Modeling the Strategic Behavior of an Active Distribution Network in the ISO Markets

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***Abstract*—With increasing integration of distributed energy resources (DERs), active distribution networks (ADNs) can actively participate in the electricity markets by dispatching their DERs, which can change the existing electricity market paradigm. It is essential to investigate the strategic behaviors of ADNs and their DER dispatch when they participate in the wholesale market as price-makers. This paper proposes a bi-level optimization model to study the strategic behavior of an ADN in both energy and reserve markets. The optimal scheduling of DERs in the ADN is modeled as the upper level problem and the joint energy and reserve market-clearing of the ISO is modeled as the lower-level problem. The two-level optimization models exchange bidding information and energy/reserve prices with each other. The proposed bi-level optimization problem is converted to a mathematical programming with equilibrium constraints (MPEC) by using Karush-Kuhn Tucker (KKT) conditions and strong duality theory. Further, the MPEC problem is reformulated as a computationally-solvable mixed integer second order cone programming (MISOCP) model. The simulation results on an illustrative case demonstrate the impact of the strategic bidding of the ADN on the day-ahead energy and reserve market prices.**

***Index Terms*—active distribution network, bilevel optimization, day-ahead market, mathematical program with equilibrium constraints, strategic bidding**

NOMENCLATURE

$C_s^{PV,P}/C_s^{PV,Q}$	Cost of generation of active/reactive power of the PV generation unit s ($/MW/MVAr).
$C_w^{WE,P}/C_w^{WE,Q}$	Cost of generation of active/reactive power for wind DG w with ES ($/MW/MVAr).
$N1(j)/N2(j)$	Set of initial/terminal nodes of distribution line.
r_{ij}/x_{ij}	Resistance/Reactance of branch ij (ohms).
$p_{j,t}^d/q_{j,t}^d$	Active/Reactive power load at node j of the ADG at time t (MW/MVAr).
$\eta^{ES,ch}/\eta^{ES,dch}$	Charging/Discharging efficiency of Energy storage units (%).
$V_{i,min}/V_{i,max}$	Lower/Upper limit of voltage at node i (V).
$P_w^{ES,max}$	Active power capacity of the ESS w (MW).
$Q_w^{ES,max}$	Reactive power capacity of the ESS w (MVAr).
$Q_w^{ES,min}$	Minimum reactive power capacity of the energy storage unit w (MVAr).
$E_w^{ES,max}$	Storage capacity of the ESS w (MWh).
$S_w^{ES,max}$	Apparent power capacity of ESS w (MVA).
$\Pi_{g,t}^{gen,\ offer}$	Genco's offer to sell energy ($/MWh)
$\Pi_{g,t}^{gen,\ res}$	Genco's offer to sell reserve ($/MWh)
ξ_t^{gen}/ξ_t^{ADN}	Probability of service failure of Gencos / ADN.
$\pi_t^{\overline{ADN,offer}}$	ADN's offer to sell energy ($/MWh).
$\pi_t^{\overline{ADN,bid}}$	ADN's bid for energy ($/MWh).
$\pi_t^{\overline{ADN,\ res}}$	ADN's offer to provide reserve ($/MWh).
R_t^{sys}	Reserve requirement of the ISO market (MW).
$P_g^{gen,max}$	Maximum power of the Genco g (MW).
$R_g^{gen,max}$	Maximum reserve of the Genco g (MW).
$P^{ADN,max}$	Boundary transformer capacity of ADN (MW).
$R^{ADN,max}$	Maximum reserve of ADN (MW).
$P_{s,t}^{PV}/Q_{s,t}^{PV}$	Active/Reactive power output of PV unit s at time t (MW/MVAr).
$r_{s,t}^{PV}/r_{w,t}^{W}$	Reserve provided by a PV/wind unit at time t (MW).
$P_{w,t}^{W}/Q_{w,t}^{W}$	Active/Reactive power output of wind DG unit w at time t (MW/MVAr).
$P_{w,t}^{ES,dch}/Q_{w,t}^{ES,dch}$	Active power output of ESS unit w at time t (MW/MVAr).
$P_{w,t}^{ES,ch}$	Active power consumption of ESS unit w at time t (MW/MVAr).
$r_{w,t}^{ES}$	Reserve provided by a ESS w at time t (MW).
$\pi_{t,k}^{LMP}$	LMP at node k ($/MWh).
$p_{ij,t}/q_{ij,t}$	Active/Reactive power flow from node i to node j of the ADN (MW/MVAr).

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l_{ij}	Square of current from node i to node j.
$p_{j,t}^{PV}/q_{j,t}^{PV}$	Active/Reactive power generated from PV units at node j (MW/MVAr).
$p_{j,t}^{W}/q_{j,t}^{W}$	Active/Reactive power generated from wind DG at node j (MW/MVAr).
$p_{j,t}^{ES,ch}$	Charging power of ESS b at node j (MW).
$p_{j,t}^{ES,dch}/q_{j,t}^{ES,dch}$	Active/Reactive power discharge by ES at node j (MW/MVAr).
$p_{j,t}^{WE}/q_{j,t}^{WE}$	Active/Reactive power injected by wind DG with ES at node j (MW/MVAr).
$p_{j,t}^{ADN,Out/in}$	Active power sold/bought at node j to ISO(MW).
r_{t}^{ADN}	Reserve provided by the ADN at time t (MW).
$u_{j,t}$	Square of voltage at the node j at time t.
$P_{g,t}^{gen}/r_{g,t}^{gen}$	Power/Reserve generated by a Genco (MW).
$P_{r,t}^{Ret}$	Power purchased by a Retailer (MW).

I. INTRODUCTION

With the integration of distributed energy resources (DERs), the role of distribution networks is evolving from load serving entity (LSE) who purchases power from wholesale market to supply its consumers, to active market players who can trade (buy or sell) both energy and ancillary services in the ISO market. FERC's Order No.2222 has opened the wholesale markets to DERs and aggregated DERs in addition to traditional resources. This milestone has marked the beginning of a new era for DERs in the U.S. Under such a scenario, further research needs to be done to redefine the ADN's potential as a price-maker (PM) player in the wholesale market. According to [1], the ADN in the power grid should be considered in a system of systems framework since the ADN's dispatch and the ISO market dispatch are two decision-making problems for two systems. Some approaches treat ADN as a price-taker (PT) player which aims to maximize the ADN profit by responding to market prices set by the ISO market. However, as DER penetration is increasing, the ADN may be able to manipulate the day-ahead energy and reserve market prices of the ISO market by dispatching its DERs strategically. [3] models the optimal bidding strategy of a DER aggregator in a day-ahead energy market in the presence of flexible demand as a stochastic mixed integer linear programming (MILP) problem. In [4], a stochastic framework for distribution company's (Disco) decision-making in day-ahead and real-time market is presented. Bahramara et al. in [5] modeled the strategic behaviors of a Disco in wholesale energy and reserve market as a bi-level problem. However, it fails to consider the network constraints in both distribution and transmission systems.

In this paper, we propose a bi-level optimization model to study the strategic bidding of an ADN with DERs as a price maker in the electricity market. The optimal scheduling of DERs in the ADN is modeled as the upper level problem and the joint energy and reserve market-clearing of the ISO is modeled as the lower-level problem. The proposed bi-level

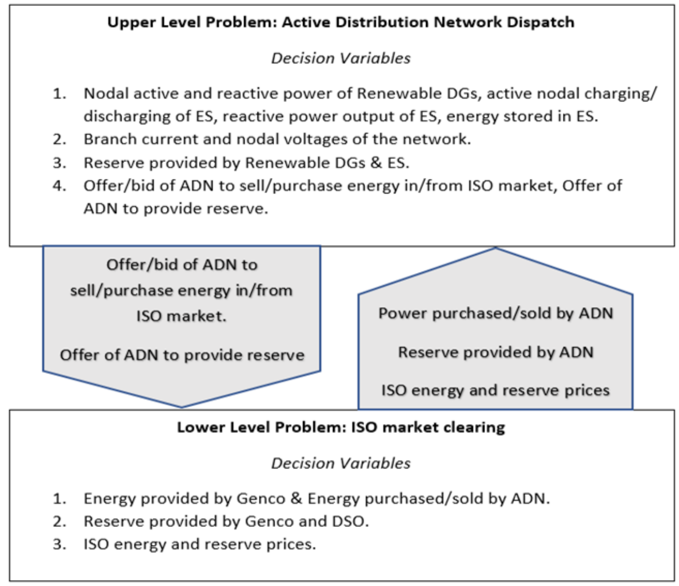

Fig. 1. Model of the Bilevel problem

optimization problem is converted to a Mathematical programming with equilibrium constraints (MPEC) by using Karush-Kuhn Tucker (KKT) conditions and strong duality . Further, the MPEC problem is reformulated as a computationally-solvable mixed integer second order cone programming (MIS-OCP) model. The simulation results on an illustrative case demonstrate the impact of the strategic bidding of the ADN on the day-ahead energy and reserve market prices. In the proposed framework, the DERs in the ADN can actively provide energy and reserve to the system through strategic bidding of the ADN in the energy and reserve markets.

II. PROBLEM DESCRIPTION

In this paper, the strategic bidding of an ADN in the ISO day-ahead energy and reserve market is modeled as a bi-level optimization problem. The ADN considered in this work consists of various types of DERs such as solar and wind generation units.The wind power generation unit is coupled with an energy storage system (ESS). The ADN is connected to the transmission network through a substation. The distribution system operator (DSO) needs to bid in the wholesale market to purchase energy and ancillary services from the ISO. An ADN can strategically play in the wholesale market and change the LMPs in the transmission network to minimize its own operation cost, by intentionally dispatching the DERs and changing the total load demand of the distribution network. The ISO market will accept offers and bids from the market players. Generation companies (Gencos) offers to sell energy and reserve to the ISO market. Retailers bid to buy energy and reserve from the ISO market.The ADN bids to buy energy from the ISO, simultaneously it also offers to sell energy and reserve to the ISO market. The ISO optimally dispatches the available resources to minimize the cost of generation. In this work, we focus on modeling and analyzing the strategic behaviors of an ADN and its DER dispatch in a competitive wholesale market. Other market participants are modeled as non-strategic players. The strategic bidding of an ADN is modeled as a bi-level optimization problem. The structure of the bi-level optimization model is shown in Fig. 1.

III. Mathematical Formulation

A. Upper Level Problem: ADN's Optimal Dispatch

The objective function of the upper-level optimization model is to minimize the total operation cost of the ADN including cost of active/reactive power and reserve from the DERs, cost of purchasing power and revenue of providing reserve in the ISO market, as shown in Eq. (1)

$$\begin{aligned}
&min\ F(X^{LP}) \\
&=\sum_t \sum_s (C_s^{PV,P} P_{s,t}^{PV} + C_s^{PV,Q} Q_{s,t}^{PV} + C_s^{PV,P} \alpha_t^{RM} r_{s,t}^{PV}) \\
&\quad + \sum_t \sum_w (C_w^{WE,P} (P_{w,t}^{W} - P_{w,t}^{ES,ch} + P_{w,t}^{ES,dch}) \\
&\quad + C_w^{WE,Q} (Q_{w,t}^{W} + Q_{w,t}^{ES,dch}) + C_w^{WE,P} \alpha_t^{RM} (r_{w,t}^{W} + r_{w,t}^{ES})) \\
&\quad - \sum_t (P_t^{ADN,Out} - P_t^{ADN,in}) \pi_{t,k}^{LMP} \\
&\quad - \sum_t (r_t^{ADN} \pi_t^{R} + \Pi_t^{inc} \alpha_t^{RM} r_t^{ADN} (1 - \xi_t^{ADN})) \\
&\quad - \Pi_t^{Pen} \alpha_t^{RM} r_t^{ADN} \xi_t^{ADN}
\end{aligned} \tag{1}$$

The first term in Eq. (1) presents cost of generating active power,reactive power and reserve for solar distributed generators (DGs) where α_t^{RM} represents the probability of calling reserve. The second term presents the cost function of wind DG coupled with ESS. The third term is the ADN's profit from sale of energy to the ISO market where $\pi_{t,k}^{LMP}$ is the ISO market's LMP at the ADN's substation which comprises of marginal costs of energy and congestion. The fourth term is the reserve sold to the ISO market at price π_t^R with an incentive Π_t^{inc} for providing reserve and a penalty Π_t^{Pen} if the ADN failed to provide reserve.The probability of service failure of ADN is included by ξ_t^{ADN}. Constraint (2)-(6) of the LSE model utilizes established linearized Distflow model for AC power flow in a radial distribution network [6], [7]. Eq. (1) is subjected to the following constraints:

1) Network power flow constraints:

$$\sum_{i \in N1(j)} (p_{ij,t} - l_{ij,t} r_{ij}) - \sum_{i \in N2(j)} p_{ij,t} + p_{j,t}^{PV} + p_{j,t}^{WE} + -p_{j,t}^{d} - p_{j,t}^{ADN,Out} + p_{j,t}^{ADN,in} = 0 \tag{2}$$

$$\sum_{i \in N1(j)} (q_{ij,t} - l_{ij,t} x_{ij}) - \sum_{i \in N2(j)} q_{ij,t} + q_{j,t}^{PV} + q_{j,t}^{WES} - q_{j,t}^{d} = 0 \tag{3}$$

$$\|2p_{ij,t} \quad 2q_{ij,t} \quad (l_{ij,t} - u_{i,t})\| \le (l_{ij,t} + u_{i,t}) \tag{4}$$

$$u_{j,t} = u_{i,t} - 2(r_{ij} p_{ij,t} + x_{ij} q_{ij,t}) + ((r_{ij})^2 + (x_{ij})^2) l_{ij,t} \tag{5}$$

$$(V_{(i,min)})^2 \le u_{i,t} \le (V_{(i,max)})^2 \tag{6}$$

$$p_{j,t}^{WES} = p_{j,t}^{W} - \frac{p_{j,t}^{ES,ch}}{\eta^{ES,ch}} + p_{j,t}^{ES,dch} \eta^{ES,dch} \tag{7}$$

$$q_{j,t}^{WES} = q_{j,t}^{W} + q_{j,t}^{ES,dch} \tag{8}$$

2) Reserve balance constraint:

$$r_t^{LSE} = \sum_s r_{s,t}^{PV} + \sum_w r_{w,t}^{W} + \sum_W r_{w,t}^{ES} \tag{9}$$

3) Solar DG constraints:

$$P_{s,t}^{PV} + r_{s,t}^{PV} \le P_s^{PV,max} \tag{10}$$

$$0 \le P_{s,t}^{PV} \tag{11}$$

$$0 \le r_{s,t}^{PV} \tag{12}$$

$$Q_s^{PV,min} \le Q_{s,t}^{PV} \le Q_s^{PV,max} \tag{13}$$

$$\left\| P_{s,t}^{PV} \quad Q_{s,t}^{PV} \right\| \le S_s^{PV,max} \tag{14}$$

The model for wind DG is similar to that of solar DG.

4) Energy Storage Constraints:

$$0 \le P_{w,t}^{ES,ch} \le P_w^{ES,max} \tag{15}$$

$$0 \le P_{w,t}^{ES,dch} \le P_w^{ES,max} \tag{16}$$

$$E_w^{ES,min} \le e_{w,t}^{ES} \le E_w^{ES,max} \tag{17}$$

$$(P_{w,t}^{ES,dch} + r_{w,t}^{ES}) / \eta_w^{ES,dch} \le e_{w,t}^{ES} \tag{18}$$

$$r_{w,t}^{ES} - P_{w,t}^{ES,ch} + P_{w,t}^{ES,dch} \le P_w^{ES,max} \tag{19}$$

$$r_{w,t}^{ES} \le P_w^{ES,max} \tag{20}$$

$$e_{w,t}^{ES} = e_{w,t-1}^{ES} + P_{w,t}^{ES,ch} - P_{w,t}^{ES,dch} \tag{21}$$

$$Q_w^{ES,min} \le Q_{w,t}^{ES} \le Q_w^{ES,max} \tag{22}$$

$$\left\| P_w^{ES,ch} - P_w^{ES,dch}, Q_{w,t}^{ES} \right\| \le S_w^{ES,max} \tag{23}$$

The solution of leader problem yields the energy bid, energy offer and reserve offer of the ADN.

B. Lower level problem: ISO's day-ahead market clearing

The ISO receives bids and offers from Gencos, Retailers and ADN, and then performs market clearing to meet the system demand with social welfare maximization as its objective. The objective function (24) of the lower level ISO market clearing problem is to minimize the total cost of energy and reserve across the whole system.

$$\begin{aligned}
&min\ F(X^{FP}) \\
&= \sum_t (\sum_g \Pi_{g,t}^{gen,offer} P_{g,t}^{gen} - \sum_r \Pi_{r,t}^{Ret,bid} P_{r,t}^{Ret} \\
&\quad + \pi_t^{\overline{ADN,offer}} P_t^{ADN,out} - \pi_t^{\overline{ADN,bid}} P_t^{ADN,in} \\
&\quad + \sum_g (\Pi_{g,t}^{gen,res} r_{g,t}^{gen} + \Pi_t^{inc} \alpha_t^{RM} r_{g,t}^{gen} (1 - \xi_t^{gen}) \\
&\quad - \Pi_t^{pen} \alpha_t^{RM} r_{g,t}^{gen} \xi_t^{gen}) + \pi_t^{\overline{ADN,res}} r_t^{ADN} \\
&\quad + \Pi_t^{inc} \alpha_t^{RM} r_t^{ADN} \left(1 - \xi_t^{ADN}\right) \\
&\quad - \Pi_t^{pen} \alpha_t^{RM} r_t^{ADN} \xi_t^{ADN})
\end{aligned} \tag{24}$$

1) Energy & Reserve balance constraints:

$$\sum_g P_{g,t}^{gen} - \sum_r P_{r,t}^{Ret} - P_t^{ADN,in} + P_t^{ADN,out} = 0 : \pi_t^E \quad (25)$$

$$\sum_g r_{g,t}^{gen} + r_t^{ADN,} = R_t^{sys} : \pi_t^R \quad (26)$$

Eqs. (25) and (26) define the energy and reserve balance in the ISO market clearing framework respectively.

2) Transmission branch flow constraint:

$$-PL_{j,max}^{TSO} \leq \sum_g GSF_{j-g}^{TSO} P_{g,t}^{gen} - \sum_r GSF_{j-r}^{TSO} P_{r,t}^{Ret} + GSF_{j,k}^{TSO}(P_t^{ADN,out} - P_t^{ADN,in}) \leq PL_{j,max}^{TSO} : \mu_{j,t}^{TSO,min/max} \quad (27)$$

Eq. (27) represents the transmission flow constraint.

3) Genco's constraints:

$$0 \leq p_{g,t}^{gen} : \mu_{g,t}^{gen,min} \quad (28)$$

$$P_{g,t}^{gen} + r_{g,t}^{gen} \leq P_g^{gen,max} : \mu_{g,t}^{gen,max} \quad (29)$$

$$0 \leq r_{g,t}^{gen} \leq R_g^{gen,max} : \mu_{g,t}^{gen,minres}, \mu_{g,t}^{gen,maxres} \quad (30)$$

Eqs. (28)-(30) define the upper and lower bounds of reserve and energy provided by the Gencos.

4) ADN's constraints:

$$0 \leq p_t^{ADN,out} : \mu_t^{ADN,out} \quad (31)$$

$$P_t^{ADN} + r_t^{ADN} \leq P^{ADN,max} : \mu_t^{ADN,max} \quad (32)$$

$$0 \leq P_t^{ADN,in} \leq P^{ADN,max} : \mu_t^{ADN,minin}, \mu_t^{ADN,maxin} \quad (33)$$

$$0 \leq r_t^{ADN} \leq R^{ADN,max} : \mu_t^{ADN,minres}, \mu_t^{ADN,maxres} \quad (34)$$

Eqs. (31)-(34) define the upper and lower bounds of reserve and energy provided by the ADN.

C. Mathematical Program with Equilibrium Constraints

In this section, the bi-level optimization problem is converted into one single-level Mathematical programming with equilibrium constraints (MPEC) problem by incorporating lower level problem into the upper level problem using KKT conditions and duality theorem . Stationary constraints are obtained from the partial differential of the Lagrange function with respect to the decision variables.

1) Stationary constraints:

$$\Pi_{g,t}^{gen,offer} - \pi_t^E - \sum_{j=1}^{Nl} \mu_{j,t}^{TSO,min} \sum_g GSF_{j-g}^{TSO} + \sum_{j=1}^{Nl} \mu_{j,t}^{TSO,max} \sum_g GSF_{j-g}^{TSO} - \mu_{g,t}^{gen,min} + \mu_{g,t}^{gen,max} = 0 \quad (35)$$

$$\Pi_{g,t}^{gen,res} + \Pi_t^{inc} \alpha_t^{RM} \left(1 - \xi_{g,t}^{gen}\right) - \Pi_t^{pen} \alpha_t^{RM} \xi_{g,t}^{gen} - \pi_t^{RM} + \mu_{g,t}^{gen,max} - \mu_{g,t}^{gen,minres} + \mu_{g,t}^{gen,maxres} = 0 \quad (36)$$

$$\pi_t^{AD\bar{N},offer} - \pi_t^E - \mu_t^{ADN,minout} + \mu_t^{ADN,maxout} - \sum_{j=1}^{Nl} \mu_{j,t}^{TSO,min} GSF_{j,k}^{TSO} + \sum_{j=1}^{Nl} \mu_{j,t}^{TSO,max} GSF_{j,k}^{TSO} = 0 \quad (37)$$

$$-\pi_t^{AD\bar{N},bid} + \pi_t^E - \mu_t^{ADN,minin} + \mu_t^{ADN,maxin} + \sum_{j=1}^{Nl} \mu_{j,t}^{TSO,min} GSF_{j,k}^{TSO} - \sum_{j=1}^{Nl} \mu_{j,t}^{TSO,max} GSF_{j,k}^{TSO} = 0 \quad (38)$$

$$\pi_t^{AD\bar{N},res} + \Pi_t^{inc} \alpha_t^{RM} (1 - \xi_t^{ADN}) - \Pi_t^{pen} \alpha_t^{RM} \xi_t^{ADN} - \pi_t^{RM} + \mu_t^{ADN,maxout} - \mu_t^{ADN,minres} + \mu_t^{ADN,maxres} = 0 \quad (39)$$

2) Complementary constraints:

$$0 \leq \sum_g GSF_{j-g}^{TSO} P_{g,t}^{gen} - \sum_r GSF_{j-r}^{TSO} P_{r,t}^{Ret} + GSF_{j,k}^{TSO}(P_t^{ADN,out} - P_t^{ADN,in}) + PL_{j,max}^{TSO} \perp \mu_{j,t}^{TSO,min} \geq 0 \quad (40)$$

$$0 \leq \sum_g GSF_{j-g}^{TSO} P_{g,t}^{gen} - \sum_r GSF_{j-r}^{TSO} P_{r,t}^{Ret} + GSF_{j,k}^{TSO}(P_t^{ADN,out} - P_t^{ADN,in}) + PL_{j,max}^{TSO} \perp \mu_{j,t}^{TSO,min} \geq 0 \quad (41)$$

$$0 \leq P_{g,t}^{gen} \perp \mu_{g,t}^{gen,min} \geq 0 \quad (42)$$

$$0 \leq (P_{g,t}^{gen,max} - P_{g,t}^{gen} - r_{g,t}^{gen}) \perp \mu_{g,t}^{gen,max} \geq 0 \quad (43)$$

$$0 \leq r_{g,t}^{gen} \perp \mu_{g,t}^{gen,minres} \geq 0 \quad (44)$$

$$0 \leq (R_{g,t}^{gen,max} - r_{g,t}^{gen}) \perp \mu_{g,t}^{gen,maxres} \geq 0 \quad (45)$$

$$0 \leq P_t^{ADN,out} \perp \mu_t^{ADN,minout} \geq 0 \quad (46)$$

$$0 \leq (P^{ADN,max} - P_t^{ADN,out} - r_t^{ADN}) \perp \mu_t^{ADN,maxout} \geq 0 \quad (47)$$

$$0 \leq (P^{ADN,max} - P_t^{ADN,in}) \perp \mu_t^{ADN,maxin} \geq 0 \quad (48)$$

$$0 \leq P_t^{ADN,in} \perp \mu_t^{ADN,minin} \geq 0 \quad (49)$$

$$0 \leq (R^{ADN,max} - r_t^{ADN}) \perp \mu_t^{ADN,maxres} \geq 0 \quad (50)$$

$$0 \leq r_t^{ADN} \perp \mu_t^{ADN,minres} \geq 0 \quad (51)$$

The complementary slackness constraints (40)-(51) are transformed as below in the model [8].

$$0 \leq x \perp y \geq 0 \Longrightarrow x \geq 0, y \geq 0, x \leq H_1 U, y \leq H_2(1-U) \quad (52)$$

U is a binary variable and H_1 & H_2 are large numbers.

Then the derived MPEC is transformed to an MISOCP model [8] through linearization and reformulation. The resulting MISOCP can be solved efficiently by off-the-shelf solvers.

IV. Numerical Results

A. Case Description

The proposed model was tested on a modified IEEE 9-bus distribution network which is connected to a modified PJM 5-bus transmission system. The ISO market has 5 Gencos, 3 retailers and one ADN as market players.The Gencos have a combined generation capacity of 1230 MW. Retailers are considered to be conventional distribution networks with no flexibility in consumer demand. In the ADN with high renewables, there are 3 wind generators with a total capacity of 30 MW coupled with ESSs with a total capacity of 4MW and 9 solar DGs with a total capacity of 24 MW. The peak load in the ADN is 53 MW. The data that the reserve market uses for probability of calling reserve and incentive/penalty for providing/not providing reserve can be found in [5]. The probability of service failure for Genco and ADN are considered as 4%. Two cases were used to analyze the strategic behaviors of the ADN by solving the proposed bi-level optimization model. In Case 0, the generation costs of DERs are set to be 0 \$/MW for both active and reactive power. Case 0 is served as the base case in which the bidding cost is zero and there is no fuel cost for renewable DERs. In Case 1, the generation costs of DER are set to 16 \$/MW for PVs and 33 \$/MW for wind power DERs. The time horizon is 24 hours.

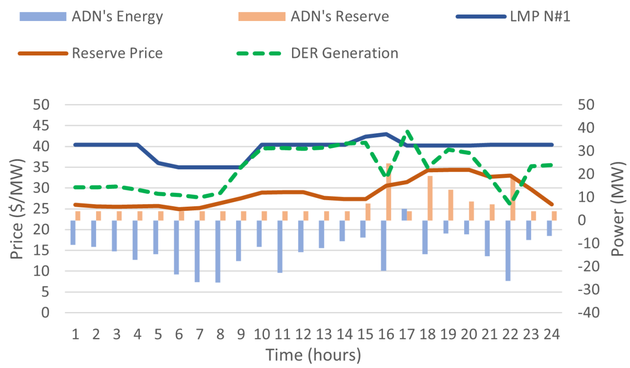

Fig. 2. Strategic behavior of ADN in the ISO market- Case 0

B. Results

The strategic behavior of the ADN in the ISO energy and reserve markets can be observed in Fig. 2. In the energy market, ADN acts as a strategic consumer in most of the hours. The negative values for ADN's energy in Fig. 2 indicate that ADN is buying power from the ISO market except in Hour 17. In the case of Hour 16, ADN bids for energy strategically to reduce the LMP at Node 1 so that it can reduce the cost of purchasing energy from the ISO market. The impact of strategic ADN can be observed in Fig. 3 when compared to a non-strategic ADN's LMP for Hour 15 and 16. The ADN is the marginal unit in the reserve market for periods 18-20. Genco#3, Genco#5 and the ADN are the reserve providers. ADN offers enough reserve bids to elevate the reserve prices to Genco#2's marginal reserve price so that the ADN can maximize its profit earned from the reserve market. Without the strategic bidding of the ADN, the reserve price of the system would be the reserve bidding price of Genco#3. Modeled as a price-maker, the ADN needs to balance the DER dispatch for providing energy and reserve so that it can gain maximum profit from the ISO energy and reserve markets. It will try to minimize the cost of energy purchase from the ISO energy market and maximize the revenue of providing reserve in the ISO's ancillary service market coordinately.

The proposed model was compared with the conventional distribution network modeled as a price-taker (PT)-ADN, i.e. strategic ADN v.s. non-strategic ADN. Both models were run for 24 hour time period to obtain the ISO energy and reserve

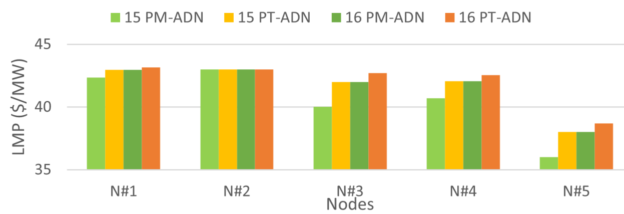

Fig. 3. LMP Comparison of PM-ADN and PT-ADN

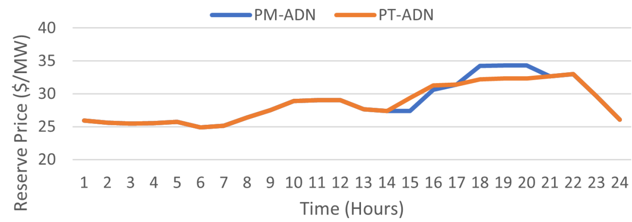

Fig. 4. ISO Reserve Price Comparison of PM-ADN and PT-ADN

prices for Case 0 and Case 1. As presented in Table I, the price-maker(PM)-ADN reduced the energy purchase cost from the ISO market by 2.8 % and 18.2% for Case 0 and Case 1, respectively. Also, there are 0.7% and 6.8% reduction for Case 0 and Case 1 in the total cost of the PM-ADN which considers the ISO market interactions, compared to a PT-ADN. As the cost of generation of DERs increases, there is an increase in the strategic behavior of PM-ADN which also results in higher profit from ISO market interactions. Fig. 3 gives a comparison between LMPs of a PM-ADN and PT-ADN for periods 15 and 16 in Case 0. The results show that a PM-ADN can reduce LMPs in the ISO market in order to reduce the buying price of energy in peak hours. Simultaneously as presented in Fig. 4, the PM-ADN increases reserve price for period 18-20. There is a dip in reserve price for period 15 and 16 as the ADN behaves as a strategic prosumer in those periods since the available DER generation was utilized to reduce energy purchase cost. Simulations were carried out on a 64-bit Laptop with Intel Core i5 CPU, 2.5 GHz and 16 GB RAM. The model with 552 quadratic constraints, 8376 continuous and 912 integer variables is solved in 14.60 seconds using Gurobi. The model will be tested on a larger test case to analyze the computational load for a real-world case in future work.

TABLE I
COMPARISON BETWEEN PROFIT OF STRATEGIC AND NON-STRATEGIC ADNS FROM ISO INTERACTIONS

Case	Cost/Revenue	PM ADN ($)	PT ADN ($)
Case-0	*Energy Cost*	13195.80	13577.51
	Reserve Revenue	5047.06	5369.54
	Total Cost	8148.73	8207.96
Case-1	*Energy Cost*	21403.62	26190.20
	Reserve Revenue	9976.24	13925.94
	Total Cost	11427.38	12264.26

V. CONCLUSION

In this paper, the strategic behavior of an ADN in the ISO market is formulated as a bilevel problem by modeling ADN as a price-maker in the ISO energy and reserve markets. The bilevel problem was converted to an MPEC problem and then reformulated as a MISOCP model. The proposed model was tested using two cases and compared with a price-taker ADN model. The results indicate that a price-maker ADN reduces its energy cost by decreasing the LMPs during peak load hours and earns profits by providing reserve to the ISO through strategic bidding. This model can be utilized to study the behaviors of an ADN and DERs in providing energy and reserve under the competitive ISO markets.

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