A Day Ahead Market Energy Auction for Distribution System Operation

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Abstract—In this paper, we study a day-ahead double energy auction in a distribution system involving dispatchable generation units, renewable generation units supported by battery storage systems (BSSs), fixed loads, price responsive loads, and supply from the Whole Sale Market (WSM) at Locational Marginal Price (LMP). The auction is implemented within a Distribution System Operator (DSO) premises using Mixed Integer Linear Programming (MIP). The proposed auction is cleared at the Distribution LMP (DLMP) and is observed to be weakly budget balanced if no penalty is applied for DSO’s deviation from originally committed supply from the WSM. Furthermore, the dynamics of LMP and DLMP, and their effect on distribution market participants scheduled quantities as well as the WSM supply to the distribution system is investigated.

Index Terms—distribution system operation; auction; budget balance; bid; social welfare.

NOMENCLATURE

Indices:

\(m\) Distribution bus index
\(g\) Generators index
\(b\) Battery storages index
\(l\) Load index
\(q\) Generation segments index
\(r\) Load segments index
\(t\) Timeslot index

Sets:

\(\mathcal{M}\) Set of distribution buses
\(\mathcal{G}\) Set of generator units
\(\mathcal{B}\) Set of battery storages
\(\mathcal{L}\) Set of price responsive loads
\(\mathcal{T}\) Set of time slots

Functions:

\(f\) Objective function indicating social welfare
\(\phi\) Deviation from commitment penalty function

Variables:

\(px\) Segment generation
\(p\) Generation output
\(e\) BSS energy output
\(s\) Supply from WSM
\(dx\) Segment load
\(d\) Total demand of load
\(c\) BSS state of charge

Binary and Integer Variables:

\(i\) Commitment state of generator units
\(j\) Commitment state of BSS units
\(y\) Startup indicator of generator units
\(z\) Shut down indicator of generator units
\(sd\) Shut down counter for generator
\(su\) Start up counter for generator
\(u\) BSS charging indicator
\(v\) BSS discharging indicator
\(cc\) Charging counter for BSS
\(dc\) Discharging counter for BSS

Parameters:

\(S\) Total fixed supply allocated by the ISO to DSO
\(P_{x}^{max}\) Maximum segment generation in each segment
\(p_{min}\) Minimum generation of a generator unit
\(p_{max}\) Maximum generation of a generator unit
\(CX\) Segment generation cost of a generator unit
\(STC\) Start-up cost of a generator unit
\(SDC\) Shut down cost of a generator unit
\(RU\) Rump up rate of a generator unit
\(RD\) Rump down rate a generator unit
\(MDTG\) Minimum down time of a generator unit
\(MUTG\) Minimum up time of a generator unit
\(MDTB\) Minimum discharge time of a BSS
\(MCTB\) Minimum charge time of a BSS
\(E_{min}\) Minimum BSS energy withdraw amount
\(E_{max}\) Maximum BSS energy withdraw amount
\(C_{min}\) Minimum state of charge of BSS
\(C_{max}\) Maximum state of charge of BSS
\(CB\) Selling cost of BSS energy

I. INTRODUCTION

The concept of distribution system operator (DSO) has recently gained a significant research momentum due to increasing penetration of renewable energy resources and the accompanying net load volatility. As an intermediate market operator, the DSO may use forecasted and (or) historical load and system distributed generation (DG) data to bid in the WSM. The independent system operator (ISO), will clear WSM and announce the DSO’s LMP and scheduled amount. In such a situation, once DSO collects the information of its scheduled power at the LMP, it may implement a DAM double auction in its own service territory to seek further efficient resource allocation and maximize social welfare. The service area under
the control of the DSO can be comprised of various loads and generation units. The generation units in the network can be of dispatchable and non-dispatchable kind. Non-dispatchable units that are mainly renewable energy resource such as wind and solar are intermittent and causes uncertainty while weakening the classical demand price correlation [1], [2]. However, these restrictions can be alleviated by channeling their output power through battery storage systems (BSSs) [3], [4].

While distinctive models for DSO are proposed by various researchers in the electricity market [5] – [8], a broader model that can handle involvement of all kinds of market participants has not yet been developed. Distribution market clearing and payment mechanisms are still open questions that are yet to be answered with viable and sound assumptions.

Seen hierarchically, the distribution system service territory starts at the bus where the utility company can bid in the wholesale market through DSO. A sub-transmission network then distributes the power to different distribution buses (D-buses), i.e. substations [5]. Each D-bus serves smaller substations at medium voltage that may cover a smaller geographic area or a community at low voltage. In the low voltage distribution system, different aggregator models have been proposed in the literature that may be incentivized to aggregate classical fixed as well as price responsive loads and bid in the distribution market [9] – [12].

This paper proposes a DAM model for DSO given the LMP and its commitment with the WSM based on forecasted or historical data. The goal of the DSO is to implement a double auction post WSM commitment so as to maximize the social welfare and the surplus of the market participants such as DGs, BSSs, and price responsive loads.

II. MODEL

In the proposed model when the DSO receives its committed energy information and the LMP from the ISO, it asks for bids form the generator units, BSSs, and load aggregators in the low voltage distribution system. Generator units are assumed to submit a three segment bid and amount as well as their ramp up/down rates and startup/shut down costs. Load aggregators are assumed to be capable of dividing the aggregated load to a fixed load segment amount that needs to be served at all times and a two segment bid and amount for its price responsive part. The fixed segment part of the load is expected to be served at the market clearing price and does not accompany any monetary bid value. This is because not all loads are price responsive, i.e. a high portion of the load is price inelastic and needs to be served at all times. We assume that renewable energy resources at the distribution level are coupled with BSSs for a smooth participation in the auction, and declare their selling price as well as their unit characteristics to the DSO for optimal operation. BSSs have the potential to help integrate deeper penetrations of renewable energy onto electricity grids and deliver efficient, low-cost, fundamental electricity-grid services [3]. It is considered in this paper that the BSSs are backed up and charged only by its own renewable energy resource(s). The proposed model can be easily extended for idle BSSs that can be charged or discharged by the grid in the DSO’s optimization problem by adding an extra set of constraints.

Equipped with the aforementioned considerations, the DSO runs the auction and clears the market by providing power to the successful biding parties at DLMP. The concept of DLMP has been proposed by many researchers for distribution system congestion management, market clearing, and loss minimization [2], [6], [13] – [15], [18], as it shows the true marginal cost of supplying the next increment of load. Although in this study we do not consider any distribution line congestion, the true value of a unit of energy at the DSO bus and at the D-buses will differ due to different bids of the market participants at those buses and is given by DLMP attained by the Lagrange multiplier of the constraint in Eqn. (2). The current model can be easily extended to include line congestions with line flow constraints using shift factors or power transfer distribution factor using DC power flow, a viable approximation at the sub transmission level of the distribution system.

Fig. 1 depicts a sample distribution system architecture with four distribution buses (D-buses) fed by sub-transmission lines from the main DSO bus in a radial configuration. Each D-bus is considered to include dispatchable generation units (denoted by G), BSSs charged by renewable resources and several small amount aggregated loads (denoted by L). The DSO receives the committed supply of $S_i$ (its demand at WSM) at LMP from the ISO and runs a day-ahead auction to determine its own unit commitment and supply distribution while maximizing the overall system social welfare.

The social welfare maximization of the system can be modeled as in Eqn. (1) subject to system constraints in Eqns. (2) – (31).

Maximize $f$:

$$f = \sum_{t} \sum_{m} \sum_{\ell} C_{m\ell} x_{m\ell} - \sum_{t} \sum_{m} \sum_{g} C_{mg} p_{mg}$$

$$- \sum_{t} \sum_{m} \sum_{g} S_{mg} q_{mg} - \sum_{t} \sum_{m} \sum_{g} S_{mg} g_{mg}$$

$$- \sum_{t} \sum_{m} \sum_{b} C_{mb} e_{mb} - \sum_{t} \sum_{m} LMP_t s_{mt}$$

subject to the following constraints $\forall m \in M, \forall g \in G, \forall b \in B, \forall l \in L, \forall t \in T$ :
The total power of each load is equal to the total power of its segment generation of that unit. Eqn. (4) shows that the demand of each individual generation unit is equal to the aggregated segment generation of that unit. Eqn. (7) assures that the power generated at each segment by a generation unit will not violate the predefined upper and lower limits of generation in that segment. If committed, the total power generated by a dispatchable unit shall lie within its upper and lower generation limits, as indicated by Eqn. (9).

The ramp up and ramp down constraints of each individual generation unit is ensured by Eqns. (10) – (11). In the same way, Eqns. (12) – (19) shows the MIP formulation for minimum uptime and minimum down time constraints of the generation units.

In order to increase the life expectancy of the BSS, minimum and maximum amount of energy withdrawal from these units are bounded by the given limits in Eqn. (20). Likewise, Eqn. (21) keeps the BSS safe from overcharging and deep discharging. Eqn. (22) indicates the BSSs’ charging state update. Consecutive minimum discharging and charging hours’ constraints of BSSs are represented by Eqns. (23) - (30).

III. SIMULATION RESULTS

The tabulated data in this section pertains to market participants bidding information and serves as basis for the simulation reported. Table I shows each BSS unit’s bidding information submitted to the DSO. The bidding information for each generator unit is summarized in Table II and the hourly WSM LMP and supply into the DSO market is shown in Table III. Load’s bidding information is not included due to space limitations as load bidding was assumed to vary over timeslots.

The MIP model presented in Eqns. (1) - (30) was coded in GAMS and solved using CPLEX solver for 24-hour horizon. The simulation summarized in the upcoming figures present the validity of the theory in the model. Several sets of analysis were further conducted to see the effect of LMP on the auction outcome. Simulation results indicates that loads, generators and BSS are very responsive to changes in LMP at the DSO bus at a given amount of supply by the WSM. At low LMP loads tend to buy more energy from the wholesale market as local generation prices are comparatively higher. As the LMP increases, more internal generation at each D-bus is scheduled. A similar effect is seen on serving the price responsive loads.

### Table I. Bidding information of each BSS at each D-bus

| Bus | Unit | (C<sub>min</sub>, C<sub>max</sub>) (MWh) | (E<sub>min</sub>, E<sub>max</sub>) (MWh/hr) | (MDTB, MCTB) (hr) | CB (S/MWh) |
|-----|------|--------------------------------------|--------------------------------------|-------------------|------------|
| 1   | BSS1 | (1 – 10) (0.4 – 2)                  | (10 – 40) (MWh/hr)                   | (3 – 6)           | 35         |
| 2   | BSS2 | (1 – 8) (0.4 – 2)                   | (10 – 40) (MWh/hr)                   | (3 – 6)           | 33         |
| 3   | BSS3 | (1 – 10) (0.4 – 2)                  | (10 – 40) (MWh/hr)                   | (3 – 6)           | 36.5       |
| 4   | BSS4 | (1 – 8) (0.4 – 2)                   | (10 – 40) (MWh/hr)                   | (2 – 6)           | 34         |
Table II. Segment generation and unit price for each D-bus

| (bus, unit) | (PWmax) | (PWmax) | (PWmax) | (RU, STC) | (STC, RD) | (STC, SDC) |
|-------------|---------|---------|---------|-----------|----------|-----------|
| (MW,$)      | (MW,$)  | (MW,$)  | (MW,$)  | ($        | ($       | ($        |
| (1, G1)     | (1.5, 36.7) | (2.3, 39.3) | (1.42)  | (2.3, 2.5) | (75, 60) |            |
| (1, G2)     | (1.6, 34.8) | (2.37, 38)  | (1.43)  | (2.5, 2.5) | (60, 60) |            |
| (2, G1)     | (1.5, 30)  | (1.7, 33)  | (1.8, 39) | (2.5, 2.5) | (45, 54) |            |
| (2, G2)     | (1.4, 36.9) | (1.8, 39.6) | (1.843) | (2.5, 2.5) | (51, 45) |            |
| (2, G3)     | (1.345)    | (1.5, 36)  | (0.5, 39.6) | (3, 3)     | (84, 45) |            |
| (3, G1)     | (1.2, 29.4) | (1.8, 30.6) | (2.345) | (2.5, 2.5) | (0, 0)   |            |
| (3, G2)     | (1.8, 32.1) | (1.45, 32.6) | (1.75, 34.5) | (2.5, 2.5) | (45, 51) |            |
| (3, G3)     | (0.8, 35.7) | (1.77, 37.5) | (0.5, 40.5) | (3, 3)     | (60, 48) |            |
| (3, G4)     | (0.95, 36.3) | (1.1, 37.5) | (0.95, 40.5) | (3, 3)   | (0, 0)   |            |
| (4, G1)     | (1.9, 37.5)| (1.7, 41.4) | (1.44, 45.5) | (2.5, 2.5) | (10, 10) |            |

Table III. Supply at the DSO bus from the ISO at the LMP

| LMP and ISO supply in 24hr scheduling horizon | LMP | S | t |
|-----------------------------------------------|-----|---|---|
|                  1                             | 2   | 3 | 4 |
| LMP              | 22.07 | 24.83 | 24.83 | 23.45 | 24.83 | 24.83 |
| S                  | 29.04 | 32.67 | 32.67 | 30.855 | 32.67 | 32.67 |
| t                  | 7    | 8  | 9  |
| LMP              | 26.21 | 27.59 | 28.97 | 30.35 | 33.11 | 30.35 |
| S                  | 34.485 | 36.3 | 38.115 | 39.93 | 34.485 | 39.93 |
| t                  | 14   | 15 | 16 |
| LMP              | 27.59 | 26.21 | 25.48 | 25.38 | 27.04 | 30.35 |
| S                  | 36.3 | 34.485 | 34.848 | 33.396 | 35.574 | 39.93 |
| t                  | 19   | 20 | 21 | 22 |
| LMP              | 31.73 | 34.49 | 31.73 | 28.97 | 26.21 | 23.45 |
| S                  | 41.475 | 45.375 | 41.745 | 38.115 | 34.485 | 30.355 |

Fig. 2 depicts DSO’s supply allocation to each D-bus out of the total committed schedule that it gets from WSM versus LMP during 24h scheduling horizon. Notice that the supply to each D-bus is very responsive to the changes in LMP. When LMP is low, more power will start to flow to the loads from WSM. However, during peak LMP the power flow from DSO drops significantly, to the extent that D-bus number three feeds power back into the distribution network, i.e. other D-bus, as it has more generation than load and loads in other D-buses are ready to purchase at higher price than some of its local loads. Fig. 3 shows each D-bus’s internal generation versus LMP. The internal generation at each D-bus increases as LMP increases. Fig. 4 shows total power demand equals the total supply which consists of supply from the WSM, internal generation and supply from BSSs. Notice that the BSSs are scheduled only during peak LMP hours for at least three consecutive hours due to their minimum discharging time constraints.

Fig. 5 depicts the BSSs’ commitment versus LMP values considering its charging/discharging limits. Note that all BSSs are set to 6 hours of minimum charging and 3 minimum discharging hours except the minimum discharge time of BSS at D-bus 4. Notice that the plot meets all the requirements set in the constraints in Eqns. (20) – (30) and the BSSs are all scheduled during high price hours with more power scheduled at peak LMP than its neighboring hours and the sum of assigned energy during scheduling horizon does not exceed each BSSs capacity.

Fig. 4 total demand and supply by the DSO, BSS and generators

Fig. 5 Supply from BSSs as DLMP changes

The plot in Fig. 6 shows the second BSSs’ scheduled behavior at two different DLMPs in D-bus number two along with its declared selling price shown with the horizontal line. As seen, the BSS is only scheduled when DLMP is higher than
its bid. The scheduled amount of power withdrawal from this BSS is also higher where the difference between its bid and the DLMP is higher. A similar observation was made when generation units’ behavior were investigated.

higher LMPs, a higher penalty is required to make the deviation zero. This means that if LMP is high, more internal generation at D-buses and BSSs will be committed, and it takes a higher penalty to force power injection from the WSM market in order to make the deviation zero.

Fig. 10 depicts the budget dynamics in ten different iterations for a fixed commitment $S_t$ from WSM with no penalty for deviation ($\gamma = 0$) versus increasing LMP. At lower LMPs during iterations one to five, the DSO makes money. It sells energy at higher price e.g. at DLMP while buying it at lower price e.g. LMP. As the LMP increases further, less power is purchased from the whole sale market and DLMP converges to LMP and the DSO’s revenue drops down to zero after the fifth iteration. Note that if DSO is penalized for deviation, according to Fig. 8 and 10, the DSO loses a monetary amount equal to $\phi(\gamma)$. This is because deviation occurs at higher LMPs after iteration five where the DSO’s revenue is zero with no penalty ($\gamma = 0$). The DSO has to pay the deviation cost given by Eqn. (31).

IV. CONCLUSION

In this paper, we modeled and studied a distribution system operator’s day-ahead market auction with prior commitment to the WSM and presence of distribution level generation units, renewable energy resources coupled with BSSs, and loads with fixed and price responsive segments using MIP. By clearing the auction with DLMP, we presented the dynamics of DLMP vs LMP and their effect on the outcome of the auction and the resulting payments. Our simulation results showed that, if the DSO is not penalized for deviating from its committed schedule with the ISO, the auction is always weakly budget balanced.
The DSO, however loses money equal to the amount of deviation times the penalty $\gamma$ if penalty is applied. We also observed that the DSO only makes money when LMP is cheaper at a given fixed supply from the ISO.

Future studies can be carried out to model the auction in an iterative and distributed manner [16], [17], and investigate general market equilibrium conditions. Game theoretic setting and analysis of the proposed model with the market participants considered as rational agents and the study of Nash Equilibria can be another interesting line of research one can take.

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