliance mix. In most of our test cases each household has conventional (non-price responsive) loads plus an electric HVAC system running in cooling mode that is controlled by a smart price-responsive controller. In some test cases each household also has an electric water heater controlled by a smart price-responsive controller.

For each test case, the thermal dynamics of each household are modeled in accordance with GridLAB-D's household ETP model [42]. This differential state-space control model assumes that the thermal state of a house at each time t is determined by its inside air temperature $T_a(t)$ and its inside mass temperature $T_m(t)$. The user-set parameters determining the functional form of this ETP model for each house are divided into two types: house size attributes; and house thermal integrity (insulation) attributes.

Three distinct correlated sets of values are then assigned to the size attributes of a house, as appropriate for "Small", "Medium", and "Large" houses. Similarly, three distinct correlated sets of values are assigned to the thermal integrity attributes of a house, as appropriate for a house with "Poor", "Normal", and "Good" thermal integrity.

Finally, as indicated in Table 2, a house is categorized as having: (i) "Low" quality if it has a "Small" size with "Poor" thermal integrity; (ii) "Medium" quality if it has a "Normal" size with "Normal" thermal integrity; and (iii) "High" quality if it has a "Large" size with "Good" thermal integrity.

House Quality Type	Low	Medium	High
House Size	Small	Normal	Large
House Thermal Integrity	Poor	Normal	Good

Table 2: Definitions for house quality types.

5.5. ITD Test Case Performance Metrics

The following reliability metrics are calculated using the voltage profiles recorded by GridLAB-D at each bus load of the distribution grid.

Reliability Metrics:

- Voltage imbalance ($\%\mathrm{VIB}_b$)
- Upper voltage magnitude limit violation ($V^{\mathsf{hi}}_{b,p}$)
- Lower voltage magnitude limit violation ($V^{\mathsf{lo}}_{b,p}$)

The voltage imbalance metric $\%\mathrm{VIB}_b$ measures voltage imbalance across the phases at each distribution grid bus b. The limit violations refer to violations of the DSO-set limits $[V^{\mathsf{max}}, V^{\mathsf{min}}]$ on voltage magnitudes at each bus load.[13] These limit violations are measured for each phase $p \in \{A, B, C\}$ at each bus b by the maximum deviation $(V^{\mathsf{hi}}_{b,p})$ above the upper voltage limit V^{max} and by the maximum deviation $(V^{\mathsf{lo}}_{b,p})$ below the lower voltage limit V^{min}. If a limit violation occurs, the DSO takes control actions in an attempt to restore voltage magnitudes to within the indicated limits.

The following welfare metrics are calculated using power and price outcomes reported in MW and \$/MWh units, respectively.[14]

Household Welfare and DSO Break-Even Metrics:

- Average hourly household comfort level ($\mathrm{CM}^{\mathsf{AvH}}$)
- Average hourly household net energy payment ($\mathrm{NEP}^{\mathsf{AvH}}$) incorporating power usage payments and compensation for ancillary service provision
- DSO's average daily lump-sum allocation to each household ($\mathrm{A}^{\mathsf{AvD}}$)

Detailed calculations for the above reliability and welfare metrics are provided in Nguyen et al. [1, App. A].

6. DSO Load-Following Performance: Results and Discussion

6.1. DSO Load-Following with Smart HVAC Management

In this section the DSO is assumed to employ the PowerMatcher TES Design described in Section 5.3 in an attempt to ensure that the aggregate power usage of 180 households with smart electric HVAC systems closely tracks a target aggregate load profile during each day D.[15] The ability of the DSO to achieve this pupose depends on the degree to which household HVAC power usage responds flexibly to changes in the DSO's price signals. This flexibility depends, in turn, on structural house attributes.

We therefore report findings from test cases undertaken to explore the ability of the DSO to achieve a load-following goal for a particular hot summer

---

[13] Unless otherwise indicated, these limits are set equal to [0.90pu,1.10pu], which is GridLAB-D's default setting for these limits.

[14] In later sections, any parameter or variable v listed in Table 1 in kW or cents/kWh units that has been converted to MW or \$/MWh units will be denoted as $\widehat{v}$.

[15] One possible interpretation is that that DSO is attempting to match a previous DAM demand bid in order to avoid RTM imbalance adjustment payments. Another interpretation is that the DSO is attempting to provide load-following as a regulation service.

day D under varied mixes of low, medium, and high house quality types as defined in Section 5.4. For the first three test cases, all 180 houses have the same quality (low, medium, or high). For the fourth test case the 180 houses consist of a (1/3,1/3,1/3) mix of quality types.[16]

Parameter values for household bid functions are commonly set as follows: TMin = 68^oF; TB = 72^oF; TMax = 76^oF; and $\theta^s = \theta^u = 100$ (cents/kWh). Outside air temperature during day D, the same for each household, is for a hot summer day (July 1, 2003) in Des Moines, Iowa [49]. To ensure diversity across households, even within quality types, the initial inside air temperature for each household is randomly drawn from the interval $[68^o\mathrm{F}, 76^o\mathrm{F}]$.

As reported in Fig. 9, for each test case the DSO is able to use a suitably selected sequence of price signals to ensure that actual aggregate household power usage closely matches the DSO's target load profile. Note that some of these price signals are negative. Thus, at some time points the DSO is relying on the compensated extraction of ancillary services (power absorption) to achieve good load tracking.

However, the findings reported in Fig. 9 also show that the DSO's price signal sequence is noticeably affected by house quality. A house's quality affects the time constant for its thermal dynamics, which in turn affects the rate of change for T_a and hence the cut-off prices $\pi^u(\mathrm{T}_a)$ and $\pi^s(\mathrm{T}_a)$. A higher-quality house has larger thermal capacity (larger size) and better thermal insulation (higher thermal integrity) than a lower-quality house. Consequently, its thermal time constant is larger and its cut-off prices change over time at a slower speed. This explains the relatively smoother price-signal sequence seen in Figure 9c with 100% high quality houses.

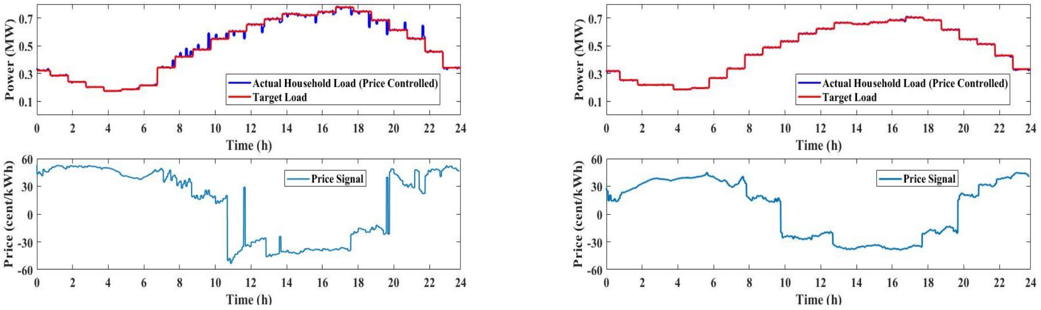
6.2. DSO Load-Following with Smart HVAC and Water Heater Management

This section briefly reports on a test case conducted to evaluate the DSO's load-following capabilities when households have multiple smart appliances.

Load-following findings are reported in Fig. 10 for a test case in which 540 households with mixed-quality houses are distributed across the 15 bus loads of the 13-bus distribution grid, with 36 houses per bus load. Each household has a smart water heater as well as a smart HVAC system. The state-conditioned bid function for a household's water heater is similar in

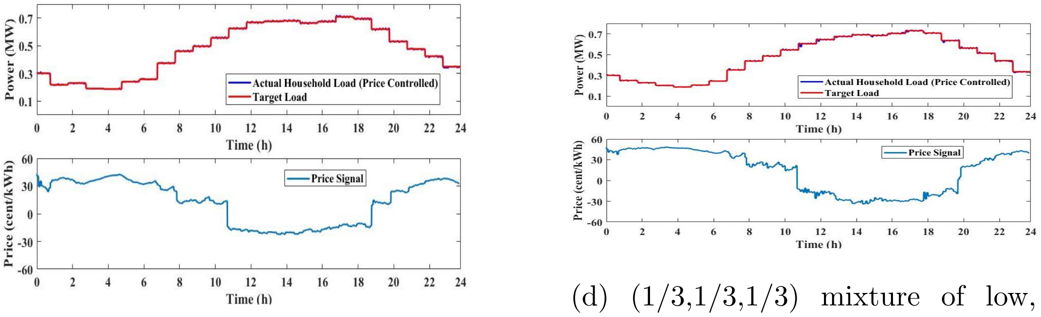
---

[16] Specifically, the twelve houses located at each of the fifteen bus loads for the distribution grid consist of four low-quality houses, four medium-quality houses, and four high-quality houses.



(a) 100% low quality houses.

(b) 100% medium quality houses.



(c) 100% high quality houses.

(d) (1/3,1/3,1/3) mixture of low, medium, & high quality houses.

Figure 9: DSO load-following capabilities with 180 houses of different quality, each with a smart electric HVAC system running in cooling mode.

form to the state-conditioned bid function for a household's HVAC system, described in Section 5.3, except that inlet water temperature replaces inside air temperature as the conditioning state variable. The DSO communicates one price signal to all 540 households at each price-signal point.

As seen in Fig. 10, the DSO is still able to ensure aggregate household power usage closely tracks a target load profile. However, the price-signal sequence is more volatile than for the HVAC-only test cases in Fig. 9.

7. ITD Performance: Results and Discussion

7.1. Overview

This section reports ITD test case findings that illustrate how the ITD TES Platform can facilitate reliability and welfare performance evaluations for TES designs implemented within ITD systems.

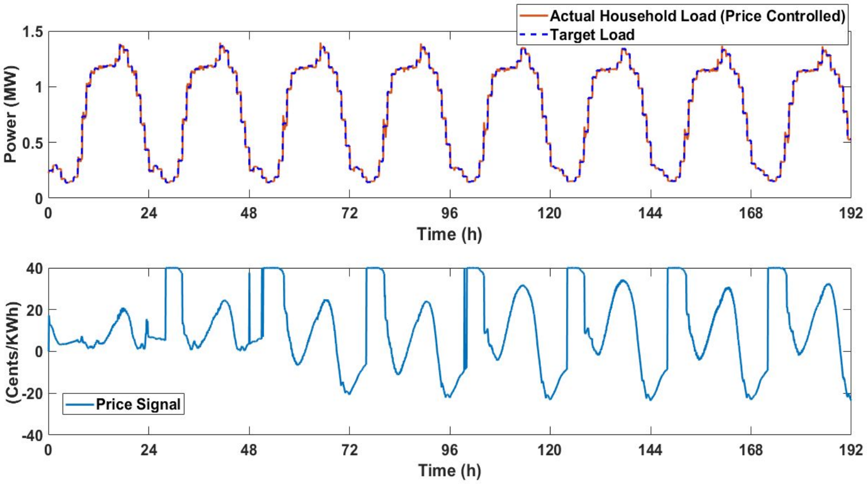


Figure 10: DSO load-following capabilities given 540 houses of mixed quality types, each with a smart water heater and a smart HVAC system running in cooling mode.

Recall from Section 5.1 the basic formulation of these ITD test cases. A 13-bus distribution grid is connected to a 5-bus transmission grid at transmission bus B3. The DSO operates at the T-D interface, i.e., at transmission bus B3, as the link between transmission and distribution system operations.

The ITD test cases reported in this section implement the activities of the DSO as follows. On each day D-1 the DSO submits into the DAM a demand bid for the following day D. This demand bid consists of 24 hourly power demands (MW) that represent the DSO's best hourly forecasts for aggregate household power withdrawals at transmission bus B3 during day D. The DSO's forecast for each specific hour H of day D is given by the actual household load observed by the DSO for hour H on day D-2.[17] The DSO must pay for these hourly forecasted household loads at the hourly LMPs determined at transmission bus B3 in the day-(D-1) DAM. In addition, the DSO will subsequently pay (or be paid) additional settlements at RTM LMPs for any deviations between its day-(D-1) DAM load forecasts for day-D household power usage and actual day-D household power usage.

---

[17] Note that the DSO participating in the DAM on day D-1 has not yet observed household load for day D-1.

The DSO communicates retail prices to households at a specified price signal rate (1/300s), in accordance with the PowerMatcher TES Design. In an attempt to secure revenues that cover its costs, the DSO sets retail power prices on any day D equal to the wholesale power prices that it has already paid in the DAM on day D-1 for its forecasted day-D household loads.

To preserve its independent status, the DSO allocates any net revenues (i.e., revenues minus costs) incurred over the course of a day back to the households at the end of this day. This allocation is either a lump-sum payment (if revenues exceed costs) or a lump-sum charge (if costs exceed revenues). The share allocated to each household on each day D is set equal to the household's relative power usage during day D.

Each ITD test case is simulated over two successive days for multiple households. Weather data is based on two hot summer days (July 3-4, 2003) in Des Moines, Iowa [49]. To ensure household diversity, the initial inside air temperature for each household is randomly drawn from $[68^o\mathrm{F}, 76^o\mathrm{F}]$.

Each household is configured to have a medium-quality type house, a smart electric HVAC system running in cooling mode, and conventional (non-price responsive) loads. The value for the parameter θ^s appearing in the "May Run as Service" household bid function in eq. (2) is set at 4 (cents/kWh). The values for $U(\mathrm{TB})$ and β in the household comfort function (1) are set to 1.5 (Utils/hr) and 0.02 (Utils/hr-$[^o\mathrm{F}]^2$), respectively. The three treatment factors considered in these ITD test cases are as follows:

- the DSO-set limits $[V^{\mathsf{min}}, V^{\mathsf{max}}]$ on voltage magnitudes at bus loads;
- the total number of households (NH);
- the scale parameter θ^u (cents/kWh) in the "May Run for Usage" household bid function given in eq. (3).

The values for all other parameters are set as in Section 6.1.

7.2. Reliability Results and Discussion

This subsection reports reliability outcomes for ITD test cases under two different treatments for the DSO-set limits $[V^{\mathsf{min}}, V^{\mathsf{max}}]$ on voltage magnitudes at bus loads: namely, GridLAB-D's default setting [0.90pu,1.10pu]; and tighter limits [0.95pu,1.05pu].

The number of households is set at NH=180. The value for the scale parameter θ^u appearing in each household's "May Run for Usage" bid function in eq. (3) is set at 1 (cents/kWh). Finally, all reliability outcomes are calculated using the reliability metrics defined in Section 5.5.

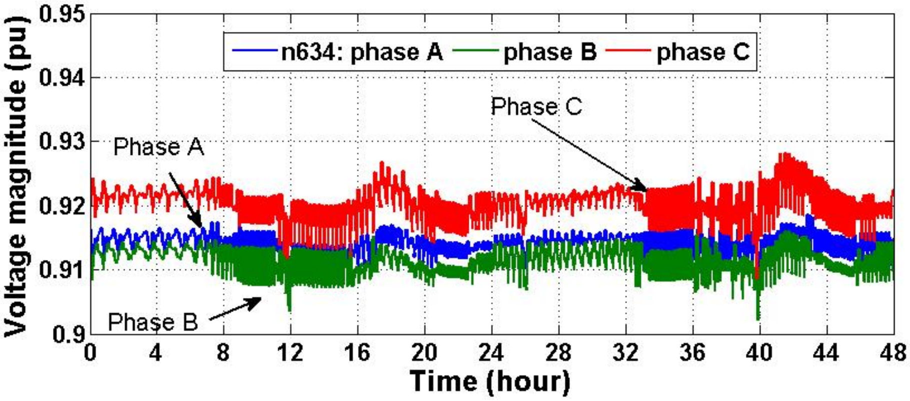
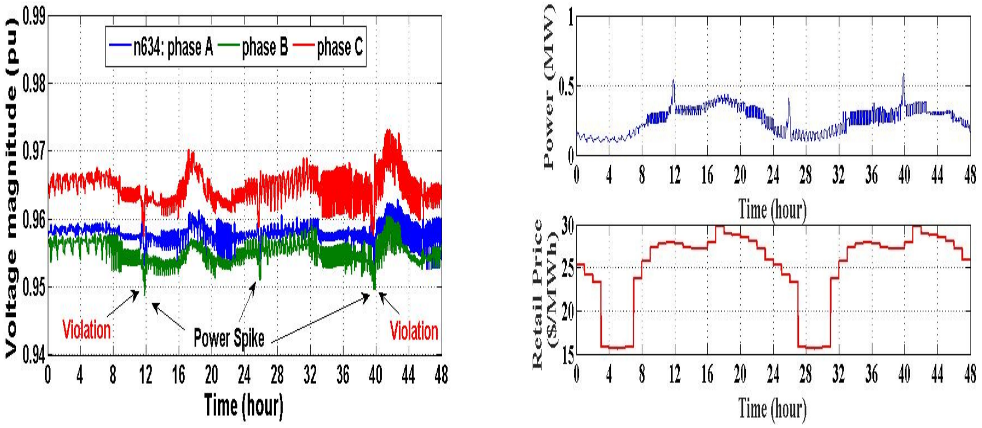


Figure 11: Phase voltage magnitudes at distribution bus 634 over two successive days, given GridLAB-D's default voltage magnitude limits [0.90pu,1.10pu].

Figure 11 reports the phase voltage magnitudes recorded at 1-minute time-steps at distribution bus 634 under the GridLAB-D default voltage magnitude limits [0.90pu,1.10pu] while Fig. 12a reports phase voltage magnitudes recorded at 1-minute time-steps at distribution bus 634 under the tighter voltage magnitude limits [0.95pu,1.05pu]. As can be seen from a comparison of these two figures, phase voltage magnitudes are very sensitive to the voltage limit setting.

Fig. 12b reports the price responsiveness of aggregate household power usage over two successive days, given the tighter voltage magnitude limits [0.95pu,1.05pu]. Note that power spikes are observed at hours 12, 26, and 40. Comparing Fig. 12a with Fig. 12b, it is seen that voltage magnitude limit violations occur for phase B at distribution bus 634 during hours 12 and 40.

As indicated by these findings, the PowerMatcher TES Design as currently formulated does not ensure the avoidance of power spikes. Although a careful study of TES design in relation to power spiking is beyond the scope of the current paper, we note that some research on this important topic has already been conducted. For example, Nazir and Hiskens [48] demon-



(a) Phase voltage magnitudes at distribution bus 634.

(b) Retail prices and corresponding aggregate household power usage.

Figure 12: Phase voltage magnitude, retail price, and aggregate household power-usage outcomes over two successive days, given the tighter voltage magnitude limits [0.95pu,1.05pu].

strate that unintended oscillations in aggregate power usage can arise from a number of different factors, including bid function formulations, distribution feeder capacity limits, and the timing of price signals. In particular, Nazir and Hiskens [48] stress the role of *lock-out conditions* during which customers require uninterrupted power supply.

The spikes in aggregate power usage observed in Fig. 12 for the PowerMatcher TES design could be due to the particular lock-out conditions inherent in the structural form of each household's state-conditioned bid function; see Section 5.3. This structural form, configured commonly for all households, implies that a household's HVAC system (in cooling mode) must be ON when the household's current state (inside air temperature) attains or exceeds TMax, the household's maximum acceptable inside air temperature. A spike in aggregate HVAC power usage could thus occur if inside air temperature attains or exceeds TMax at the same time for a large number of households. This in turn would result in voltage sags, as observed in Fig. 12a.

Table 3 reports reliability outcomes at distribution buses 634 and 675 for voltage magnitude limit violations and voltage imbalance under the two tested settings for voltage magnitude limits. Voltage imbalance is observed at both buses under both settings, while limit violations are observed at bus

634 only under the tighter setting.

(a) Voltage Magnitude Limits: 0.90pu $\leq V \leq$ 1.10pu

Bus	Metrics	Phase A	Phase B	Phase C
634	$V^{\mathsf{hi}}_{b,p}/V^{\mathsf{lo}}_{b,p}$	0/0	0/0	0/0
	%VIB$_b$		**0.86%**	
675	$V^{\mathsf{hi}}_{b,p}/V^{\mathsf{lo}}_{b,p}$	0/0	0/0	0/0
	%VIB$_b$		**1.27%**	

(b) Voltage Magnitude Limits: 0.95pu $\leq V \leq$ 1.05pu

634	$V^{\mathsf{hi}}_{b,p}/V^{\mathsf{lo}}_{b,p}$	0/0	0/**0.0012**	0/0
	%VIB$_b$		**0.14%**	
675	$V^{\mathsf{hi}}_{b,p}/V^{\mathsf{lo}}_{b,p}$	0/0	0/0	0/0
	%VIB$_b$		**2.01%**	

Table 3: Reliability metrics calculated at distribution buses 634 and 675.

The limit violations reported in Table 3 occur even though the DSO takes restorative volt/var control actions in response to limit violations. These and earlier reported reliability findings indicate it would be prudent to include more proactive DSOs in centrally-managed TES designs that can undertake preventive volt/var control actions in advance of limit violations. To preserve the decentralized architecture of TES designs, these controls could take the form of load controls triggered automatically at the level of buses, bus loads, or even households. Alternatively, the controls could take the form of DSO-implemented price-signal adjustments.

7.3. Welfare Results and Discussion

This subsection reports welfare outcomes generated for ITD test cases under a range of settings for two treatment factors: namely, the total number of households (NH); and the household bid-function scale parameter θ^u (cents/kWh) in currency-adjusted form $\hat{\theta}^u$ (\$/MWh). The GridLAB-D default setting [0.90pu,1.10pu] is used for the DSO-set limits $[V^{\mathsf{min}}, V^{\mathsf{max}}]$ on voltage magnitudes at bus loads. All welfare outcomes are calculated using the welfare metrics defined in Section 5.5.

Table 4 reports household welfare outcomes for two successive simulated days (July 3-4, 2018), given systematically varied settings for NH and $\widehat{\theta}^u$. Specifically, ex-post welfare metrics are reported for average hourly household comfort $\mathrm{CM}^{\mathsf{AvH}}$, average hourly household net energy payments $\mathrm{NEP}^{\mathsf{AvH}}$, and average daily household lump-sum allocations $\mathrm{A}^{\mathsf{AvD}}$.

Case	NH	$\widehat{\theta}^u$ (\$/MWh)	$\mathrm{CM}^{\mathsf{AvH}}$ (Utils/hr)	$\mathrm{NEP}^{\mathsf{AvH}}$ (\$/hr)	$\mathrm{A}^{\mathsf{AvD}}$ (\$/day)
1	180	1	1.17	0.0060	-0.0278
2	180	40	1.34	0.0062	-0.0280
3	180	80	1.44	0.0064	-0.0283
4	180	10,000	1.47	0.0065	-0.0287
5	360	1	1.17	0.0060	-0.0300
6	360	40	1.34	0.0062	-0.0305
7	360	80	1.44	0.0063	-0.0311
8	360	10,000	1.47	0.0065	-0.0323

Table 4: Welfare Metrics Averaged Over Two Successive Days

Several interesting regularities are seen in Table 4. For example, comfort $\mathrm{CM}^{\mathsf{AvH}}$ and net energy payments $\mathrm{NEP}^{\mathsf{AvH}}$ each systematically increase with increases in $\widehat{\theta}^u$, all else equal, and are each essentially invariant to changes in NH, all else equal. On the other hand, the household lump-sum allocations $\mathrm{A}^{\mathsf{AvD}}$ systematically become more negative with increases either in NH or in $\widehat{\theta}^u$, all else equal.

In addition, the values for $\mathrm{A}^{\mathsf{AvD}}$ reported in Table 4 are persistently negative. Recall that the DSO sets retail prices on day D equal to the actual prices (DAM LMPs) it paid for power in the DAM on day D-1. Thus, these negative values imply that, on average, the DSO is making payments in the RTM not covered by retail price charges. These uncovered RTM payments are additional costs to the DSO that must be allocated to households as lump-sum charges in order for the DSO to break even over time.

These persistent lump-sum charges could arise for two reasons. First, the DSO could be underestimating actual real-time household power usage in its DAM demand bids, forcing the DSO to bid and pay for additional power in the RTM at RTM LMPs that exceed DAM LMPs. Second, the total power the DSO imports from the transmission system in real-time operations could exceed the total power usage of households due to power losses, resulting in RTM power charges that cannot be recouped from households.

8. Conclusion

This study presents a newly developed ITD TES Platform that permits transactive energy system (TES) designs for integrated transmission and distribution (ITD) systems to be carefully evaluated using both reliability and welfare metrics. The evaluation capabilities of the ITD TES Platform are illustrated by means of ITD test cases that implement a version of PowerMatcher [9], a well-known field-tested TES design.

Reported test-case findings highlight the strengths and weaknesses of this PowerMatcher-based TES design. On the plus side, local household goals, constraints, and privacy rights are fully respected. On the minus sign, power spiking, voltage imbalance, and voltage magnitude limit violations are observed during successive days of operation.

These findings suggest important future research directions the ITD TES Platform is well equipped to facilitate. First, how can TES designs be formulated and implemented in a practical manner to assure the reliability as well as the efficiency of day-to-day ITD system operations? Such assurance requires proper harnessing and remuneration of existing grid-edge resources, taking into account local goals and constraints. Key TES design features such as bid-function formulation, price and control signals, and signal timing will all need to be studied with care.

Second, how can TES designs be formulated and implemented in a practical manner to ensure the *longer-run* reliability and efficiency of ITD system operations? As shown in [34], the interactions between wholesale market transactions and retail price-responsive power bids can induce increasing price and quantity volatility (unstable “cobweb dynamics”) over successive days of operation. A key problem here is that TES designs, as currently proposed and implemented, lack any form of transversality condition to ensure prices and quantities remain within suitable limits over longer time horizons.

Third, as surveyed in [34, Section II], power system researchers are currently exploring three distinct types of demand-response designs: incentive-based load control; dynamic pricing based on one-way communication (prices to devices); and TES designs based on two-way communication, either peer-to-peer designs or centrally-managed designs. Which approach will ultimately prove to be superior in terms of practicality, short-run performance, longer-run performance, and/or robustness to strategic manipulation?

The authors intend to use the ITD TES Platform in future studies to address these and other critical TES design issues.

Acknowledgements

The authors thank the Editor and two anonymous reviewers for constructive comments that have greatly improved the exposition of our paper. The authors are particularly grateful to Tom McDermott (PNNL) and Rob Pratt (PNNL) for important advice and help regarding our use of FNCS and the GridLAB-D ETP modeling of household thermal dynamics.

References

[1] H. T. Nguyen, S. Battula, R. R. Takkala, Z. Wang, L. Tesfatsion, Transactive energy design for integrated tranmission and distribution systems, Economics Working Paper 18004, Iowa State University (2018).
URL `https://lib.dr.iastate.edu/econ_workingpapers/41/`

[2] GridWise Architecture Council, GridWise Transactive Energy Framework Framework Version 1.0, Tech. rep., PNNL-22946 (2015).

[3] L. Tesfatsion, AMES Wholesale Power Market Test Bed: Homepage.
URL `http://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm`

[4] GridLAB-D: The Next Generation Simulation Software (2018).
URL `http://www.gridlabd.org/`

[5] S. Ciraci, J. Daily, J. Fuller, A. Fisher, L. Marinovici, K. Agarwal, FNCS: A framework for power system and communication networks co-simulation, in: Proceedings of the Symposium on Theory of Modeling & Simulation-DEVS Integrative, 2014, p. 36.

[6] J. Lally, Financial transmission rights: Auction example, Financial transmission rights draft 01-10, ISO New England (2002).

[7] W. H. Kersting, Radial distribution test feeders, in: IEEE Power and Engineering Society Proceedings, Vol. 2, 2001, pp. 908–912.

[8] J. Hu, G. Yang, K. Kok, Y. Xue, H. W. Binder, Transactive control: a framework for operating power systems characterized by high penetration of distributed energy resources, Journal of Modern Power Systems and Clean Energy 5 (3) (2017) 451–464.

[9] The PowerMatcher: Homepage.
URL `http://www.PowerMatcher.net/`

[10] K. Koen, The powermatcher: Smart coordination for the smart electricity grid, Siks Dissertation Series No. 2013-17, Dutch Research School for Information and Knowledge Systems, TNO, The Netherlands (2013).
URL `http://dare.ubvu.vu.nl/handle/1871/43567`

[11] H. T. Nguyen, ITD TES Platform: Code and data repository.
URL `https://github.com/htnnguyen/ISU_PNNL-TESP`

[12] S. Widergren, K. Kok, L. Tesfatsion, IEEE Transactive Energy Webinar, March 10, 2016.
URL `http://smartgrid.ieee.org/resources/webinars`

[13] K. Kok, S. Widergren, A society of devices: Integrating intelligent distributed resources with transactive energy, IEEE Power & Energy Magazine 14 (3) (2016) 34–45.

[14] M. Olken, Transactive energy: Everyone gets into the act, IEEE Power & Energy Magazine 14 (3) (2016) 4–16.

[15] D. P. Chassin, S. Behboodi, Y. Shi, N. Djilali, H2-optimal transactive control of electric power regulation from fast-acting demand response in the presence of high renewables, Applied Energy 205 (2017) 304–315.

[16] S. Behboodi, D. P. Chassin, N. Djilali, C. Crawford, Transactive control of fast-acting demand response based on thermostatic loads in real-time retail electricity markets, Applied Energy 210 (2018) 1310–1320.

[17] Y. Kabalci, A survey on smart metering and smart grid communication, Renewable and Sustainable Energy Reviews 57 (2016) 302–318.

[18] GridLAB-D Wiki.
URL `http://gridlab-d.shoutwiki.com/wiki/Transactive_controls`

[19] J. Hansen, T. Edgar, J. Daily, D. Wu, Evaluating transactive controls of integrated transmission and distribution systems using the framework for network co-simulation, in: American Control Conference (ACC), 2017, IEEE, 2017, pp. 4010–4017.

[20] L. Tesfatsion, Electric power markets in transition: Agent-based modeling tools for transactive energy support, in: C. Hommes, B. LeBaron (Eds.), Handbook of Computational Economics, Vol. 4, Elsevier, 2018, Ch. 13, pp. 715–766.

[21] Y. Xia, K. Chan, M. Liu, Direct nonlinear primal–dual interior-point method for transient stability constrained optimal power flow, IEEE Proc.: Generation, Transmission and Distribution 152 (1) (2005) 11–16.

[22] D. Chatterjee, A. Ghosh, Improvement of transient stability of power systems with statcom-controller using trajectory sensitivity, International J. of Electrical Power & Energy Systems 33 (3) (2011) 531–539.

[23] K. M. Gegner, A. B. Birchfield, T. Xu, K. S. Shetye, T. J. Overbye, A methodology for the creation of geographically realistic synthetic power flow models, in: IEEE Power & Energy Conference at Illinois (PECI), 2016, pp. 1–6.

[24] Distributed generation and sustainable electrical energy centre: United kingdom generic distribution system (UK GDS) 2015 (2018).
URL `https://github.com/sedg/ukgds`

[25] Power Systems Test Case Archive: Transmission Networks (2018).
URL `https://www2.ee.washington.edu/research/pstca/`

[26] IEEE Test Feeders (2018).
URL `http://sites.ieee.org/pes-testfeeders/resources/`

[27] F. Li, R. Bo, Small test systems for power system economic studies, in: IEEE Power & Energy Society General Meeting Proc., 2010, pp. 1–4.

[28] D. Krishnamurthy, W. Li, L. Tesfatsion, An 8-zone test system based on ISO New England data: Development and application, IEEE Transactions on Power Systems 31 (1) (2016) 234–246.

[29] R. D. Zimmerman, C. E. Murillo-Sánchez, R. J. Thomas, et al., Matpower: Steady-state operations, planning, and analysis tools for power systems research and education, IEEE Transactions on Power Systems 26 (1) (2011) 12–19.

[30] H. Li, L. Tesfatsion, ISO net surplus collection in wholesale power markets under locational marginal pricing, IEEE Transactions on Power Systems 26(2) (2011) 627–641.

[31] Pacific Northwest National Laboratory, Olympic Peninsula: Pacific Northwest GridWise Testbed Demonstration Projects: Part I Report, pnnl-17167 Edition (2007).

[32] P. Aristidou, G. Valverde, T. Van Cutsem, Contribution of distribution network control to voltage stability: A case study, IEEE Transactions on Smart Grid 8 (1) (2017) 106–116.

[33] N. Pilatte, P. Aristidou, G. Hug, TDNetGen: An open-source, parametrizable, large-scale, transmission, and distribution test system, IEEE Systems Journal (2017) 1–9.

[34] A. G. Thomas, L. Tesfatsion, Braided cobwebs: Cautionary tales for dynamic pricing in retail electric power markets, IEEE Transactions on Power Systems 33 (6) (2018) 6870–6882.

[35] Q. Huang, T. McDermott, Y. Tang, A. Makhmalbaf, D. Hammerstrom, A. Fisher, L. Marinovici, T. Hardy, Simulation-based valuation of transactive energy systems, IEEE Transactions on Power Systems, to appear.

[36] PNNL, Transactive energy simulation platform (TESP) (2017).
URL `https://tesp.readthedocs.io/en/latest/`

[37] W. Li, M. Ferdowsi, M. Stevic, A. Monti, F. Ponci, Co-simulation for smart grid communications, IEEE Transactions on Industrial Informatics 10 (4) (2014) 2374–2384.

[38] FERC, Wholesale power market platform, White Paper, U.S. Federal Energy Regulatory Commission (April 2003).

[39] CAISO, Market optimization details, Technical Bulletin 2009-06-05, California ISO (November 2009).

[40] X. Ma, H. Song, M. Hong, J. Wan, Y. Chen, The security-constrained commitment and dispatch for Midwest ISO day-ahead co-optimized energy and ancillary service market, in: IEEE Power & Energy Society General Meeting Proceedings, 2009, pp. 1–8.

[41] J. Ellison, L. Tesfatsion, V. Loose, R. Byrne, A survey of operating reserve markets in U.S. ISO/RTO-managed electric energy regions, Sand 12-1000, Sandia National Laboratories Report (2012).

[42] GridLAB-D: Residential Module User's Guide (2018).
URL `http://gridlab-d.shoutwiki.com/wiki/Residential_module_user's_guide`

[43] R. Sonderegger, Dynamic models of house heating based on equivalent thermal parameters, PhD Dissertation, Princeton University (1978).

[44] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, C. Weinhardt, Designing microgrid energy markets: A case study, Applied Energy 210 (2018) 870–880.

[45] S. K. C. D. Fuller, C, Analysis of residential demand response and double-auction markets, in: Proceedings of the IEEE Power & Energy Society General Meeting, 2011, pp. 1–7.

[46] S. Li, W. Zhang, J. Lian, K. Kalsi, Market-based coordination of thermostatically controlled loads part i: A mechanism design formulation, IEEE Transactions on Power Systems 31 (2) (2016) 1170–1178.

[47] X. Zhou, E. Dall'Anese, L. Chen, A. Simonetto, An incentive based online optimization framework for distribution grids, IEEE Transactions on Automatic Control 63 (7) (2018) 2019–2031.

[48] M. Nazir, I. Hiskens, A dynamical systems approach to modeling and analysis of transactive energy coordination, IEEE Transactions on Power Systems, to appear, DOI:doi.org/10.1109/TPWRS.2018.2834913.

[49] NREL: Des Moines International Airport Weather (Des Moines Intl AP.tmy3) (2018).
URL `http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html`