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# Transactive Energy: A Review of State of The Art and Implementation

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***Abstract*—In future smart grids, large-scale deployment of distributed energy resources (DERs) and renewable energy sources (RES) is expected. In order to integrate a high penetration level of DERs and RES in the grid while operating the system safely and efficiently, new control methods for power system operations are in demand so that the flexibility of the responsive assets in the grid can be further explored. Transactive control, considered as one of the most novel distributed control approaches for power system operations, has been extensively discussed and studied around the world in recent years. This paper provides a bibliographical review on the researches and implementation of the transactive energy concepts and transactive control techniques in power systems. The ideas of transactive control are introduced mainly according to the transactive energy framework proposed by the GridWise Architecture Council. The implementation pilots and research studies on transactive control applications in power systems are reviewed subsequently.**

***Index Terms*—Demand response, smart grid, transactive control, transactive energy.**

## I. Introduction

With increasing penetration level of distributed energy resources (DERs) and renewable energy sources (RES) in power systems, transactive energy is emerging as one of the most innovative and effective approaches towards the future smart grid. It has been a hot topic and widely discussed not only in the United States but around the world from the past few years. It is advertised as a sustainable business and regulatory model for electricity [1]. By negotiating contracts between various components in the systems in place of or in addition to the conventional control, transactive control techniques are believed to enable the optimal integration of RES and DERs (especially in the distribution systems) while maintaining the system reliability. A lot of attention has been paid to the ideas of transactive energy and transactive control techniques in both academia and industry. Pilot projects and researches on related topics have been initiated and widely conducted recently.

In this paper, a review on the researches and implementation of the transactive energy concepts and transactive control techniques in power systems is presented. The concepts of transactive energy and transactive control are introduced mainly according to the transactive energy framework proposed by the GridWise Architecture Council in Section II. The pilot projects and research studies on transactive control applications in power systems are reviewed in Section III and IV respectively, followed by the conclusions and perspectives of future works in Section V.

## II. Transactive Control Concepts

Transactive energy is a relatively new but widely discussed concept. It combines information and energy to enable transactions which implements highly coordinated self-optimization. The definition of transactive energy system has been provided by a number of sources. The Smart Grid Dictionary defined transactive energy as follows [2]:

"*A software-defined grid managed via market-based incentives to ensure grid reliability and resiliency. This is done with software applications that use economic signals and operational information to coordinate and manage devices' production and/or consumption of electricity in the grid. Transactive energy describes the convergence of technologies, policies, and financial drivers in an active prosumer market where prosumers are buildings, EVs, microgrids, VPPs or other assets.*"

The GridWise Architecture Council proposed a more general definition of transactive energy in [3] as follows:

"*A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.*"

The definition from the GridWise Architecture Council is purposely broad that it allows people not only to recognize the existing use of such techniques but also to consider more broadly how the new techniques can be used in distribution systems and other situations. However, in order to complete the view and help facilitate discussions on transactive energy, the GridWise Architecture Council also defined detailed attributes of transactive energy including architecture, extent, transacting parties, transaction, transacted commodities, temporal variability, interoperability, value discovery mechanism, assignment of value, alignment of objectives and assuring stability in [3].

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In a transactive energy network, price signals embedded throughout the energy system enable a kind of electronic commerce for energy. The universal language of price bridges all kinds of devices and institutional boundaries, making possible distributed decision-making that optimizes use of resources [4]. Rooted in the idea of transactive energy, transactive control, or transactive-based control, is defined as a means of executing transactions through automatic control of the operating state of building equipment and other energy systems in response to data and value streams [5]. The transactive control approach is believed viable and with many useful attributes. It makes full use of the response potential, has a certain system reaction while maintaining market efficiency and raising no privacy issues [6]. For instance, in the Olympic Peninsula GridWise project, it demonstrated a practical value of a high degree of automation, by which the responsive assets were called upon only when and to the degree their responses were needed, and this automation resulted in successful operation of multiple complex assets to meet a severe constraint [7].

A classic example of transactive control applications is the control for building systems given by Pacific Northwest National Laboratory [5], [8], [9]. A transactive control system is applied in the heating, ventilation, and air conditioning (HVAC) systems of buildings which are controlled by thermostats. Conventionally, the current zone temperature and desired temperature set by the customer are the only information required to control the amount of heating and cooling to the zone in the building. Nevertheless, in the transactive control system, the thermostats use market information, including bids and clearing prices to make control decisions. Fig. 1 illustrates how the bid and response strategy for the transactive HVAC control are determined in the cooling mode of the example [9].

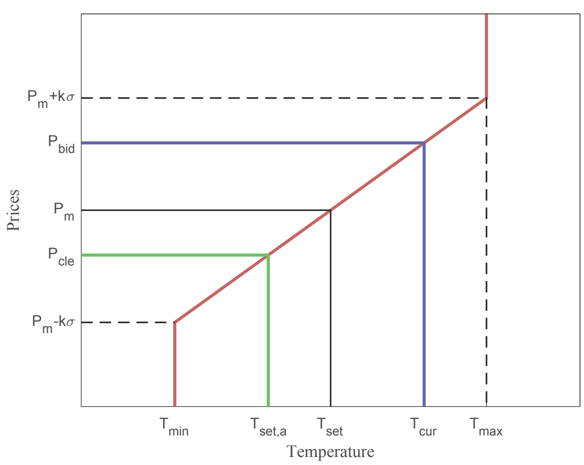


Fig. 1. Illustration of the bid and the response strategy for transactive control of building HVAC systems

In the transactive control scheme, the customers set the desired temperature $T_{set}$ and the acceptable range of zone temperature defined by $[T_{min}, T_{max}]$. The customers are also allowed to develop a bid curve a priori which functionally relates cost of service to comfort as shown in Fig. 1. The bid curve is derived from the mean price $P_m$ and the standard deviation of electricity price $\sigma$ and the minimum and maximum temperature set points corresponding to $k$ standard deviations from $P_m$. First, the bid price $P_{bid}$ is determined by the difference between $T_{set}$ and the current temperature $T_{cur}$, and the user selected parameters $k$, $T_{min}$ and $T_{max}$ as (1).

$$P_{bid} = P_m + (T_{cur} - T_{set})\frac{2k\sigma}{T_{max} - T_{min}} \tag{1}$$

Then the transactive market establishes the clearing price $P_{cle}$ with the posted bids in the market. After receiving the market clearing price, the adjusted zone set point $T_{set,a}$ is calculated as (2).

$$T_{set,a} = T_{set} + (P_{cle} - P_m)\frac{T_{max} - T_{min}}{2k\sigma} \tag{2}$$

Finally, the zone temperature set point of the thermostat is reset to the new adjusted zone set point. Once the set point is adjusted, the conventional control takes over and such transactive control process continues for each market clearing cycle.

## III. Pilot Projects with Transactive Control

A series of pilot projects regarding transactive control implementation have been carried out in recent years. One of the most well known project is the U.S. Department of Energy (DOE) funded Olympic Peninsula (OlyPen) GridWise project, which is one of the principal projects of the Pacific Northwest GridWise Testbed Demonstration [10]. The purpose of the OlyPen project was to create and observe a futuristic energy-pricing experiment that illustrates several values of grid transformation that align with the GridWise concept. The term GridWise here refers to the various future smart grid-management technologies based on real-time, electronic communication and intelligent devices. By enabling an overall increase in asset utilization, these technologies should be capable of deferring and, in some cases, entirely preventing the construction of conventional power-grid infrastructure in step with anticipated future load growth. The fundamental objectives of the project were to

- show that a common communications framework can enable the economic dispatch of dispersed resources and integrate them to provide multiple benefits;
- gain an understanding of how these resources perform individually and when interacting in near real time to meet common grid-management objectives;
- evaluate economic rate and incentive structures that influence customer participation and the distributed resources they offer.

The responsive assets in the OlyPen project included residential thermostats, residential water heaters, residential clothes dryers, commercial HVAC systems, distributed diesel generators, a gas turbine, and municipal water pumps.

Totally 112 homes were recruited to install the energy-management systems that supported two-way communications in the OlyPen project.

Another demonstration project using transactive control in system operations was the American Electric Power, Ohio (AEP Ohio) gridSMART Real-Time Pricing Double Auction (RTPda) demonstration project [11]. It was part of the overall AEP Ohio gridSMART program. The project engaged residential households to adapt their electricity use in response to a fluctuating 5-minute price signal. In particular, HVAC units were managed by intelligent software in the home that interacted with a real-time electricity market. The research objective of the project was fourfold:

- The potential benefits of RTPda for system-capacity and feeder-capacity issues.
- The potential benefits of improving wholesale purchases in the real-time market and participation in a spinning reserve market.
- The impacts of RTPda from the consumers perspective, including consumer bills and consumer configuration of the thermostat set point and adjustments of it over time.
- A characterization of the sensitivity of the RTPda loads to price fluctuations and their behavior when called upon for system events.

The RTPda system in the project followed a transactive control approach to coordinate household equipment participation in system operations. A distributed decision-making approach was used in the project that allowed suppliers and consumers of energy to arrive at a coordinated solution for how each participant will operate based upon a trade-off of the value they place on electricity for a specified time. In this case, an energy market was used to resolve which HVAC loads will run in the next operating interval.

The Pacific Northwest Smart Grid Demonstration (PNWSGD) project was a regional smart grid demonstration project co-funded by the DOE from 2009 to 2015 [12]. It implemented one of the world's first transactive coordination systems. 25 of the project's 55 asset systems were made responsive to the transactive coordination system. The main objectives of the project were to accomplish the following:

- Create the foundation for a sustainable regional smart grid.
- Develop and validate an interoperable communication and control infrastructure using incentive signals to coordinate a broad range of customer and utility assets.
- Measure and validate smart grid costs and benefits.
- Contribute to the development of standards and transactive control methodologies.
- Apply smart grid capabilities to support the integration of a rapidly expanding portfolio of renewable resources in the region.

## IV. Transactive Control Researches on Power System Operations

Currently, a lot of efforts have been made on the conceptual design and analysis of the hierarchical transactive control architecture. An analytics framework for end to end management and control of a hierarchical transactive control architecture for the electricity grid is presented in [7], [13]. The schematic of the proposed hierarchical structure is shown in Fig. 2. A physical point anywhere in the electric power grid where demand may be aggregated and predicted is defined as a node in the architecture. At each node in this hierarchy a demand signal is aggregated from its children nodes, and a price or value signal is calculated using information obtained from its parent nodes. How these decentralized signals can be estimated from the information flowing at each node of the hierarchical network are introduced in the papers.

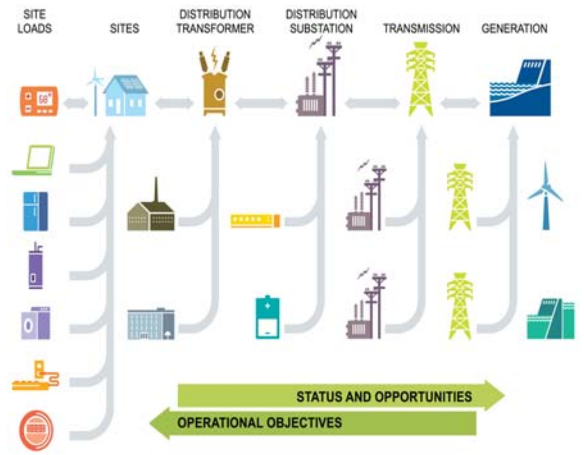


Fig. 2. Representation of transactive control hierarchy proposed in [7], [13]

In this figure, the value signals flow downstream towards the left (labeled as operational objectives), while the corresponding demand signals flow upstream towards the right (labeled as status and opportunities). Note that responsive assets (respectively, value signal calculations) do not occur only at the extreme downstream (respectively, upstream) locations in the figure. Indeed, just as every node in the hierarchy can interject the degree of meeting its own operational objectives, responsive assets can reside quite far upstream, even at the transmission nodes in form of flow control devices, resource dispatch practices, and voltage control devices.

A large-scale network simulation model is developed in [14] for the hierarchical transactive control system evaluation. The proposed network simulation model illustrates how transactive control can be used to manage the distribution problem of peak demand, and improve system efficiency and reliability at a large scale. The architecture of the transactive control system simulated in the paper is as shown in Fig. 3. The transactive control system communicates local supply conditions using incentive signals and load adjustment responses using feedback signals in a distributed fashion in order to match the consumer-desired load to the utility-desired supply scenario. Both linear and non-linear load adjustment models are studied in the paper. The simulation results indicate that the control mechanism can perform adequately in adjusting the aggregate supply-demand mismatch and is robust to steady transactive signal losses.

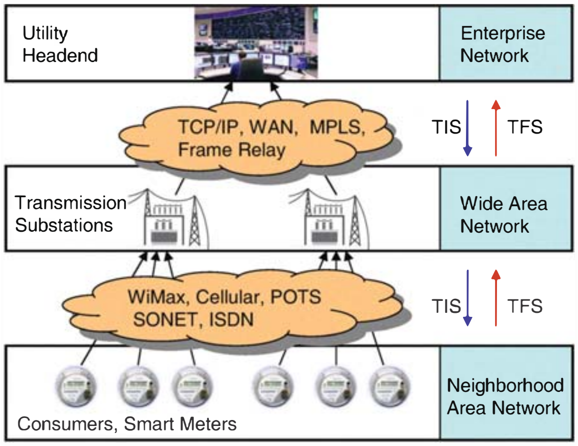


Fig. 3. Two-level transactive control system architecture [14]

Besides, the costs and benefits of renewables for all market participants using the GridWise transactive energy framework [3] are classified in [15]. Reference [16] reports on the preliminary findings of a residential demand response demonstration that uses the bidding transactions of supply and end-use air conditioning resources communicating with a real-time market to balance the various needs of the participants on a distribution feeder.

Meanwhile, the concepts and techniques of transactive control have been applied in a series of distributed control schemes for power system operations. A hierarchical transactive control architecture is proposed for renewable integration in smart grids in [17], [18]. The proposed architecture combines electricity market transactions at the primary, secondary and tertiary control of the power system. The goal of the proposed hierarchical control methodology is to ensure frequency regulation using optimal allocation of resources in the presence of uncertainties in renewables and load. Global asymptotic stability of the overall system is established in the presence of uncertainties at all three time-scales. The proposed control architecture is as shown in Fig. 4.

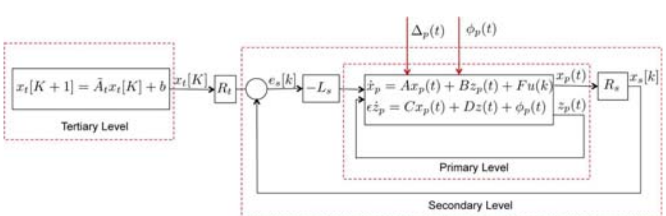


Fig. 4. Hierarchical transactive control structure proposed in [17], [18]

The overall model of the system, including the primary, secondary, and tertiary level dynamics of the grid is assembled as shown in the equations (3)-(7).

$$\Sigma_{Pri} : \begin{cases} \dot{x}_p = (A + E_p)x_p(t) + Bz_p(t) + Fu[k] \\ c\dot{z}_p = Cx_p(l) + Dz_p(l) + \phi_p(l) \end{cases} \tag{3}$$

$$\mathcal{I}_{Pri} : u[k+1] = u[k] - L_s x_s[k] + L_t x_t[K] \tag{4}$$

$$\Sigma_{Sec} : x_s[k+1] = (\widetilde{A}_s + C_s E_s)x_s[k] + B_s L_t x_t[K] \tag{5}$$

$$\mathcal{I}_{Sec} : e_s[k+1] = (\widetilde{A}_s + C_s E_s)e_s[k] + C_s E_s R_t x_t[K] \tag{6}$$

$$\Sigma_{Ter} : x_t[K+1] = \widetilde{A}_t x_t[K] + hk_\rho E_t e_s[K] + b \tag{7}$$

In the tertiary level of the whole control architecture, a dynamic economic dispatch paradigm is proposed based on the notion of disequilibrium process where the generation companies, consumer companies and ISO exchange information. In the paradigm, the goal of the generating companies and consumer companies is to maximize its overall profit and utility function while the ISO clears the market by maximizing social welfare. Such dispatch paradigm serves as the tertiary control of the system instead of the centralized action of the ISO so that the overall system operates in the most economical way and satisfies all stability and reliability criteria. The main focus of the work lies in both the information flows between the three control levels and the tertiary level dynamics and decision-making in (7).

Reference [19] demonstrates the effects of a double-auction market on the operation of distribution systems. The paper introduces the need for analytical models at multiple levels within the simulation through a demand response program utilizing distributed and centralized control. Transactive controllers are used to handle the residential demand response for the end-users in the market. The responsive assets are the HVAC systems of the end-users. The capacity management market to manage the congestion at the distribution feeders is also analysed in the paper. Rather than demonstrating the optimal method of controlling demand response or decreasing congestion on a feeder, the cases in the paper mean to provide a demonstration of the level of detail needed to perform analysis on smart grid technologies. Detailed transactive control models are not provided in the paper.

An experimental controller is proposed in [20] under a transactive market. The controller presented in the paper operates to centrally collect data, track the history of assets as each simulator committed to a dispatch for each subsequent scenario driven transactive feedback signal period, and manage virtual results for each operation forecast period using two different dispatch methods: a mixed integer linear programming (MILP) micro-grid dispatch system [21], and an artificial neural network (ANN) dispatch system [22]. Six scenarios have been performed in the paper to test the proposed distributed dispatch controller with a transactive market mechanism. The simulation results show that a collection of independent simulator results may be used in real-time for an assessment of operations strategy in an inter-connect, control area or micro-grid.

The application of transactive control also lies in the demand side management (DSM) to provide frequency control ancillary service to the grid. Reference [23] introduces the simulation demonstration on the provision of time critical frequency control ancillary service by DSM of residential houses.

As a DSM technology, a cluster of electricity producing and consuming devices are coordinated by creating a transactive energy market, namely PowerMatcher (PM) which is one of the major transactive energy based coordination mechanisms in Europe. The simulation architecture of the demand side management is shown in Fig. 5. The results shown in the paper validate the capability of PM to provide frequency control using a transactive energy market to coordinate demand and generation profiles.

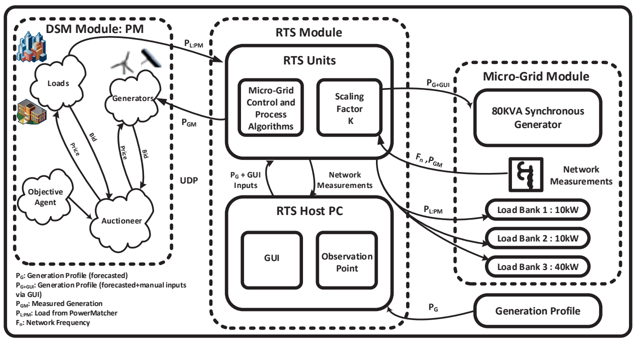


Fig. 5. DSM simulation architecture proposed in [23]

The transactive energy market architecture and simulation platform of the demand side management are also used in [24] to facilitate the plan for the performance analysis of the demand side participation for frequency containment within a web of cells architecture as shown in Fig. 6.

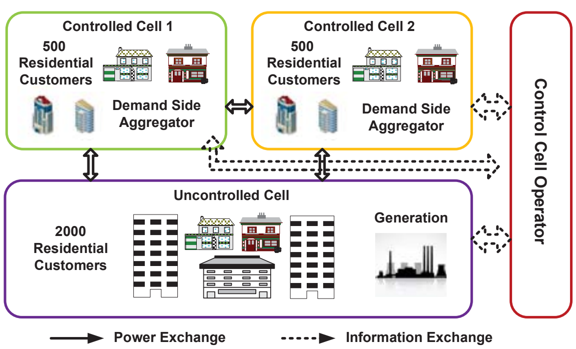


Fig. 6. Web of cells DSM architecture proposed in [24]

Another attempt of the transactive control application is the demand coordination of building HVAC systems. A virtual transactive market structure for commercial building HVAC systems is presented in [25]. The purpose of the proposed transactive market in the paper is to design a distributed transactive control strategy instead of to represent a real energy market. The market structure is shown in Fig. 7. Based on the virtual transactive market, a transactive control approach of commercial building HVAC systems for demand response is proposed in the paper. The transactive market is assumed to be a competitive market managed by a nonprofit entity such as the building manager. The nonprofit entity clears the virtual transactive market by solving the social welfare maximization problem. With the proposed transactive control approach, the responsive assets in the commercial building HVAC systems can provide demand response including peak shaving, load shifting and strategic conservation effectively according to the simulation results of the paper.

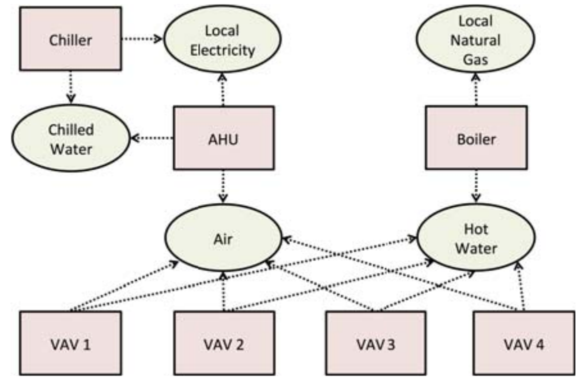


Fig. 7. Transactive market structure for commercial building HVAC systems [25]

Additionally, transactive control has also been applied in the distributed scheduling of EV charging. A network-constrained transactive control paradigm of day-ahead EV charging planning is proposed in [26], [27] for secure distribution network operations. An iterative pricing and scheduling coordination mechanism between the aggregators and DSO is presented in the study so that the day-ahead EV charging demand meets the distribution network constraints. Shadow prices that reflect the distribution network constraints are generated by the iterations of scheduling updates and information exchange between the aggregators and DSO. The EV charging scheduling is based on the generated shadow prices in the proposed framework so that the distribution network constraints are respected.

A study of EV charging and vehicle-to-grid (V2G) scheduling with transactive control in a real-time framework is presented in [28]. EVs are considered participating in a retail double auction electricity regulation market in the study. Price-responsive charging of EVs is modelled in conjunction with real-time retail price signals from the utility. EVs defer charging or even discharge when the retail prices are high. The bidding strategies of the EV charging and V2G operations are determined according to the customer preference.

From a practical point of view, reference [29] characterizes the opportunities and challenges that arise in developing a transactive control strategy for grid integration of electric vehicle supply equipment (EVSE) to provide various types of services to utilities, society, and EV owners.

## V. Conclusions and Future Work

The transactive control has drawn a lot of attention from both academia and industry in recent years. Researches and implementation projects of transactive control on power system operations have been widely conducted. At present, the literature mainly focuses on the design and analysis of the hierarchy architecture of transactive control schemes. The idea of transactive control has also been applied in the distributed dispatch or control systems of responsive assets in the grid. However, the detailed control method of the end-users in the transactive control schemes requires further investigations. Focusing on the validation of transactive control, the response levels of assets in the transactive markets are mainly based on the assumptions of the customers' comfort setting preferences in the existing studies, which may reduce the prognosticative value of the analysis and simulation results. Therefore, the optimal bidding strategies of the responsive assets in the transactive markets need to be researched in future studies. Besides, two other topics are also beneficial in future researches in order to enhance our understanding of the effects and benefits of transactive control in practical power system operations. Firstly, most of the studies at present focus on the cases of real-time control. A few studies research the cases of the day-ahead scheduling of responsive assets using transactive approaches. A combined multi-level transactive control mechanism is in the scope of future studies in order to obtain a more complete picture of the benefits and characteristics of transactive approaches. Secondly, the current studies mainly work on the transactive control of the loads in a site or a few sites under a distribution market. However, the energy and information flows in the transactive control framework are not restricted in the distribution level but all the nodes in the hierarchical structure, especially in practical applications. The relation between the wholesale and retail markets with transactive approaches needs to be further researched. Additionally, the detailed design of transactive approaches under uncertainties of the demand and renewables in distribution markets for more robust operations is another interesting topic for future works.

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