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A Novel Demand Response Market Clearing Auction Model for Independent System Operators

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SUMMARY

Demand response (DR), which enables customers to reduce their electricity consumption in response to prices and system needs, is playing an increasingly important role in power system operation. DR allows the Independent System Operator (ISO) to tap into existing infrastructure, such as factories or hospitals, and procure reserves and energy balancing services. DR programs are being implemented by ISOs to alter the load shape in response to price signals or operator requests during critical conditions. Many ISOs are transitioning the procurement of wholesale DR from a contract-based method to a market-based approach referred to as *DR Auction* to improve customer participation. This is one of the key features of smart grids that have strengthened the interest in demand-side resources such as distributed generation, on-site storage and DR. In the context of electricity markets, these features can improve the flexibility of demand, but at the cost of added uncertainty, however, DR markets are envisaged to provide an enduring mechanism to develop and expand upon DR resources. Therefore, how to implement the DR Auction in deregulated electricity markets, is worth consideration.

DR resources are considered important elements for reliable and economic operation of the transmission system and the wholesale markets. In the context of energy and ancillary service markets facilitated by the ISOs/Regional Transmission Organizations (RTOs), the DR market can offer energy, ancillary services, and/or capacity, depending on the ISO/RTO market design and applicable operational standards. To address the problems induced by the demand-side participation features together with deregulated electricity markets, this paper presents a new auction mechanism, which develop a mixed integer linear optimization model for DR markets. This paper also presents an algorithm guaranteeing better convergence to carry out the proposed auction mechanism. The concept of a stepped supply curve's relative slope is defined in the algorithm.

KEYWORDS
Demand Response (DR), Distributed Energy Resources (DER), Auction Market, Independent System Operators (ISOs).

1. INTRODUCTION
Independent System Operators (ISOs) are entrusted with the responsibility to maintain the security and reliability of the system which is typically ensured by maintaining provisions for capacity resources to meet the peak demand requirements and a pre-determined reserve margin [1-3]. Capacity markets are

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being initiated in various U.S. electricity markets, for example, in NYISO, ISO NE and PJM, where these markets are in place, auctions care carried out to provide participants with commitments to maintain their resources and afford more lead-time and certainty for investment in new resources.

PJM has been using the Loss of Load Expectation (LOLE) method since the 1960's to determine the Installed Reserve Margin (IRM) for their interconnections. The method used is the traditional two area convolution method, PJM as one area and the neighboring systems as the second area. Power flow analysis is used to determine Capacity Emergency Transfer Limits for the sub-regions. These parameters form the key inputs to the PJM capacity market [8-12]. PJM initiated the Reliability Pricing Model (RPM) in 2007/08, which has a three year forward Base Residual Auction that clears resources using a *demand curve* modeled in the PJM region and in the constrained sub-regions. Capacity market participants bid power supply resources into the market that either increase energy supply or reduce demand. These resources include new generators, upgrades for existing generators, Demand Response (DR), and transmission upgrades. The participants are committed to increase supply or reduce demand on the PJM system by the amount they offered, three years in the future.

The NYISO managed Installed Capacity (ICAP) market is based on the obligation placed on load serving entities (LSEs) to procure ICAP to meet minimum requirements. The requirements are determined by forecasting each LSE's contribution to its transmission district peak load, plus an additional amount to cover the Installed Reserve Margin. The amount of capacity that each supplying resource is qualified to provide to the New York Control Area (NYCA) is determined by an Unforced Capacity (UCAP) methodology. ICAP auctions are designed to accommodate LSEs and suppliers' efforts to enter into UCAP transactions. In order to maintain reliability, the NYISO has the responsibility for the determination of locational reserve requirements that recognize the transmission constraints which produce bottling effect. Such locational installed reserve requirements identify the minimum capacity of resources which must be located within each respective location. Presently, the NYISO expresses the capacity value of a resource in terms of its UCAP, which is essentially a convenient measure of a generation resource availability to provide energy and ancillary services to the control area. The UCAP concept was initially implemented in PJM, and later adopted by the NYISO and ISO-NE in the interest of facilitating a liquid capacity market between the three ISOs/RTOs.

2. PROPOSED DR AUCTION MARKET FRAMEWORK

The proposed DR auction can be carried out on a semi-annual or annual basis to determine the optimal set of DR contracts for the ISO with the DR providers. The DR offers submitted by Demand Auction Participants (DAPs) will be compared to the DR curve established by the ISO. Each DAP may submit multiple offers, where the DR offer price is in $/MW-day based on the number of business days in a Commitment Period and the DR offer quantity is any quantity up to the participant's Qualified Demand Response determined in a Demand Response Qualification Process, carried out *a priori*. The proposed DR auction model can accommodate DR offer laminations from participants to reflect the different costs of providing various levels of DR service; the first lamination should be more than or equal to a minimum quantity, *say*, 1 MW. Each DR offer lamination can have a Partial/Full flag indicating whether the quantity offered has to be fully cleared or can be partially cleared in increments, of say, 0.1 MW. However, even partial offers cannot be allowed to clear below 1 MW in total, and all lower-price laminations within one offer must clear before any higher-price laminations are cleared in the same offer. These submitted DR offers are expected to be in a ".csv" file format, to be called by the DR Auction Engine. The submitted DR offers will be processed by the DR Auction Engine prior to the optimization process in order to accommodate the partial selection of DR offers in increments of 0.1 MW**.** The mathematical model of the DR auction engine is developed as a mixed-integer linear programming (MILP) model, with the objective of maximizing the social welfare, which is the shaded area in Figure 1. The MILP optimization model clears the auction by stacking the processed, submitted DR offers based on price (from lowest to highest) and selecting offers up to the DR limit for each zone, while not exceeding the maximum auction clearing price. Some exceptions exist where higher-priced offers will be selected rather than lower-price full offers, *e.g.*, if a full offer cannot be entirely cleared.

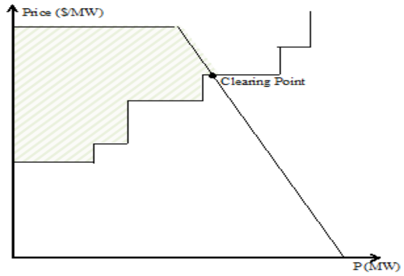

Figure 1 DR Auction Clearing Mechanism Maximizing Social Welfare

However, the auction model ensures that lower-price laminations within one offer are always be selected before higher-price laminations in the same offer. Each zone may have a Zonal Total DR Limit and a Zonal Virtual DR Limit, determined from planning and reliability studies, respectively. The Zonal Virtual DR Limit is imposed as an upper constraint on virtual resources in a zone during the clearing process; however, this limit will not create a zonal price if reached. The Zonal Total DR Limit is applied as an upper constraint on all resources in a zone during the clearing process and creates a zonal price if reached. Zonal DR prices can be lower than system DR prices but never higher.

3. PROPOSED DR AUCTION MARKET: MATHEMATICAL MODEL

As stated earlier, the objective of the DR auction market is to maximize the social welfare, which is shown by the shaded area in Figure 1, which can be defined as the ISO's gross surplus from the DR auction market net of the cost of the procured DR offers from DAPs. The MILP optimization tool will stack the submitted offers for each impacted zone and select offers up to the Minimum Demand Response limit for that zone, so long as such selection does not exceed the Maximum Auction Clearing Price. The input data from market participants "parameters of the optimization model" will be submitted as in Table 1. These DR offers submitted by participants, and received by the ISO, will have to be processed in a particular manner so as to be used by the DR auction model in the most convenient way.

Table 1: Format of DR Offers Received by Auction Market

Offer Submission Timestamp	Zone, i	Participant, p	Lamination, l	DR Offer		DR Offer Flag (Binary: 1 or 0)	
				Quantity, MW $CQ^o_{i,p,m}$	Price, $/MW-day $CP^o_{i,p,m}$	$U^o_{i,p,m}$	$X^o_{p,l}$

The pre-processing of DR offer data need be carried out before the auction market clearing process, to accommodate partial DR offers being cleared are in steps of 0.1 MW.

Objective Function: The ISO's demand curve for procuring DR services is assumed to be known *a priori*, and it comprises two areas as shown in Figure 2:

Area-1: Price: p_1 Quantity: q_1

Area-2: Price: p_0 Quantity: $(q_0 - q_1)$ (1)

A fraction of Area-2 from Figure 2, from fundamentals of area of triangles, can be written as:

$$\frac{1}{2}(\text{Price})DC_2 = X_2(\text{Area - 2}) = X_2\left[\frac{1}{2}(p_1 - p_0)DQ_2\right] \tag{2}$$

And since, $Price=p_1+p_{cleared}$; the price is in effect the mid-price between the price cap and the DR auction cleared price. Therefore,

$$DC_2 = \frac{p_1}{m} - \sqrt{p_1^2 - (p_1 - p_0)^2 X_2} \tag{3}$$

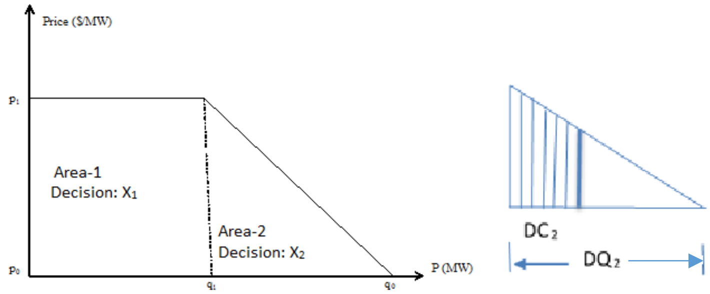

Figure 2: DR Requirement of the ISO and the DR Price Cap

Each DR participant p can have N_{l_p} number DR offer laminations, each lamination l ($l \in N_{l_p}$) with an offer price $DP_{i,p,l}$ and quantity $DQ_{i,p,l}$. The DR auction model is formulated with the objective of maximizing the social welfare J, as follows:

$$J = \overline{DP_1} DQ_1 X_1 + \frac{1}{2}(p_1 - p_0) DQ_2 X_2 - \sum_{i \in I} \sum_{p \in P} \sum_{l=1}^{N_{l_p}} DP_{i,p,l} DQ_{i,p,l} \{U_{i,p,l} + V_{i,p,l}\} \quad (4)$$

The first and second terms of (4) represent the gross payments made by the ISO to customers; while the third term represents the cost of DR services, as per the offer price of selected participants.

DR Auction Market Model Constraints

DR Procurement Balance: This constraint ensures that the total DR procured is equal to the DR requirement as set out by the ISO's demand curve. Note that this is a nonlinear equality constraint (DC_2 is from Eq. (3)).

$$DQ_1 X_1 + DC_2 = \sum_{i \in I} \sum_{p \in P} \sum_{l=1}^{N_{l_p}} DQ_{i,p,l} \{U_{i,p,l} + V_{i,p,l}\} \quad (5)$$

Zone Limit: These constraints ensure that the total DR from all participants within a specific zone i is within the DR procurement limit specified for the zone, $\overline{CQ_i}$:

$$DCQ_i = \sum_{p \in P} \sum_{l=1}^{N_{l_p}} DQ_{i,p,l} \{U_{i,p,l} + V_{i,p,l}\} ; \qquad DCQ_i \le \overline{DQ}_i \quad (6)$$

DR Procurement Limit: These constraints ensure that the total DR procured by the ISO over the entire system is within the system DR cap limits, CL_{Max} *and* CL_{Min}.

$$DCQS = \sum_{i \in I} DCQ_i \qquad CL_{Min} \le DCQS \le C_{Max} \quad (7)$$

Participant Limit: This constraint ensures that the total DR cleared for a given participant x in zone i is within the DR limit of the participant, $PRL_{i,x}$

$$\sum_{l=1}^{N_{l_p}} DQ_{i,x,l} \{U_{i,x,l} + V_{i,x,l}\} \le PRL_{i,x} \quad (8)$$

DR Price Cap: These constraints ensure that the maximum DR auction clearing price is less than the specified DR price cap of each zone, and also the DR price cap of the system.

$$DP_{i,p,l} U_{i,p,l} \le DCP_i \le \overline{DP} \qquad DP_{i,p,l} Y_{i,p,l} \le DCP_i \le \overline{DP} \qquad Y_{i,p,l} = 1 \quad \forall V_{i,p,l} > 1 \quad (9)$$

Continuous Selection of DR Offers: This constraint ensures that for a given participant p, the offers have to be selected in increasing order of offer prices.

$$W_{i,p,l} \le \frac{\sum_{m=1}^{b_1 - 1} W_{i,p,m}}{b_1 - 1} \qquad \forall b_1 = 2,....,N_{l_p} \text{ and } \qquad W_{i,p,l} = U_{i,p,l} + V_{i,p,l} \quad (10)$$

Control on Variables: The following constraints define the relationships between the variables $U_{i,p,l}$ and $V_{i,p,l}$ and between X_1 and X_2, as follows:

a. Select only full offer or partial offer for a DR participant:

$$U_{i,p,l} + V_{i,p,l} \le 1; \qquad 0 \le V_{i,p,l} < 1; \qquad V_{i,p,l} \le V0_{i,p,l} \tag{11}$$

b. Selection of ISO's DR demand areas: These constraints ensure that Area-2 is selected only when Area-1 is fully selected, *i.e.*, to model the constraint that, if $X_1<1$, then $X_2=0$:

$$X_2 \le M(X_1 - 1) + 1; \qquad 0 < X_1 \le 1; \qquad 0 \le X_2 \le 1 \tag{12}$$

where M is a large positive number.

DR Price Cap Based on ISO's Demand Curve: These constraints ensure that the ISO's demand curve is included in the DR market price determination process:

$$\overline{DP}1 = p_1 \quad \forall \quad CCQS \le q_1; \qquad \overline{DP}2 = p_1 + m(DCQS - q_1) \quad \forall \quad q_1 \le CCQS \le q_0 \tag{13}$$

Clearance of Partial Quantity in Multiples of 0.1 MW: The following constraints ensure that if partial selection of a DR offer takes place, it would be in multiples of 0.1 MW.

$$PQC_{i,p,l} = 0.1\left[M^1_{i,p,l} + 2M^2_{i,p,l} + 4M^3_{i,p,l} + ... + 2^{(KMAX-1)}M^{KMAX}_{i,p,l}\right] \tag{14}$$

$$\text{where, } KMAX = RoundUp\left[\frac{Log_{10}\left(\frac{DQ_{i,p,l}}{0.1}\right)}{Log_{10}(2)}\right] \tag{15}$$

$$PQC_{i,p,l} \le DQ_{i,p,l}; \qquad V_{i,p,l} = \frac{PQC_{i,p,l}}{DQ_{i,p,l}} \tag{16}$$

The above DR auction model is a *mixed integer nonlinear programming* (MINLP) problem which is difficult to solve for a large scale problem. In order to address the computational complexities associated with the MINLP model, the ISO's demand curve is considered to be piece-wise linear with N_d number of steps, as shown in Figure 4, where each load block j has a bid price DP_j and quantity DQ_j.

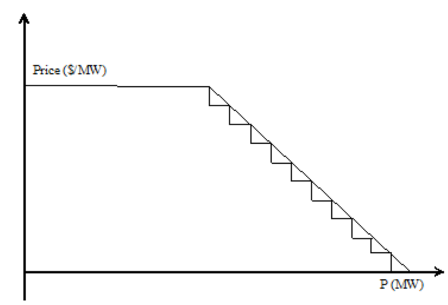

Figure 3: Linearized Demand Curve of ISO

The DR auction market, formulated with the objective of maximizing the social welfare (J), is now expressed as follows:

$$\max \quad J = DP_1 DQ_1 W_1 + \sum_{j=2}^{N_d} DP_j DQ_j W_j - \sum_{i \in I} \sum_{p \in P} \sum_{l=1}^{N_{lp}} DP_{i,p,l} DQ_{i,p,l} U_{i,p,l} \tag{17}$$

The first term of (17) represents the gross linearized ISO's payment to customers while the second term represents the cost of DR services.

4. CASE STUDIES

The following case studies demonstrate the effectiveness of the developed DR auction model.

Case 1: DR Auction Cleared at a Quantity Less than Maximum Quantity at the Highest Price, shown in Fig.4 (a)

Case 2: DR Auction Cleared on the ISO DR curve. No limit on zonal DR- Since there are no limits on zonal DR procurement, significantly large quantity of DR is procured in each zone, 116.5 MW in zone-1, 165.5 MW in zone-2, and 195.5 MW in zone-3; and the auction clears at the intersection of the offer curve and DR demand curve of the ISO, as shown in Fig.4(b).

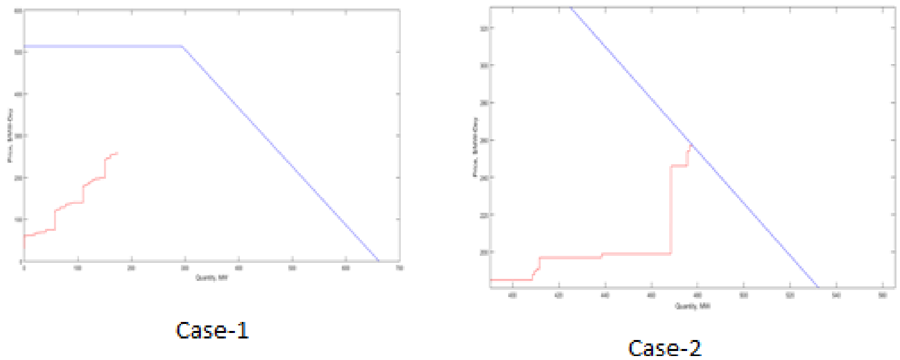

Figure 4: DR Auction Clearing in Case-1 and Case-2

Case 3: Same Input Data as Case-2, but Imposing Zonal DR Limits- In this case, each zone has a maximum DR procurement limit of 150 MW. Note that when zonal DR limits of 150 MW are imposed, the DR auction is cleared below the ISO's DR demand curve. The DR quantities cleared are 145.5 MW, 148.9 MW, and 150 MW, in the three zones, respectively (Fig.5(a)).
Case 4: DR Auction Cleared at a Quantity Greater than Maximum Quantity at the Highest Price- shown in Fig 5(b).

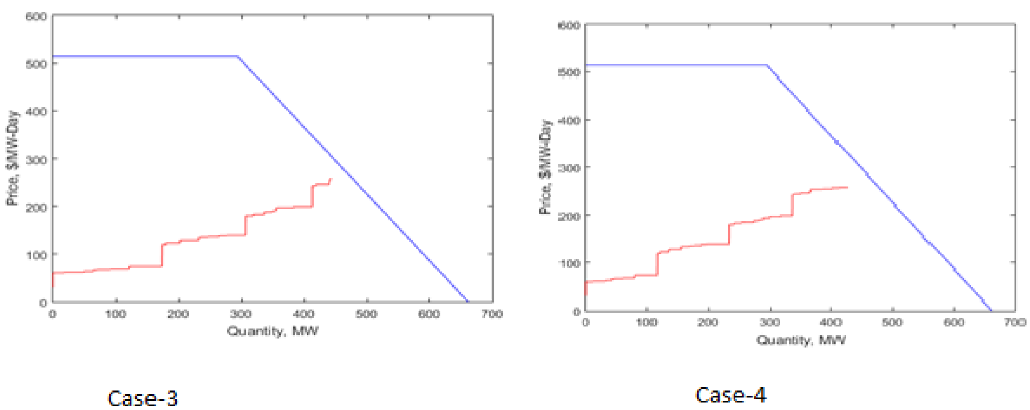

Figure 5: DR Auction Clearing in Case-3 and Case-4

5. CONCLUSIONS

This paper provides an overview of the proposed DR Auction Engine, with particular focus on the mathematical model developed to clear the auction. This paper presents the details of the proposed optimization model including descriptions of how the optimization problem is modeled and the methodology for data processing required to address partial offers and other considerations.

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