A Hierarchical Electricity Market Structure for the Smart Grid Paradigm

Saeed D. Manshadi, *Student Member, IEEE*, and Mohammad E. Khodayar, *Member, IEEE*

***Abstract*—This paper proposed a hierarchical structure for the electricity market to facilitate the coordination of energy markets in distribution and transmission networks. The proposed market structure enables the integration of microgrids, which provide energy and ancillary services in distribution networks. In the proposed hierarchical structure, microgrids participate in the energy market at the distribution networks settled by the distribution network operator (DNO), and load aggregators (LAs) interact with microgrids and generation companies (GENCOs) to import/export energy to/from the distribution network electricity markets from/to the wholesale electricity market. The proposed approach addressed the synergy of energy markets by introducing dynamic game with complete information for GENCOs, microgrids, and LAs. The proposed hierarchical competition is composed of bi-level optimization problems in which the respective upper-level problems maximize the individual market participants' payoff, and the lower-level problems represent the market settlement accomplished by the DNO or the independent system operator. The bi-level problems are solved by developing sensitivity functions for market participants' payoff with respect to their bidding strategies. A case study is employed to illustrate the effectiveness of the proposed approach.**

***Index Terms*—Bidding strategy, distribution network electricity market (DNEM), dynamic game, hierarchical electricity markets, microgrids, wholesale electricity market (WEM).**

NOMENCLATURE

Indices

b	Index for branch.
e	Index for the generation dispatch blocks.
l	Index for load aggregator (LA).
m	Index for microgrid.
o	Index for electricity network bus.
j	Index for generation company (GENCO).

Variables

P_j	Generation dispatch of generator j [MW].
P_m	Generation dispatch of microgrid m [MW].
$P_l^{\exp}, P_l^{\mathrm{imp}}$	Power "exported from"/"imported to" distribution network electricity market (DNEM) by LA l [MW].
R_j	Payoff function of GENCO j [$].
R_m	Payoff function of microgrid m [$].
R_l, R_l'	Payoff function of LA l in the DNEM/wholesale electricity market (WEM) [$].
$\boldsymbol{\rho}_m, \boldsymbol{\rho}_l$	Bidding vector of microgrid m/LA l in the DNEM [$/MW].
$\boldsymbol{\rho}_j', \boldsymbol{\rho}_l'$	Bidding vector of GENCO j/LA l in the WEM [$/MW].
$\boldsymbol{\psi}_m, \boldsymbol{\psi}_l$	Bidding strategy vector of microgrid m/LA l in the DNEM.
$\boldsymbol{\psi}_j', \boldsymbol{\psi}_l'$	Bidding strategy vector of unit j of GENCO i/LA l in the WEM.
$\boldsymbol{\tau}', \boldsymbol{\varphi}'$	Vector of slack variables.
$\boldsymbol{\theta}', \boldsymbol{\pi}', \boldsymbol{\theta}, \boldsymbol{\pi}$	Vector of Lagrangian multipliers.
$\lambda_0, \lambda_0', \lambda_b'^{+}, \lambda_b'^{-}$	Lagrange multipliers.

Constants

B_j^o, B_l^o	Set of buses o corresponds to the market participants j and l.
$\bar{F}_b, \underline{F}_b$	Minimum/maximum limits for power flow in branch b [MW].
$\mathbf{I}$	Identity matrix.
P^D	Total demand in the distribution network [MW].
$P_o'^D$	Demand on bus o in the WEM [MW].
$\bar{P}_l^{\exp}, \underline{P}_l^{\exp}$	Minimum/maximum power exported from the DNEM by LA l [MW].
$\bar{P}_l^{\mathrm{imp}}, \underline{P}_l^{\mathrm{imp}}$	Minimum/maximum power imported to the DNEM by LA l [MW].
$\bar{P}_{(.)}, \underline{P}_{(.)}$	Minimum/maximum generation dispatch [MW].
SF_b^o	Shift factor of branch b with respect to injection at bus o.
$\alpha_{(.)}, \beta_{(.)}, \gamma_{(.)}$	Coefficients for generation cost function.
$\underline{\boldsymbol{\psi}}_{(.)}, \bar{\boldsymbol{\psi}}_{(.)}$	Upper/lower limit of the bidding strategy vector in the DNEM.
$\underline{\boldsymbol{\psi}}'_{(.)}, \bar{\boldsymbol{\psi}}'_{(.)}$	Upper/lower limit of the bidding strategy vector in the WEM.

Manuscript received November 30, 2014; revised March 9, 2015 and April 13, 2015; accepted April 21, 2015. Date of publication May 25, 2015; date of current version June 17, 2016. Paper no. TSG-01181-2014.

The authors are with the Department of Electrical Engineering, Southern Methodist University, Dallas, TX 75205 USA (e-mail: manshadi@smu.edu; mkhodayar@lyle.smu.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2015.2428194

I. INTRODUCTION

DEVELOPING the hierarchal market structure composed of generation entities and demand aggregators facilitates the participation of small demand entities and end customers in the electricity market. With the advent of active distribution networks with distributed energy resources, responsive demands, and intelligent controls, there is a concern on the increased number of intelligent supply and demand entities in the distribution network that affects the WEM operation. Scheduling of such entities by independent system operator (ISO) will increase the scale of the day-ahead and real-time scheduling problem and corresponding computational burden. Moreover, the competition among these entities is not fully addressed as a result technical limitations and lack of effective business model in this paradigm. This paper proposed a framework to facilitate competition among larger number of market participants in the WEM and the DNEM. The presented framework is further extendable to support the participation of microgrids in the WEMs. LAs were considered as intermediate agents between the utility operator and consumers to perform demand response in [1]–[3]. While the proposed structures addressed the interaction between the customers and aggregators who respond to the price of electricity, the pricing scheme does not reflect the synergy between the utility grid, aggregator, and the customers. As microgrids are deployed in low or medium voltage distribution networks, they exchange energy with the main grid through an aggregator which represents the middle agent who interacts with the microgrid and the WEM. Distribution companies (DISCOs) participate in the WEM and the DNEM and interact with GENCOs, distributed generations (DG), and interruptible loads (IL). DISCOs bid for energy and ancillary services in the WEMs [4]–[9]. DGs and ILs controlled by DISCOs will benefit from participating in electricity markets while DISCOs are considered as agents with no financial benefits in [5] and [6]. A multiperiod framework for participating DISCO in day-ahead electricity market is proposed in [7] using bi-level optimization technique to maximize the DISCOs profit while minimizing the operation cost of the system. A framework to facilitate the participation of DISCOs in a day-ahead bi-lateral and pool energy markets is presented in [8]. In these publications, the interaction between DGs, ILs, and DISCOs through competition was not addressed. In [9], the synergy between DISCOs and GENCOs is considered in the WEM where DISCOs bid based on the available capacities of DGs and ILs, and GENCOs bid based on the marginal cost of the generators owned. DISCO can also participate in the DNEM operated by the distribution network operator (DNO) [10]. Here, the interaction between DISCOs and GENCOs in the WEM is not considered. The synergy between DERs and demand resources within the microgrids with the energy service providers, who participate in the energy market is addressed in [11], while the interaction between the WEM and local DNEM is ignored. Several research efforts presented frameworks for the participation of microgrids and DISCOs in a competitive electricity market by a two-stage hierarchical optimization framework for the day-ahead and real-time electricity markets [12]–[14]. However, the impact of the microgrids on the locational marginal prices (LMPs) of electricity in the WEM was not addressed.

The synergy between the microgrids and the WEM to maximize the social welfare is presented in [15]. The electricity market is represented by randomize auction framework ignoring the role of "microgrid aggregators" as a broker with respective bidding strategies. Direct participation of microgrids in the WEM is not applicable for the following reasons: 1) technical limitations on voltage levels, generation, and demand capacity; 2) lack of an efficient business model and technical infrastructure to provide microgrids with access to open access same-time information system and open access nondiscriminatory transmission services; 3) shortage in an efficient framework to evaluate the potential services provided by microgrids in the WEM; and 4) increase in the number of microgrids, with diverse capacities and coverage areas; and the technical restraints on transmitting electricity to the bulk power network including congestion and voltage constraints [16], [17].

A system of system framework is proposed in [18] to address the interaction between the DISCOs and microgrids as independent systems, which exchange energy. The proposed approach addressed the optimal operation of the distribution network and does not consider any interaction between DGs and DISCOs to maximize the agent's payoff in the WEM or the DNEM. In the coordinated energy management structure presented in [19], microgrids and the DNO exchange electricity to minimize their operation cost, while the DNO exchanges electricity with the WEM. However, the electricity prices are considered as parameters in the coordinated energy management structure. Hence, no mechanism is proposed to represent the simultaneous active participation of LAs in the DNEM and the WEM.

In this paper, LAs are considered as brokers who participate in the DNEM, which is cleared by the DNO as well as the WEM settled by the ISO. Introducing LAs in the proposed framework reduces the number of market participants in the WEM and promotes the competition among participants in the WEM and the DNEM. Here, DGs and ILs are merged to form microgrids and the new market paradigm facilitates the participation of multiple microgrids in the WEM. In the proposed hierarchical market structure, each market participant will categorize the unknown strategies and information correspond to other market participants by realizing several "types," which eventually would transform the incomplete information game into a complete information game with imperfect information using the joint probability distribution function to address the uncertainties associate with the types of market participants. In this paper, the complete information game between the market participants is presented and the incomplete information game is considered as an extension to the proposed approach. The main contributions of this paper are summarized as follows.

1) The synergies between the WEM and the DNEM are presented. In this paradigm, each LA is an intermediate agent that participates in the WEM and the DNEM. Hence, the strategy chosen in one market would impact the strategy taken in the other.
2) The proposed hierarchical electricity market structure provides the required infrastructure for microgrids to participate in energy market in the distribution and transmission networks, without increasing the computational burden on the ISO associated with the increased number of market participants.

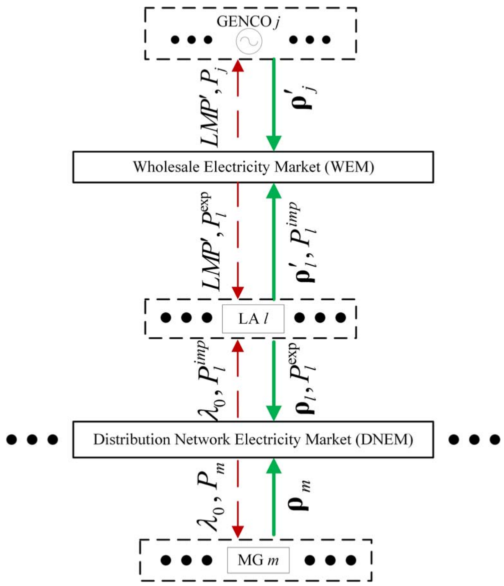

Fig. 1. Hierarchical electricity market structure.

3) The proposed hierarchical market structure is an application of dynamic game to facilitate the synergy between multiple electricity markets, where the WEM interacts with the DNEM [20], [21].

Fig. 1 shows the proposed hierarchical market structure that composed of these markets. Here, each market participant bids in associated electricity market, while each LA is an intermediate agent that participates in both markets to address the synergy of the two markets. The LA bids in the WEM and presents the awarded dispatch in the DNEM as demand on its bus in the WEM. The ISO clears the market and provide the awarded dispatch for the LA and LMP at the LAs bus. The LA bids in the DNEM and presents the awarded dispatch in the WEM as demand on its bus in the DNEM. The DNO clears the market and provide the awarded dispatch for the LA and the market clearing price (MCP) of the market.

This paper is organized as follows. Section II describes the problem formulation. Section III introduces the proposed multilevel dynamic game with complete information. Section IV presents a case study. Finally, Section V presents the conclusion.

II. Problem Formulation

A method for analyzing the competition among GENCOs in the WEM is described in [22]. The competition is modeled as a bi-level optimization problem in which the upper-level problem represents the profit maximization of the GENCOs and the lower-level problem represents the WEM clearing process. A framework for calculating multiparticipant Nash equilibria in a transmission-constrained electricity market is presented in [23], where the noncooperative complete information game is formulated for market participants with discrete bidding strategies. In this section, the profit maximization problem for each market participant is presented as a mathematical problem with equilibrium constraints (MPECs) which is formulated as a bi-level optimization problem. The upper-level problem addresses the profit maximization while the lower-level problem is the operation cost minimization. The noncooperative complete information game for the WEM and the DNEM is represented as an equilibrium problem with equilibrium constraints (EPECs). An EPEC is formed by several MPECs, in which the lower-level problems are the same for all MPECs. The EPEC renders a generalized Nash equilibrium (GNE) problem as the strategy taken by each market participant is dependent on the decisions made by other participants in the WEM and the DNEM [24]. Hence, the proposed hierarchical market is composed of multiple EPECs in which the equilibrium at one EPEC is dependent on the equilibrium of the other interdependent EPECs.

A. GENCOs Objective

GENCO j maximizes the payoff function which is shown in (1), subjected to the constraints on the bidding vector as shown in (2). The payoff function represents the revenue of GENCO, which is the first term in (1) as well as the generation cost, which is the second term in (1). GENCO maximizes the payoff by proposing the bidding vector, which is formulated in (3)

$$R_j = \max_{P_j, \psi'_j} \left[\sum_{o \in B_j^o} \text{LMP}'_o * P_j - \left(\alpha_j P_j^2 + \beta_j P_j + \gamma_j \right) \right] \quad (1)$$

$$\underline{\boldsymbol{\psi}}'_j \leq \boldsymbol{\psi}'_j \leq \bar{\boldsymbol{\psi}}'_j \quad (2)$$

$$\boldsymbol{\rho}'_j = \boldsymbol{\psi}'_j (2\alpha_j \mathbf{P}_{je} + \beta_j); \sum_e \mathbf{P}_{je} = P_j. \quad (3)$$

B. Microgrids Objective

Microgrid m maximizes the payoff function (4), subjected to the limitations on the bidding vector as shown in (5). Here, the first term in the payoff function is the revenue of the microgrid and the second term is the generation cost. The generation dispatch of microgrids is provided by curtailing the IL and dispatching the DERs. The microgrid may adopt several policies to serve its demand. One policy is to serve local demand and bid the excess generation in the DNEM while the other is to bid on its total generation capacity in the DNEM and serve the local demand economically from the distribution network. In both cases, the bidding vector for generation in microgrid m is shown in (6)

$$R_m = \max_{P_m, \boldsymbol{\psi}_m} \left[\lambda_0 \cdot P_m - \left(\alpha_m P_m^2 + \beta_m P_m + \gamma_m \right) \right] \quad (4)$$

$$\underline{\boldsymbol{\psi}}_m \leq \boldsymbol{\psi}_m \leq \bar{\boldsymbol{\psi}}_m \quad (5)$$

$$\boldsymbol{\rho}_m = \boldsymbol{\psi}_m (2\alpha_m \mathbf{P}_{me} + \beta_m); \sum_e \mathbf{P}_{me} = P_m. \quad (6)$$

Here, λ_0 is the Lagrangian multiplier associated with the generation and load balance constraint within the distribution network.

C. LAs Objective

Each LA participates in the WEM and the DNEM. The LA acts as a broker playing two different roles: 1) buy electricity from the WEM and sell the same volume to the DNEM, if the LMP on the LAs bus in the WEM is lower than that in the DNEM; and 2) purchase electricity from the DNEM and sell the same volume to the WEM, if the MCP in the DNEM is lower than the LMP on the LAs bus in the WEM.

Considering role "1," LA l maximizes the payoff function which is shown in (7), subjected to the bidding vector constraint (8). Here, LMP' is the marginal price of electricity on the LAs bus in the WEM which is determined as the cost of providing electricity to the distribution network. The LAs bidding vector in the DNEM is given in (9)

$$R_l = \max_{\psi_l, P_l^{\mathrm{imp}}} \left[\left(\lambda_0 - \sum_{o \in B_l^o} \mathrm{LMP}'_o \right) P_l^{\mathrm{imp}} \right] \tag{7}$$

$$\underline{\psi}_l \leq \psi_l \leq \bar{\psi}_l \tag{8}$$

$$\rho_l = \psi_l * \sum_{o \in B_l^o} \mathrm{LMP}'_o \tag{9}$$

$$R'_l = \max_{\psi'_l, P_l^{\mathrm{exp}}} \left[\left(\sum_{o \in B_l^o} \mathrm{LMP}'_o - \lambda_0 \right) P_l^{\mathrm{exp}} \right] \tag{10}$$

$$\underline{\psi}'_l \leq \psi'_l \leq \bar{\psi}'_l \tag{11}$$

$$\rho'_l = \psi'_l * \lambda_0. \tag{12}$$

Considering role "2," the LA l maximizes the payoff function which is shown in (10), subjected to the constraints on the bidding vector (11). The MCP (λ_0) in the DNEM is the marginal cost of providing electricity to the WEM. The bidding vector of LA l in the WEM is shown in (12).

D. WEM Clearing Process

In the WEM, the ISO minimizes the operational cost subjected to generation and transmission network constraints. The WEM clearing problem is formulated as

$$\min \quad \sum_j \rho'_j * P_j + \sum_l \rho'_l * P_l^{\mathrm{exp}} \tag{13}$$

$$\text{s.t.} \quad \sum_j P_j + \sum_l P_l^{\mathrm{exp}} = \sum_o P_o^{\prime D} + \sum_l P_l^{\mathrm{imp}} \quad \lambda'_0 \tag{14}$$

$$\underline{F}_b \leq \left(\sum_{o \in B_j^o} \mathrm{SF}_b^o . P_j + \sum_{o \in B_l^o} \mathrm{SF}_b^o . P_l^{\mathrm{exp}} \right) - \mathrm{SF}_b^o . P_o^D - \sum_{o \in B_l^o} \mathrm{SF}_b^o . P_l^{\mathrm{imp}} \leq \bar{F}_b \quad \forall b, \ \left(\lambda_b^{\prime +}, \lambda_b^{\prime -}\right) \tag{15}$$

$$\underline{P}_j \leq P_j \leq \bar{P}_j \qquad \forall j \tag{16}$$

$$\underline{P}_l^{\mathrm{exp}} \leq P_l^{\mathrm{exp}} \leq \bar{P}_l^{\mathrm{exp}} \qquad \forall l \tag{17}$$

$$\mathrm{LMP}'_o = \lambda'_0 + \sum_b \left(\mathrm{SF}_b^o\right)^T \cdot \left(\lambda_b^{\prime +} - \lambda_b^{\prime -}\right). \tag{18}$$

The objective function which is shown in (13), is the operation cost of the system which includes the awarded dispatch of market participants multiplied by their bids. The load balance constraint is shown in (14). The transmission line capacity constraint is shown in (15). The generation capacity constraint is shown in (16), and the limitation on the electricity exported by each LA is shown in (17). As shown in (18), the Lagrangian multipliers associated with the load balance and transmission line capacity constraints are employed to calculate the LMPs on each bus in the WEM.

E. DNEM Clearing Process

The DNO minimizes the operational cost of distribution network as shown by

$$\min \quad \sum_m \rho_m * P_m + \sum_l \rho_l * P_l^{\mathrm{imp}} \tag{19}$$

$$\text{s.t.} \quad \sum_m P_m + \sum_l P_l^{\mathrm{imp}} = P^D + \sum_l P_l^{\mathrm{exp}} \quad \lambda_0 \tag{20}$$

$$\underline{P}_m \leq P_m \leq \bar{P}_m \qquad \forall m \tag{21}$$

$$\underline{P}_l^{\mathrm{imp}} \leq P_l^{\mathrm{imp}} \leq \bar{P}_l^{\mathrm{imp}} \quad \forall l. \tag{22}$$

The load balance in the distribution network is shown in (20). The constraints on the awarded generation for microgrids and the imported power by the LA are shown in (21) and (22), respectively. Here, λ_0 is the Lagrangian multiplier for the generation and load balance constraint in the distribution network as it is assumed that the electricity delivery is not limited by the line congestions.

III. Multilevel Complete Information Game

In case of competition with complete information, each market participant recognizes the opponents' payoff functions and bidding strategies. Hence, the WEM clearing problem which is shown in (13)–(17), and the DNEM clearing problem which is shown in (19)–(22), are linear programming problems that are rewritten in general form as

$$\min \quad \mathbf{c}'^{\mathbf{T}} \mathbf{x}' \tag{23}$$

$$\text{s.t.} \quad \mathbf{A}'\mathbf{x}' = \mathbf{b}' \qquad \boldsymbol{\pi}' \tag{24}$$

$$\underline{\mathbf{x}}' \leq \mathbf{x}' \leq \bar{\mathbf{x}}' \qquad \boldsymbol{\theta}' \tag{25}$$

$$\min \quad \mathbf{c}^{\mathbf{T}} \mathbf{x} \tag{26}$$

$$\text{s.t.} \quad \mathbf{A}\mathbf{x} = \mathbf{b} \qquad \boldsymbol{\pi} \tag{27}$$

$$\underline{\mathbf{x}} \leq \mathbf{x} \leq \bar{\mathbf{x}} \qquad \boldsymbol{\theta}. \tag{28}$$

The bi-level problem for GENCO j is composed of the upper-level problem, i.e., the payoff maximization, which is shown in (1) and (2); and the lower-level problem, which is shown in (23)–(25). Accordingly, the bi-level problem for microgrid m is composed of the upper-level problem, which is shown in (4) and (5); and the lower-level problem, which is shown in (26)–(28).

Since the LA l participates in multiple markets, if the LA plays role "1" the upper-level problem is the payoff maximization problem which is shown in (7) and (8) and the lower-level problem is shown in (26)–(28). If the LA plays role "2" the upper-level problem is shown in (10) and (11) and the lower-level problem is shown in (23)–(25). In the three types of the bi-level problems presented, the upper-level problems are the payoff maximization of the GENCOs, microgrids, and LAs while the lower-level problems represent the operation cost minimization by the ISO or the DNO, subjected to the prevailing constraints. The proposed bi-level problems are solved for the market participants in the WEM and the DNEM simultaneously to determine the bidding strategies of market participants in the respective markets. In this paradigm, microgrids and LAs participate in the DNEMs while GENCOs and LAs bid in the WEM. Each LA which links the upper level market (WEM) and the lower level market (DNEM), determines its bidding strategy and role based on the outcomes of each electricity market. The interaction between the market participants in the WEM and the DNEM continues until none of the market participants in both markets would update their bidding strategies. The synergy between the market participants in the WEM and the DNEM is presented as Cournot game while the interaction between the WEM and the DNEMs is presented as a dynamic game. Here, microgrids, GENCOs, and LAs update their bidding strategies, based on the sensitivity of the payoff function to the bidding strategy chosen. Considering the WEM, the bi-level linear problems are converted into single level nonlinear problems using the Karush–Kuhn–Tucker (KKT) optimality conditions for the lower-level problems. Assuming that the lower bound of inequality (25) is zero, the KKT optimality conditions for (23)–(25) are presented in (29)–(34). Here, $\mathbf{X}' = \mathrm{Diag}(\mathbf{x}')$, $\mathbf{\Phi}' = \mathrm{Diag}(\boldsymbol{\varphi}')$, $\mathbf{T}' = \mathrm{Diag}(\boldsymbol{\tau}')$, and $\mathbf{\Theta}' = \mathrm{Diag}(\boldsymbol{\theta}')$

$$\mathbf{A}'^{\mathbf{T}}\boldsymbol{\pi}' + \boldsymbol{\tau}' - \boldsymbol{\theta}' = \mathbf{c}' \tag{29}$$

$$\mathbf{A}'\mathbf{x}' = \mathbf{b}' \tag{30}$$

$$\mathbf{x}' + \boldsymbol{\varphi}' = \overline{\mathbf{x}}' \tag{31}$$

$$\mathbf{X}'\boldsymbol{\tau}' = \mathbf{0} \tag{32}$$

$$\mathbf{\Phi}'\boldsymbol{\theta}' = \mathbf{0} \tag{33}$$

$$\left(\mathbf{x}', \boldsymbol{\tau}', \boldsymbol{\theta}', \boldsymbol{\varphi}'\right) \geq \mathbf{0}. \tag{34}$$

By differentiating (29)–(34) with respect to the GENCOs' and LAs' bidding vector components, the equality (35) is obtained.

Here, the coefficient on the left-hand side and the term on the right-hand side of the system of equations (35) are $\mathbf{H}'$ and $d\mathbf{c}'$, respectively. In (35), $\mathbf{H}'$ is a low rank sparse matrix, and once the least-square technique [25] is employed to solve this system of nonlinear equations, the sensitivity function vector denoted as $d\mathbf{z}' = [\partial\boldsymbol{\pi}'/\partial\boldsymbol{\psi}'\ \partial\mathbf{x}'/\partial\boldsymbol{\psi}'\ \partial\boldsymbol{\tau}'/\partial\boldsymbol{\psi}'\ \partial\boldsymbol{\theta}'/\partial\boldsymbol{\psi}']^T$ is given as (36)

$$\begin{bmatrix} \mathbf{A}'^T & \mathbf{0} & \mathbf{I} & -\mathbf{I} \\ \mathbf{0} & \mathbf{A}' & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{T}' & \mathbf{X}' & \mathbf{0} \\ \mathbf{0} & -\mathbf{\Theta}' & \mathbf{0} & \mathbf{\Phi}' \end{bmatrix} \begin{bmatrix} \frac{\partial \boldsymbol{\pi}'}{\partial \boldsymbol{\psi}'} \\ \frac{\partial \mathbf{x}'}{\partial \boldsymbol{\psi}'} \\ \frac{\partial \boldsymbol{\tau}'}{\partial \boldsymbol{\psi}'} \\ \frac{\partial \boldsymbol{\theta}'}{\partial \boldsymbol{\psi}'} \end{bmatrix} = \begin{bmatrix} \frac{\partial \mathbf{c}'}{\partial \boldsymbol{\psi}'} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} \tag{35}$$

$$d\mathbf{z}' = \mathbf{H}'^T\left(\mathbf{H}'\mathbf{H}'^T\right)^{-1} d\mathbf{c}'. \tag{36}$$

In the proposed iterative approach, the payoff of each market participant is maximized by calculating $d\mathbf{z}'$ from (36) iteratively. The sensitivity functions calculated in (36) are employed in (37), (38), (41), and (42) to acquire the sensitivity of the payoff of each market participant with respect to its bidding strategy at each iteration. The sensitivity of the payoff of GENCO j with respect to the bidding strategy chosen is shown in (37). Other components in (37) were calculated in (38)–(40)

$$\frac{\partial R_j^k}{\partial \psi_j'^k} = \frac{\partial R_j^k}{\partial P_j^k}\frac{\partial P_j^k}{\partial \psi_j'^k} + \frac{\partial R_j^k}{\partial \mathrm{LMP}_o'^k}\frac{\partial \mathrm{LMP}_o'^k}{\partial \psi_j'^k} \quad \forall j \in B_j^o \tag{37}$$

$$\frac{\partial \mathrm{LMP}_o'^k}{\partial \psi_j'^k} = \frac{\partial \lambda_0'^k}{\partial \psi_j'^k} + \sum_b \mathrm{SF}_b^o \cdot \left(\frac{\partial \lambda_b'^{+,k}}{\partial \psi_j'^k} - \frac{\partial \lambda_b'^{-,k}}{\partial \psi_j'^k}\right) \quad \forall j \in B_j^o \tag{38}$$

$$\frac{\partial R_j^k}{\partial P_j^k} = \mathrm{LMP}_o'^k - \left(2\alpha_j P_j^k + \beta_j\right) \quad \forall j \in B_j^o \tag{39}$$

$$\frac{\partial R_j^k}{\partial \mathrm{LMP}_o'^k} = P_j^k \qquad \forall j \in B_j^o. \tag{40}$$

Similar formulation is applied for microgrid m in the DNEM, with respective variables and indices. For LA l with bidding strategy $\psi_l'^k$, the sensitivity of the payoff with respect to the bidding strategy chosen, is shown in (41). The components which are shown in (41) are calculated in (42)–(44)

$$\frac{\partial R_l^{\exp,k}}{\partial \psi_l'^k} = \frac{\partial R_l^{\exp,k}}{\partial P_l^{\exp,k}}\frac{\partial P_l^{\exp,k}}{\partial \psi_l'^k} + \frac{\partial R_l^{\exp,k}}{\partial \mathrm{LMP}_o'^k}\frac{\partial \mathrm{LMP}_o'^k}{\partial \psi_l'^k} \quad \forall l \in B_l^o \tag{41}$$

$$\frac{\partial \mathrm{LMP}_o'^k}{\partial \psi_l'^k} = \frac{\partial \lambda_0'^k}{\partial \psi_l'^k} + \sum_b \mathrm{SF}_b^o\left(\frac{\partial \lambda_b'^{+,k}}{\partial \psi_l'^k} - \frac{\partial \lambda_b'^{-,k}}{\partial \psi_l'^k}\right) \forall l \in B_l^o \tag{42}$$

$$\frac{\partial R_l^{\exp,k}}{\partial P_l^{\exp,k}} = \mathrm{LMP}_o'^k - \lambda_0^k \quad \forall l \in B_l^o \tag{43}$$

$$\frac{\partial R_l^{\exp,k}}{\partial \mathrm{LMP}_o'^k} = P_l^{\exp,k} \qquad \forall l \in B_l^o. \tag{44}$$

Similar formulation is applied for LA l importing power to the distribution network. Here, (45) and (46) are employed for updating the bidding strategies of GENCOs and LAs in the WEM, respectively, and δ is the constant for each step. Similar formulation is applied for updating the bidding strategies of microgrids and LAs importing power to the distribution network

$$\psi_j'^{k+1} = \psi_j'^k + \delta\frac{\partial R_j^k}{\partial \psi_j'^k} \tag{45}$$

$$\psi_l'^{k+1} = \psi_l'^k + \delta\frac{\partial R_l^{\exp,k}}{\partial \psi_l'^k}. \tag{46}$$

The presented game is considered as a dynamic game as the LAs observe the actions of other market participants in one market before updating their bidding strategy in the other. Here, LAs consider the decision made by GENCOs once bidding in the DNEM. Similarly, LAs observe the decision made by microgrids once bidding in the WEM. The bidding vector of LAs in each market is determined based on the awarded dispatch and the price of electricity at the LAs' bus in the other market. The observability indicator v is a binary parameter, which indicates that the LAs observed the actions of participants in the other market at each iteration. The bidding strategy of market participants update iteratively until the convergence

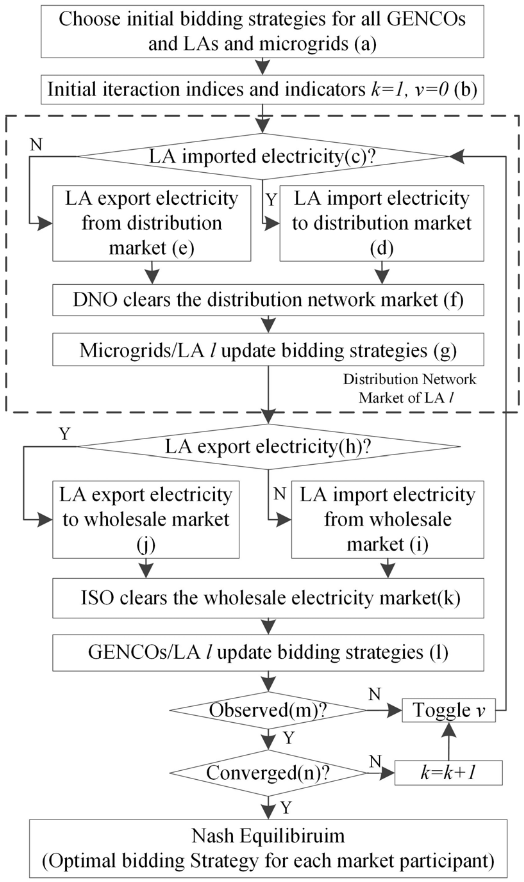

Fig. 2. Competition in the hierarchical electricity market.

criteria are satisfied and the GNE is established. The presented game may have one, multiple or no GNE. However, the market regulations will limit the bidding strategy of market participants and improve convergence to a state in which the market participants are either unwilling to unilaterally update their bidding strategy or they cannot do so. As illustrated in Fig. 2, the steps a)–n) are taken to procure the GNE of the proposed dynamic game. While multiple LAs could participate in the WEM, for the sake of simplicity, only one LA (LA l) is considered in this algorithm. The following approach can be extended to address multiple LAs in multiple DNEMs.

a) Set the initial value of power import/export of the LA to zero with respective arbitrary large initial marginal costs and initiate $\psi_j'^0$, ψ_m^0, $\psi_l'^0$, ψ_l^0 for each generator, microgrid, and LA; then go to "b."
b) Set the iteration indices $k = 1$ and LAs observability indicator $v = 0$; then go to "c."
c) If the inequality (47) holds LA imports electricity to DNEM; then go to "d." Otherwise go to "e"

$$P_l^{\text{imp},k-1+v} > P_l^{\text{exp},k-1+v}. \quad (47)$$

d) Set the parameters using (48)–(50) for the DNEM while the LAs role is to import electricity to this market; then go to "f"

$$\text{LMP}_o'^k = \text{LMP}_o'^{k-1+v} \quad (48)$$
$$\bar{P}_l^{\text{imp},k} = P_l^{\text{imp},k-1+v} - P_l^{\text{exp},k-1+v} \quad (49)$$
$$P_l^{\text{exp},k} = 0. \quad (50)$$

e) Set the parameters using (48), (51), and (52) for DNEM while LAs role is to export electricity from this market; then go to "f"

$$\bar{P}_l^{\text{imp},k} = \bar{P}_l^{\text{imp},k-1+v} \quad (51)$$
$$P_l^{\text{exp},k} = P_l^{\text{exp},k-1+v}. \quad (52)$$

f) DNO clears DNEM; then go to "g."
g) The bidding strategy of microgrids and LA l within the distribution network are updated using the sensitivity functions of their payoff with respect to their bidding strategy; then go to "h."
h) If the inequality (53) holds, LA exports electricity to the WEM; then go to "i." Otherwise go to "j"

$$P_l^{\text{imp},k} < P_l^{\text{exp},k-1+v}. \quad (53)$$

i) Set the parameters using (54)–(56) for the WEM while LAs role is to export electricity to the WEM; then go to "k"

$$\lambda_0^k = \lambda_0^{k-1+v} \quad (54)$$
$$\bar{P}_l^{\text{exp},k} = P_l^{\text{exp},k-1+v} - P_l^{\text{imp},k} \quad (55)$$
$$P_l^{\text{imp},k} = 0. \quad (56)$$

j) Set the parameters using (54) and (57) for the WEM while LAs role is to import electricity from the WEM; then go to "k"

$$\bar{P}_l^{\text{exp},k} = \bar{P}_l^{\text{exp},k-1+v}. \quad (57)$$

k) ISO clears the WEM; then go to "l."
l) The bidding strategy of the GENCOs and LA l within the WEM are updated using the sensitivity functions of their payoff with respect to their bidding strategy; then go to "m."
m) Check if the observability indicator is equal to 1.0, go to "n." Otherwise, toggle the observability indicator go to "c."
n) If the conditions (58), (59) hold for all market participants in the WEM and DNEM, then GNE is established; otherwise, set $k = k + 1$, set the observability indicator to zero, and go to "c"

$$\left|\psi_{(.)}^k - \psi_{(.)}^{k-1}\right| \le \varepsilon \quad (58)$$
$$\left|\psi_{(.)}'^k - \psi_{(.)}'^{k-1}\right| \le \varepsilon. \quad (59)$$

Assuming the existence of an equilibrium, convergence to different local equilibriums depends on the initial bidding strategies. As the feasible region for each market participant is nonconvex, the equilibrium among MPECs represent a local optimum solution. In [26], the MPECs are rewritten as a mathematical problem with primal dual constraints (MPPDCs). Considering fixed dual variable associated with the strong duality constraint of the MPPDC, the EPEC is further formulated as a parameterized mixed-integer linear problem (MILP). The solution of the MILP is a local Nash equilibrium or a saddle point depending on the choice of the fixed dual variable. In [27], the existence of a unique equilibrium under certain assumptions is proved, while the existence and uniqueness of

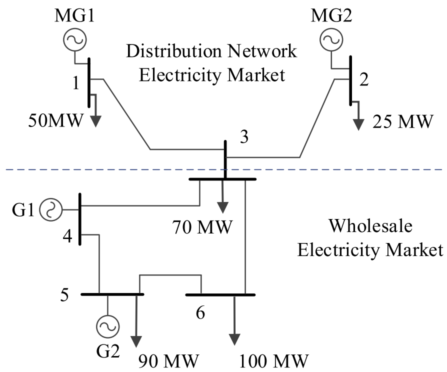

Fig. 3. Power network topology.

TABLE I
TRANSMISSION AND DISTRIBUTION NETWORK DATA

Line	From bus	To bus	Reactance (p.u)	Capacity limit (MW)
L1	3	4	0.0098	160
L2	4	5	0.0105	250
L3	5	6	0.02	190
L4	6	3	0.01	130
L5	1	3	0.005	100
L6	2	3	0.008	90

TABLE II
GENERATION COST CURVE OF MICROGRIDS AND GENCOs

Market Participant	Min. capacity (MW)	Max. capacity (MW)	α (\$/MW^2)	β (\$/MW)	γ (\$)
MG1	0	60	0.125	25	0
MG2	0	60	0.250	20	0
G1	0	210	0.073	6.926	0
G2	0	210	0.066	7.352	0

an equilibrium is proved in [28] by relaxing some constraints. The alternative method to the sensitivity function employed in this paper, is to reformulate the problem in to nonlinear complementarity problem [29], [30].

IV. CASE STUDY

In order to evaluate the effectiveness of the proposed approach, a WEM with two generators, and one DNEM including two microgrids and one LA are considered. Fig. 3 shows the proposed network configuration. Here, the DNEM and the WEM have the total demand of 75 and 260 MW, respectively.

Table I shows the network data for both electricity markets. The coefficients of the generation cost curve for GENCOs and microgrids are shown in Table II. As shown in this table, the marginal cost of electricity generation for the microgrids is higher than that for the GENCOs. The lower and upper limits for the bidding strategy vector for market participants are 0.5 and 4.0, respectively. The lower limit for the bidding strategy of LA is 1.0. The initial bidding strategy for LA is set to 1.0. The multiplier δ and the threshold for convergence ε are set to be 1E-5 and 1E-4, respectively. The initial marginal cost of LA in the WEM and DNEM is 1000 \$/MWh.

TABLE III
BIDDING STRATEGY AND AWARDED DISPATCH IN CASE 1

	MG1	MG2	LA	G1	G2
Bidding Strategy	3.74	4	1.05 (imports power)	3.64	4
Awarded Dispatch (MW)	40	20	15	140	135

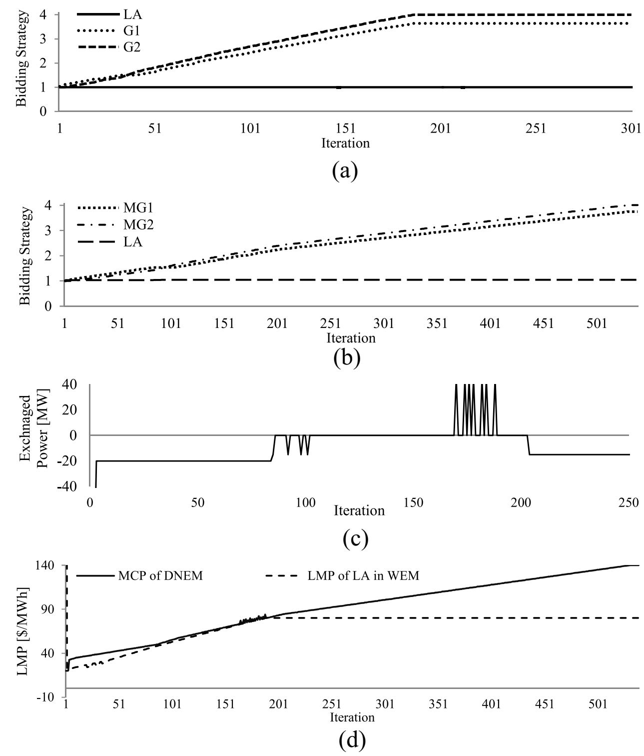

Fig. 4. Bidding strategies of market participants, exchanged power, and energy price in case 1. (a) Bidding strategy of market participants in the WEM. (b) Bidding strategy of market participants in the DNEM. (c) Exchanged power for the LA (negative/positive values represent imported power to/exported power from the DNEM). (d) LMP of LAs bus in the WEM and MCP of DNEM.

The following three cases are presented.

Case 1) Higher marginal cost of electricity in microgrids with no congestion in the wholesale electricity market.

Case 2) Higher marginal cost of electricity in micro-grids with congestion in the wholesale electricity market.

Case 3) Lower marginal cost of electricity in microgrids with no congestion in the wholesale electricity market.

Case 1) Higher Marginal Cost of Electricity in Microgrids With No Congestion in the Wholesale Electricity Market: In this case, the microgrids provide higher marginal cost for electricity compared to the GENCOs as shown in Table II. The bidding strategies and the awarded dispatches for each market participant are listed in Table III. Since there is no congestion in the WEM, the MCP is 80 \$/MWh, while the MCP in the DNEM is 140 \$/MWh. In this case, the lower price of electricity in the WEM provides incentives for the LA to import electricity from this market to the DNEM. The payoff of MG1, MG2, LA, G1, and G2 are \$4400, \$2300,

TABLE IV
BIDDING STRATEGY AND AWARDED DISPATCH IN CASE 2 (L1 IS CONGESTED)

	MG1	MG2	LA	G1	G2
Bidding Strategy	1	4	4 (exports power)	4	4
Awarded Dispatch (MW)	60	42.25	27.25	210	22.75

TABLE V
BIDDING STRATEGY AND AWARDED DISPATCH IN CASE 2 (L4 IS CONGESTED)

	MG1	MG2	LA	G1	G2
Bidding Strategy	4	2.89	1.02 (imports power)	4	4
Awarded Dispatch (MW)	20	40	15	157.48	117.52

TABLE VI
BIDDING STRATEGY AND AWARDED DISPATCH IN CASE 3

	MG1	MG2	LA	G1	G2
Bidding Strategy	1.75	4	1 (exports power)	3.64	4
Awarded Dispatch (MW)	60	60	45	140	75

\$900, \$8800, and \$8604, respectively. Hence, the LA spent \$1200 to purchase 15 MW electricity and earned \$2100 by selling the same volume in the DNEM. The exchanged power, the LMP, and the bidding strategies of the market participants in the WEM and the DNEM are illustrated in Fig. 4.

In the first iteration an arbitrary large number is assigned as the LMP at the LAs bus in the WEM (1000 \$/MWh) and LA bids into the DNEM based on the assigned LMP at the WEM. The awarded dispatch imported to DNEM and the MCP at the DNEM is determined. As shown in Fig. 4(a), in iterations 2–36, the bidding strategy of G1 is greater than G2, which in turn is greater than the bidding strategy of the LA in the WEM. Similarly, as shown in Fig. 4(b), the bidding strategy of MG1 is greater than that of MG2, which in turn is greater than the bidding strategy of the LA in the DNEM. As shown in Fig. 4(c) and (d), the LA is awarded 20 MW in the DNEM and the MCP in the DNEM is significantly larger than the LMP at LAs bus in the WEM. At iteration 95, the LMP at the LAs bus in the WEM becomes closer to the MCP of DNEM which would lead to zero power import by the LA in the DNEM. As the demand in the DNEM is inelastic to the MCP, MG1 bids lower than MG2 to increase the generation in the DNEM as shown in Fig. 4(b). At iteration 171, the LMP at the LAs bus in the WEM is larger than that in the DNEM which inspires the LA to export electricity from the DNEM as illustrated in Fig. 4(a). However, the response of the GENCOs to such decision will alter the exported dispatch of the LA in the WEM.

At iteration 189, G2 reaches the upper limit of the bidding strategy regulated by the market rules. In response, the bidding strategy of G1 reaches 3.64, and the LMP of LAs bus in the WEM will be 80 \$/MWh as shown in Fig. 4(a) and (d). Ultimately, the LA is awarded 15 MW in the DNEM at iteration 204, as the MCP at the DNEM is higher than the LMP of LAs bus at the WEM. This situation continues until MG2 reaches its highest possible bidding strategy (i.e., 4.0) limited by the market regulation. As illustrated in Fig. 4(b), the bidding strategy of MG1 reaches 3.74, and the MCP of DNEM becomes 140 \$/MWh.

Case 2) Higher Marginal Cost of Electricity in Microgrids With Congestion in the Wholesale Electricity Market: In this case, the impact of transmission line congestion is considered in two different cases.

A. Congestion in Line 1

In this case, the capacity limit of line L1 is set to 70 MW. Because of the congestion on L1, the LMP on bus 3 in the WEM is increased to 841.20 \$/MWh while the MCP in the DNEM is 180 \$/MWh. This would provide incentives for the LA to export 27.25 MW from the DNEM to the WEM. As listed in Table IV, G2 is only awarded 22.75 MW with the LMP equal to 48 \$/MWh, while G1, is awarded its maximum generation capacity of 210 MW with the LMP equal to 253.78 \$/MWh on bus 4. In this case MG1s strategy is to sell more electricity with lower price while MG2s strategy is to sell less electricity with higher price. The payoff of MG1, MG2, LA, G1, and G2 are \$8850, \$6313, \$18 802, \$48 620, and \$886, respectively. Here, the payoff of G2 decreased dramatically compared to that in case 1, as a result of congestion while the payoffs of other market participants especially G1 and LA were increased.

B. Congestion in Line 4

In this case, the capacity limit of line L4 is set to 30 MW. As a result of the congestion on line L4, the LMP on bus 3 in the WEM is 72.53 \$/MWh which is lower than that in case 1. The awarded dispatch for the LA in the DNEM is 15 MW. The imported electricity to the DNEM mitigates the congestion on line L4 in the transmission network, and the LA has the incentive to increase the electricity import to the DNEM to reduce the LMP at bus 3 in the WEM.

Here, the MCP in the DNEM is 130 \$/MWh, which is lower than that in case 1. As shown in Table V, G2 is awarded 117.52 MW with the LMP equal to 80 \$/MWh while G1 is awarded 157.48 MW with the LMP equal to 88 \$/MWh as a result of congestion on line L4. MG1 and MG2 were awarded 20 and 40 MW in the DNEM, respectively. In this case, MG2 proposes lower bid resulting in the increase in its awarded generation and the decrease in the imported power from the WEM. The payoff of MG1, MG2, LA, G1, and G2 are \$2050, \$4000, \$862, \$10 956, and \$7626, respectively. In this case, the payoffs of LA, MG1, and G2 decreased compared to those in case 1, while MG2 and G1 had much higher payoffs as a result of congestion on line 4.

Case 3) Lower Marginal Cost of Electricity in Microgrids With No Congestion in the Wholesale Electricity Market: In this case, the generation costs for microgrids are reduced to 20% of those shown in Table II, which is lower than the marginal costs of GENCOs in the WEM. The bidding strategy and the awarded dispatch for each market participant are listed in Table VI. Here, the LMP at all buses in the WEM is 80 \$/MWh, while the MCP in the DNEM is 36 \$/MWh.

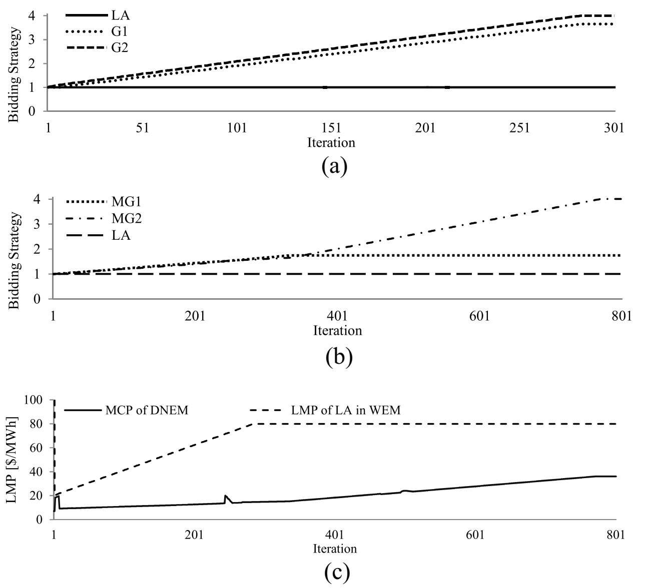

Fig. 5. Bidding strategies of market participants and energy prices in case 3. (a) Bidding strategy of market participants in WEM. (b) Bidding strategy of market participants in DNEM. (c) LMP of LA bus in WEM and MCP of DNEM.

The payoffs of MG1, MG2, LA, G1, and G2 are \$1770, \$1740, \$1980, \$8800, and \$5077, respectively. Here, the LMP at LAs bus in the WEM is higher than the MCP in the DNEM, hence, the LA exports power from the DNEM. Compared to case 1, G1 has the same profit, the profit of G2 is decreased, and the profit of LA is increased. Since the LMP at LAs bus in the WEM is higher than that in the DNEM, the LA exports electricity to the WEM.

Once the market participants bid on their marginal prices of electricity, the payoff of MG1, MG2, LA, G1, and G2 are \$697, \$667, \$84, \$400, and \$577, respectively, and the LMP at all buses in the WEM is 20 \$/MWh and the MCP in the DNEM is 18.12 \$/MWh. In this case, the LA export 45 MW to the WEM. The total payoff of all market participants is decreased by \$15 046 in this case compared to the case in which the market participants bid strategically.

Fig. 5 shows the bidding strategies of the market participants in the WEM and the DNEM, the LMP of LAs bus in the WEM, as well as the MCP of DNEM. Similar to case 1, in the first iteration an arbitrary large number is assigned as the LMP at the LAs bus in the WEM (1000 \$/MWh) and LA bids in the DNEM based on the assigned LMP at WEM. In this case, the awarded dispatch imported to the DNEM is zero and the MCP at DNEM is determined. As shown in Fig. 5(a), in all of the iterations, the bidding strategy of G2 is greater than that of G1, which in turn is greater than the bidding strategy of LA in the WEM. As shown in Fig. 5(b), in iterations 2–353, the bidding strategy of MG1 is close to that of MG2 and the bidding strategies of MG1 and MG2 are greater than the bidding strategy of the LA in the DNEM. As shown in Fig. 5(c), the LMP at LAs bus in the WEM is significantly larger than the MCP in the DNEM, hence, the LA is awarded 45 MW in the WEM. At iteration 283, G2 reaches the upper limit for the bidding strategy regulated by the market. In response, the bidding strategy of G1 reaches 3.64, and the LMP of LAs bus in the WEM will be 80 \$/MWh as shown in Fig. 5(a) and (c). The bidding strategy of MG1 reaches 1.75 in iteration 363. This situation continues until MG2 reaches its highest possible bidding strategy (i.e., 4.0) limited by the market regulation, and the MCP of DNEM becomes 36 \$/MWh, as illustrated in Fig. 5(b).

V. Conclusion

Microgrids are the building blocks of active distribution networks in the smart grid paradigm which provide energy and ancillary services in distribution and WEM. In this paper, the hierarchical market structure for the smart grid paradigm which is composed of the WEM and the DNEM is proposed. Here, the LA represents as the middle agent which participates in the distribution network and the WEMs competing with microgrids and GENCOs. The competition among market participants in both electricity markets with complete information is presented as a dynamic game. The bidding strategy chosen by each market participant is procured using bi-level linear programming problem with the upper-level problem representing the market participant's payoff maximization and the lower-level problem minimizing the operation cost of the network. The bi-level problems are solved by developing sensitivity functions for the market participants' payoff with respect to their bidding strategies. The result shows the impact of LAs bidding strategy on the bidding strategy and payoffs of other market participants in the WEM and the DNEMs. While the noncooperative dynamic game with complete information is proposed in this paper, the proposed approach can be extended to address the noncooperative dynamic game with incomplete information.

References

[1] L. Gkatzikis, I. Koutsopoulos, and T. Salonidis, "The role of aggregators in smart grid demand response markets," *IEEE J. Select. Areas Commun.*, vol. 31, no. 7, pp. 1247–1257, Jul. 2013.

[2] M. Parvania, M. Fotuhi-Firuzabad, and M. Shahidehpour, "Optimal demand response aggregation in wholesale electricity markets," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1957–1964, Dec. 2013.

[3] M. Zugno, J. M. Morales, P. Pinson, and H. Madsen, "A bilevel model for electricity retailers' participation in a demand response market environment," *Energy Econ.*, vol. 36, pp. 182–197, Mar. 2013.

[4] M. Mashhour, M. A. Golkar, and S. M. Moghaddas-Tafreshi, "Extending market activities for a distribution company in hourly-ahead energy and reserve markets—Part I: Problem formulation," *Energy Convers. Manage.*, vol. 52, no. 1, pp. 477–486, Jan. 2011.

[5] H. Haghighat and S. W. Kennedy, "A bilevel approach to operational decision making of a distribution company in competitive environments," *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 1797–1807, Nov. 2012.

[6] M. Doostizadeh and H. Ghasemi, "Day-ahead scheduling of an active distribution network considering energy and reserve markets," *Eur. Trans. Elect. Power*, vol. 23, no. 7, pp. 930–945, 2013.

[7] H. Li, Y. Li, and Z. Li, "A multi-period energy acquisition model for a distribution company with distributed generation and interruptible load," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 588–596, May 2007.

[8] R. Palma-Behnke, J. L. A. Cerda, L. Vargas, and A. Jofre, "A distribution company energy acquisition market model with the integration of distribution generation and load curtailment options," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1718–1727, Nov. 2005.

[9] A. A. Foroud, M. Amirahmadi, M. Bahmanzadeh, and A. A. Abdoos, "Optimal bidding strategy for all market players in a wholesale power market considering demand response programs," *Eur. Trans. Elect. Power*, vol. 21, no. 1, pp. 293–311, 2011.

[10] J. M. López-Lezama, A. Padilha-Feltrin, J. Contreras, and J. I. Muñoz, "Optimal contract pricing of distributed generation in distribution networks," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 128–136, Feb. 2011.

[11] G. E. Asimakopoulou, A. L. Dimeas, and N. D. Hatziargyriou, "Leader-follower strategies for energy management of multi-microgrids," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1909–1916, Dec. 2013.

[12] H. Kim and M. Thottan, "A two-stage market model for microgrid power transactions via aggregators," *Bell Labs Tech. J.*, vol. 16, no. 3, pp. 101–107, Nov. 2011.

[13] A. A. S. Algarni and K. Bhattacharya, "A generic operations framework for discos in retail electricity market," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 356–367, Feb. 2009.

[14] A. Safdarian, M. Fotuhi-Firuzabad, and M. Lehtonen, "A stochastic framework for short-term operation of a distribution company," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4712–4721, Nov. 2013.

[15] L. Zhang, Z. Li, and C. Wu, "Randomized auction design for electricity markets between grids and microgrids," in *Proc. ACM SIGMETRICS Int. Conf. Meas. Model. Comput. Syst.*, Austin, TX, USA, 2014, pp. 99–110.

[16] M. H. Shariatkhah and M. R. Haghifam, "Using feeder reconfiguration for congestion management of smart distribution network with high DG penetration," in *Proc. Integr. Renew. Distrib. Grid*, Lisbon, Portugal, May 2012, pp. 1–4.

[17] G. Koeppel, M. Geidl, and G. Andersson, "Value of storage devices in congestion constrained distribution networks," in *Proc. Power Syst. Technol. (PowerCon)*, vol. 1. Singapore, pp. 624–629, Nov. 2004.

[18] A. Kargarian, Y. Fu, S. DorMohammadi, and M. Rais-Rohani, "Optimal operation of active distribution grids: A system of systems framework," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1228–1237, May 2014.

[19] Z. Wang, B. Chen, J. Wang, and M. M. Begovic, "Coordinated energy management of networked microgrids in distribution systems," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 44–53, Jan. 2015.

[20] T. Basar and G. J. Olsder, *Dynamic Non-Cooperative Game Theory*, 2nd ed. New York, NY, USA: Academic, 1995.

[21] G. Romp, *Game Theory: Introduction and Applications*. Oxford, U.K.: Oxford Univ. Press, 1997.

[22] T. Li and M. Shahidehpour, "Strategic bidding of transmission constrained GENCOs with incomplete information," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 437–447, Feb. 2005.

[23] M. E. Khodayar and M. Shahidehpour, "Optimal strategies for multiple participants in electricity markets," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 986–987, Mar. 2014.

[24] S. A. Gabriel, A. J. Conejo, J. D. Fuller, B. F. Hobbs, and C. Ruiz, *Complementarity Modeling in Energy Markets.* Berlin, Germany: Springer-Verlag, 2012.

[25] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation and Control*, 2nd ed. Hoboken, NJ, USA: Wiley, 1996.

[26] C. Ruiz, A. J. Conejo, and Y. Smeers, "Equilibria in an oligopolistic electricity pool with stepwise offer curves," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 752–761, May 2012.

[27] H. D. Sherali, "A multiple leader Stackelberg model and analysis," *Oper. Res.*, vol. 32, no. 2, pp. 390–404, Mar. 1984.

[28] V. DeMiguel and H. Xu, "A stochastic multiple-leader Stackelberg model: Analysis, computation, and application," *Oper. Res.*, vol. 57, no. 5, pp. 1220–1235, Sep. 2009.

[29] S. Leyffer and T. Munson, "Solving multi-leader-common-follower games," *Optim. Methods Softw.*, vol. 25, pp. 601–623, Aug. 2010.

[30] R. Fletcher and S. Leyffer, "Solving mathematical programs with complementarity constraints as nonlinear programs," *Optim. Methods Softw.,* vol. 19, pp. 15–40, Feb. 2004.

Saeed D. Manshadi (S'14) received the B.S. degree from the School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran, in 2012, and the M.S. degree from the University at Buffalo, State University of New York, Buffalo, NY, USA, in 2014, both in electrical engineering. He is currently pursuing the Ph.D. degree in electrical engineering with the Department of Electrical Engineering, Southern Methodist University, Dallas, TX, USA.

His current research interests include microgrids, bi-level optimization, and power system operation and planning.

Mohammad E. Khodayar (M'12) received the B.S. degree from the Amirkabir University of Technology, Tehran, Iran, in 2003; the M.S. degree from the Sharif University of Technology, Tehran, in 2006; and the Ph.D. degree from the Illinois Institute of Technology, Chicago, IL, USA, in 2012, all in electrical engineering.

He was a Senior Research Associate with the Robert W. Galvin Center for Electricity Innovation, Illinois Institute of Technology. He is currently an Assistant Professor with the Department of Electrical Engineering, Southern Methodist University, Dallas, TX, USA. His current research interests include power system operation and planning.