A real-time TE system for pervasive DERs

Rohan Gupta, Donal O'Mahony
School of Computer Science & Statistics, Trinity College Dublin, Ireland

***Abstract*—The grid is witnessing an increasing emergence of small distributed energy resources (DERs), along with a greater prevalence of storage systems. These participants have highly dynamic properties and thus introduce several transactional challenges. We propose a rapidly convergent, privacy preserving, real-time transactive energy (TE) system which uses a dynamic pay-as-bid double auction. We describe a prototype which simulates the behavior of the auction system and its participants who negotiate prices with individual bidding strategies. The proposed system allows the participants to transact without seeking numerous quantity-price trading pairs, thereby protecting confidentiality of cost curves of each competing participant. A less information-rich input does introduce some element of higher price volatility as an outcome, which, in this context, can be tolerated as parties perform small-ticket transactions. Such a TE system can be a step forward in preparing for a future where large generating firms and smaller complementary DERs participate in the market on an equal footing.

***Index Terms*—Distributed energy resources, Double auction, Energy trading, Real-time, Storage systems**

I. INTRODUCTION

The conventional trade of electricity involves a limited number of participants, including large generating firms as well as medium to large distributing entities. The trade is documented in the form of bilaterally arranged long term power purchase agreements (PPA). The distribution entities pass on power to end users under different tariff regimes in compliance with the regulations. Further, the advent of renewables and cheaper batteries has led to the deployment of massive renewable energy facilities and storage farms. The integration of such large-scale DERs (distributed energy resources) with the grid has been established with stable day-ahead trading processes transacting MwH of energy.

However, the growing use of electric vehicles and household- based solar, battery or combined systems introduces much smaller and pervasive DERs. Additionally, electric vehicles may move around plugging and unplugging from different locations – providing highly changeable demand as well as supply potential. The structure of these participants, a specific form of nanogrids, enable them to operate in isolation from or integrated with the grid. These prosumer DERs need to regularly make micro-choices like i) mode of operation (isolated or integrated), ii) managing excess (sell to grid or store locally) and deficit (buy from grid or consume from local store), iii) scheduling of loads. DERs can have embedded intelligence, in the form of agents, which can exchange information with the grid to guide these decisions.

Such DERs can transact to consume or offer energy as locally as possible supplementing or displacing normal grid supply. A transactive energy (TE) mechanism which supports such highly dynamic, opportunistic transactions with small amounts of energy (of the order of KwH and below), can encourage participation of small-scale DERs. These DERs come with complex attributes like i) a fluctuating SoC (State of Charge), ii) varying composition (fixed or schedulable loads and energy sources), iii) diverse sizes (a single electric vehicle to a community of households), and, iv) distributed and non-uniform points of connection (plugging at different locations at different times).

These dynamic characteristics present transactional challenges of i) less predictability of last-minute supply and demand, ii) asymmetric information about availability of power and behavior of other participants, and, iii) need for complete and granular internal information, about each bidder's behavior, in the auction inputs to enable price discovery.

Real-time TE mechanisms, which can cater to such challenges, need to i) comply with grid constraints like matching of last-minute supply and demand needs, ii) conclude soon enough requiring minimal computation and communication, for highly frequent and large-scale use, and, iii) seek minimal information in bid submissions to encourage participation of large generating firms as well as smaller DERs.

Section II outlines the progress made in real-time TE mechanisms. Section III elaborates on the proposed system, wherein the bids are placed in form of single limit orders and discriminatory prices are sequentially discovered in each trading round. Section IV describes the prototype, quantifies and benchmarks the observations from the simulation and traces potential future directions. Section V concludes and identifies the promise of such a TE system.

II. RELATED LITERATURE

Power distribution has been traditionally looked at as a resource allocation problem: X amount of power (variable quantity), *available exactly at time t*, needs to be distributed across N buyers (with varying needs). The auctioneer aggregates individual cost curves and identifies an equilibrium price and clearing quantity to match supply and demand. However, the utilization of storage systems introduces the idea of an 'inventory' of power and reduces the significance of 'time' in its availability. This change in the intrinsic composition of grid participants endows them with the ability

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to hold and store and thus, also attaches a commodity-like character to power. Therefore, an effective TE mechanism that satisfies these emergent needs must resolve resource allocation at the said time as well as enable a physical commodity trade.

Electricity is traded in several wholesale markets, each with a different time scale ranging from 20-year long arrangements, to shorter day-ahead, intra-day and real time trading. Each market at a particular time scale plays a unique role. The real time or balancing market is critical in handling last minute variations in the system [1]. Morey [2] mentions that at such short time scales, it becomes increasingly difficult to find participants to trade electricity in smaller quantities, and therefore, the opportunity cost of discovering a suitable trading counterparty (either a seller or a buyer) is high. Thus, grid participants prefer a mediated market, with availability of supply and demand from many other pre-registered participants, over traditional self-arranged bilateral markets. The mediation can be performed by an auctioneer (or an energy exchange) with auctions at frequent regular intervals ahead of the physical delivery.

A TE system which can mediate transactions between smaller DERs, apart from the larger participants, must be simple and inexpensive to use [3]. Thus, it must reduce bidding participatory cost and limit complexity to encourage participation [2]. However, many prior works indicate that it is complex to design and operate such a system. The ability to communicate prices and market information is a critical challenge and further contributes to asymmetry in information [4]. Dynamic auctions, which use multiple rounds to enable participants observe price movements, can be more difficult to implement than static auctions and complex to participate in [5]. Thus, simplification is a key objective of an effective TE system.

The notion of multiple sellers and buyers in an electricity market have encouraged the study and use of double auctions in the past [6][7]. Double auctions have attracted renewed interest with the advent of DERs and evolution of electricity buyers from traditional consumers into prosumers.

A market simulation study compares double-sided auctions and supplier-only auctions to observe that double-sided auctions are more efficient as they limit the generating firms in exerting market power and yield a stable market clearing price as an outcome of elastic demand [8]. Flikkema [9] introduces a uniform clearing price based multi-round double auction at different time scales. This requires bid participants to submit offer functions and utilizes average bid and ask prices as market signals. A smart contract based Continuous Double Auction (CDA) which allows trading of energy in designated time intervals, before the delivery period, uses a visible order book enabling participants to evaluate others' preferences [10].

Energy exchanges across the world, including Columbia in United States [11][2], Guangdong in China [12] and all regions in India [13] use a uniform Market Clearing Price (MCP) and Market Clearing Volume (MCV), in association with Locational Marginal Pricing (LMP).

These mechanisms either require the participants to submit portfolio bids (offer functions over a range of prices) or make the order book visible. The need for a complete view of market information to determine energy price has driven the use of centrally controlled uniform price auctions. Such auctions usually need participants to share their preferences over blocks of time [2], thus making the allocation of power a feasible exercise amongst limited participants.

Our work addresses these limitations and aims to propose initial steps in the design of a TE mechanism which can operate in an environment of limited information. Such a mechanism might need iterations, each involving an exchange of partial information, to determine the value of power and make subsequent allocations.

Negotiation protocols have been proposed earlier in the form of iterative pricing using constrained tatonnement [14] and continuous double auction [10]. The convergence in constrained tatonnement was investigated for single-sided auctions. However, it may not be possible to apply overall capacity constraints in the presence of multiple prosumers and smaller DERs who plug into the TE system on an ad-hoc basis. Mezquita et al [15] leverage the notion of transaction fees to minimize the number of transactions performed as part of the negotiation process.

Our proposed mechanism uses discriminatory pricing since a lack of total information hinders the ability to determine a uniform price. Discriminatory price auctions also bring other advantages. Nicolaisen, Petrov and Tesfatsion [6] argue that the practice of implicit collusion is difficult in discriminatory price auctions. There might be large gaps in the value that each participant attaches to power in such a scenario, and techniques like mid-point pricing can be used to mitigate the impact of a possibly high bid-ask spread. Midpoint pricing is the use of the average of ask and bid prices in matched orders as a reference price.

Further, the use of storage systems introduces a shift from 'time-of-use' pricing to 'time-of-sale' pricing as it enables the users to exploit the storage as a buffer during low or high prices. A shift in the time of use must also be coordinated amongst the participants [14]. This further motivates the need for such a design as it must allow participants to make and dynamically improvise their offers. Nunna, Sesetti, Rathore and Doolla [16] present an example of an energy trading platform which integrates storage systems and uses continuous double auctions.

III. Proposed TE System design

The main contributions of this work include:

- A multi round periodic double auction which uses discriminatory pricing
- Simplification of bidding format with single limit orders & use of minimal information in price discovery
- Rapid convergence: i) Allows shorter periods of trading (close to real time) ii) Reduces communication frequency
- A performance evaluation of TE system with a prototype-based simulation

Auction process flow
Beginning of trading for time slot t
1. Repeat for each time slot
A. Repeat until rounds close
i) Bid preparation
ii) Bid collection
iii) Bid matching
I. Bid sorting
II. Allocation
iv) Bid result unicast
v) Fulfilment check
vi) Price revision
B. Trading for time slot t stops
C. Broadcast of slot average prices
D. Draw or supply power
E. Update State of Charge (SoC)

Fig 1. Process specification of proposed auction

Identifiers	
i	Auction participant
j	Trading round within time slot k
k	Time slot
z_a	Constant, where a ∈ {1,2}
Energy quantities	
$Q_{i,j,k}$	Demand or capacity on sale
$L_{i,k}$	Primary load demand
$B_{current,i,j,k}$	Current SoC (State of Charge)
$B_{max,i}$	Storage system capacity
$C_{i,k}$	Primary generation capacity
Fulfilment levels	
$L_{fulfil,i,j,k}$	% of load requirement
$B_{fulfil,i,j,k}$	% of storage-related demand
$C_{sold,i,j,k}$	% of generation capacity sold
$B_{sold,i,j,k}$	% of stored capacity committed
Prices	
$P_{i,j,k}$	Estimated price of power
$P_{min,i}$	Minimum selling price

Fig 2. Description of variables used

The trading begins with the announcement of the opening of the first round for time slot t. Each time slot involves trading of energy across multiple rounds (Fig 1). Each TE participant is modeled as a combination of a *primary* component (fixed load or generating unit) and a *storage* system. The behavior of each participant is modeled using i) a demand or supply curve of the form of Q = f(P) based on the principles of microeconomics, and ii) a dynamic bidding strategy which revises bid (or ask) prices depending on several factors including energy requirements in the current slot and the ability to self-fulfill the requirement with its current local storage.

Equation (1) represents the demand quantity $Q_{i,j,k}$ of a potential buyer i in the j^{th} round for k^{th} time slot at price $P_{i,j,k}$. The bids and asks are submitted as single limit orders for each round in the format of {quantity, unit price}.

$$Q_{i,j,k} = \left\{L_{i,k} \times \left(1 - L_{fulfil,i,j,k}\right) - z_1 \times \left(\frac{B_{current,i,j,k}}{L_{i,k}}\right) \times P_{i,j,k}\right\} + \left\{\left(B_{max,i} - B_{current,i,k}\right) \times \left(1 - B_{fulfil,i,j,k}\right) - z_2 \times \frac{B_{current,i,j,k}}{B_{max,i}} \times P_{i,j,k}\right\} \quad (1)$$

Similarly, each seller determines a portion of its primary or/and storage capacity to be offered for sale in the j^{th} round at a given price as depicted in (2).

$$Q_{i,j,k} = \left\{C_{i,k} \times \left(1 - C_{sold,i,j,k}\right)\right\} + \left\{\left(1 - \frac{P_{min,i}}{P_{i,j,k}}\right) \times B_{current,i,j,k} \times \left(1 - B_{sold,\,i,j,k}\right)\right\},\ when\ P_{i,j,k} > P_{min,i} \quad (2)$$

The auctioneer arranges the bids in an increasing order (for asks) and a decreasing order (for bids) as shown in Fig 3. Once the bids are sorted, allocation is performed by fulfilling the highest paying bid with lowest ask. For instance, the bid priced at \$10.03 per KWh is matched with asks of \$3.02 kWh and partially with \$5.15 kWh to fulfil its demand of 5.12 kWh. The price discovered is thus unique to each successful transaction.

Asks		Bids	
Quantity	Price	Quantity	Price
4.03 KWh	\$ 3.02 per KWh	5.12 KWh	\$10.03 per KWh
10.45 KWh	\$5.15 per KWh	2.54 KWh	\$8.27 per KWh
2.39 KWh	\$12.23 per KWh	9.26 KWh	\$4.52 per KWh

Fig 3. Ordered bids and asks from different participants

The round is open for a pre-defined period and only accepts single limit orders. Each participant dynamically updates its bidding strategy for a round. For instance, the foremost objective of a buyer participant in the initial rounds is to fulfil its primary load requirement. Thus, it is willing to raise its bid prices in a play-safe mode to avoid any unmet demand scenario [17]. A buyer's demand is unmet when its primary load requirement cannot be fulfilled by purchased electricity and/or the local storage.

As the rounds progress and the key objective is achieved, the focus of the buyer shifts to buying additional power at opportunistically low prices. Here, the buyer is more price sensitive and the approach is to store incrementally purchased power for future needs. In this mode, the buyer begins to experiment with a lower bid price and adjusts it in the next rounds according to the success or failure of previous bid. The sellers act in a reciprocal manner.

At the end of the round, the result of each bid (partial success, complete success or complete failure) is unicast to the respective bid owners. Participants can update their set of local parameters on basis of the power quantity they could buy or sell in this round.

The auctioneer uses a set of rules to decide the last round and announce closure of trading for the time slot: i) there are no more bids in the round ii) last n rounds contribute to less than x% percent of the total trade, iii) last m consecutive rounds effectively saw zero quantity being traded. The average slot prices are broadcast to all the participants to inform their bids for the next time slot. The participants draw or supply the committed levels of power during the delivery period and update their SoC.

IV. Discussion

A software protoype was developed to simulate the proposed TE mechanism with two selling as well as two buying participants. Each participant is modeled as a combination of a fixed load (or energy source) and an appropriately sized storage system. Several parameters including a primary load forecast, capacity and SoC (State of Charge) can be configured to initialize the model. Empirical observations from the protoype are reported here.

It was observed that more than 87% of the time slots saw completion of trade in less than or equal to 4 rounds (Fig.4). The chosen bidding strategy enables the participants to ensure fulfilment of demand (buyers) and offloading of any excess unstorable capacity (sellers), in the initial set of rounds. Fig.5 shows an auction scenario where the auctioneer applies *lenient* rules for trading slot closure to allow a higher number of rounds. Oscillating prices can be observed in later rounds, since once the primary needs are met, participants operating with limited market information, use a trial-and-error process to engage in negotiations with the objective of making a profit.

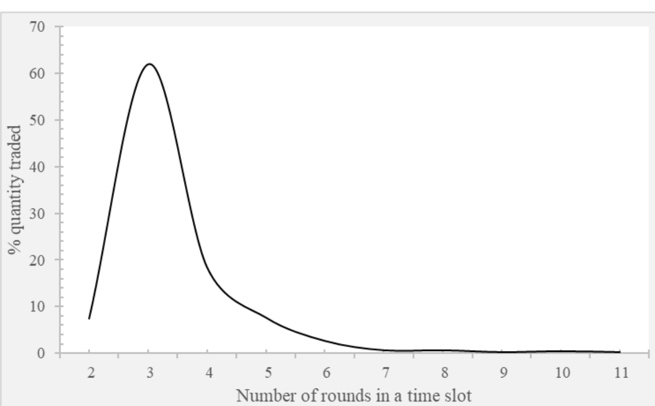

Fig 4. Frequency distribution of rounds needed to close the trading in a time slot (500 time slots).

Fig 5. A comparative bid price history for four participants across different rounds in a single time slot

We use a uniform-price power auction to benchmark and evaluate the performance of our proposed auction in terms of price volatility [18]. The Price volatility Index (PVI) measures the degree of change in market clearing prices (MCP) across different cycles (or time slots). It is defined as "the root mean square (RMS) of the differences between two consecutive market clearing prices over a period of time" as shown in (3), where τ_{clear} represents the market clearing price in a single time slot [17].

$$PVI = \sqrt{\frac{\sum_{k=2}^{T}[\tau_{clear}(k) - \tau_{clear}(k-1)]^2}{T-1}} \quad (3)$$

Both auction mechanisms were compared under the same test scenario with an identical set of grid participants, initial state conditions and slot-wise energy requirements. The proposed auction yielded a Price Volatility Index (PVI) of 11.47 for buyers and 8.47 for sellers (Fig 6). Since the proposed TE system uses discriminatory prices for each transaction across several rounds, a weighted average of bid and ask price of successful transactions is used to depict the price for a given time slot.

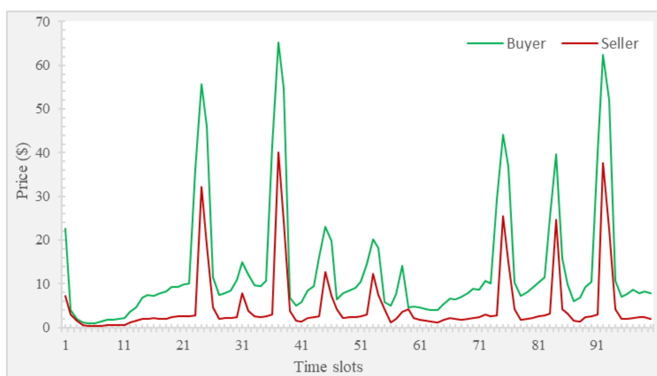

Fig 6. Average successful ask and bid prices in the proposed TE system

However, the uniform price double auction uses a single market clearing price for all participants in each time slot. A lower PVI of 0.13 (Fig 7) was observed for uniform price auctions with a more stable clearing price across time slots.

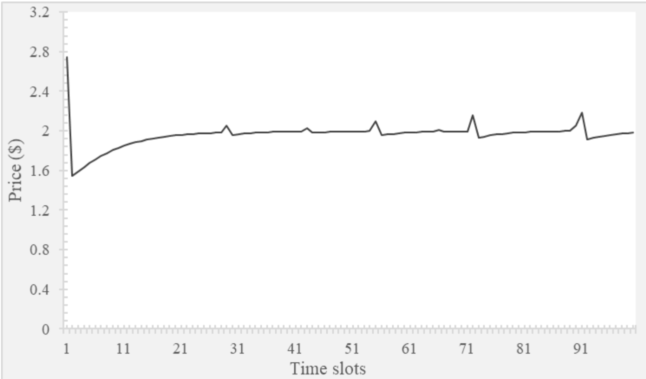

Fig 7. Stable market clearing prices in the uniform price double auction

A higher PVI can be attributed to the fact that auction inputs contain limited information and participants need to engage in a trial-and-error process to discover prices and make trades. Thus, the ability of a TE system to operate using limited information (with simple bidding requirements and single limit orders) may cause some degree of price volatility. Price volatility can be tolerated to some extent in this scenario since these are high-volume small-ticket transactions meant to serve last minute unmet requirements.

Some of the next design enhancements include a suitable choice of granularity and information richness in market signaling responses (broadcasted or unicasted, from the auctioneer to the TE system participants) to improve the quality of bids in the next rounds. The speed of convergence must also be carefully configured, and incentivized, as a very rapid closure hinders the ability of the participants to negotiate and develop prices.

A further refined design of dynamic ad-hoc auction mechanism can yield emergent characteristics that can possibly satisfy all the performance objectives of a real-time TE system. Encouraging empirical results further motivate the need for a mathematical validation of the results and proof of scalability.

V. CONCLUSION

There is an evident transformation in the composition and mobility of a growing set of grid users which prompts a change in the way they participate in the electricity market. An ideal TE system, which can treat electricity as a resource as well as a commodity, must allow its participants to fulfill their energy requirements as well as negotiate for opportunistic trade. In this paper, we recognize this need, lay out a brief design, present an initial working mechanism and outline several considerations for further improvements. This work is a first step towards an ad-hoc energy interchange between prosumers which completes quickly, yields a reasonable price with minimum need for information sharing with untrusted parties.

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