Electric Power Systems Research 157 (2018) 187–199

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

An advanced retail electricity market for active distribution systems and home microgrid interoperability based on game theory

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ARTICLE INFO

Article history:
Received 16 July 2017
Received in revised form 2 December 2017
Accepted 25 December 2017

Keywords:
Active distribution network
Retail electricity market
Game theory
Nikaido-Isoda relaxation algorithm
Home microgrid
Microgrid interoperability

ABSTRACT

The concept of active distribution network has emerged by the application of new generation and storage technologies, demand flexibility, and communication infrastructure. The main goal is to create infrastructure and algorithms to facilitate an increased penetration of distributed energy resources, application of demand response and storage technologies, and encourage local generation and consumption within the distribution network. However, managing thousands of prosumers with different requirements and objectives is a challenging task. To do so, market mechanisms are found to be necessary to fully exploit the potential of customers, known as Prosumers in this new era. This paper offers an advanced retail electricity market based on game theory for the optimal operation of home microgrids (H-MGs) and their interoperability within active distribution networks. The proposed market accommodates any number of retailers and prosumers incorporating different generation sources, storage devices, retailers, and demand response resources. It is formulated considering three different types of players, namely generator, consumer, and retailer. The optimal solution is achieved using the Nikaido-Isoda Relaxation Algorithm (NIRA) in a non-cooperative gaming structure. The uncertainty of the generation and demand are also taken into account using appropriate statistical models. A comprehensive simulation study is carried out to reveal the effectiveness of the proposed method in lowering the market clearing price (MCP) for about 4%, increasing H-MG responsive load consumption by a factor of two, and promoting local generation by a factor of three. The numerical results also show the capability of the proposed algorithm to encourage market participation and improve profit for all participants.

1. Introduction

While the ever-increasing penetration of distributed renewable generation within distribution networks threatens reliable and secure power system operation as a whole, numerous opportunities are emerging which actively engage distribution systems and consumers in the power system operation. To exploit these new opportunities, two concepts have been developed as the major enabling ideas. First, the prosumer concept was born in recent years [1–4] as the ability of electricity consumers to become an active agent in the power system's operation through local generation, demand flexibility, and storage. The second concept was H-MG [5–11] which is supposed to host a variety of local generation, demand flexibility resources, and storage devices to encourage the possibility of short- or long-term autonomous operation of the system in severe conditions [12,13]. Combining these two enabling concepts necessitates an advanced retail electricity market with new functionality to enable interactions around energy and ancillary services products. The new market structure is expected to be scalable to accommodate any number and type of participants, and provide the means to encourage local interactions among different prosumers. Additionally, it should offer a comprehensive solution to facilitate the exploitation of available flexibility for the benefit of

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https://doi.org/10.1016/j.epsr.2017.12.024
0378-7796/

Nomenclature

Acronyms

DR demand response
DMS distribution management system
DSO distribution system operator
DER distributed energy resource
DGU dispatchable generation unit
DNO distribution network operator
EMS energy management system
ES energy storage
ES+, ES- ES during charging/discharging mode
EV expected value
HEMS home energy management system
H-MG home microgrid
MCEMS modified conventional energy management system
MCP market clearing price
MO market operator
MT microturbine
NDU non-dispatchable unit
NIRA Nikaido-Isoda/relaxation algorithm
NRL non-responsive load
PBUC price-based unit commitment
PV photovoltaic
RLD responsive load demand
SOC state-of-charge
TGE total generated energy
TCE total consumed energy
TOAT Taguchi's orthogonal array testing
WT wind turbine

Sets and indices

θ, β load demand curve coefficients
a^j, b^j, c^j coefficients of cost function of DGU in H-MG j
$n/n/n''/n$ number of generators/consumers/retailers/H-MGs
N_s number of uncertainty scenarios
π^{ES+} consumer's bids for battery during charging, i.e., ES+ ($/kWh)
Δt time interval, hour

Constants

ζ^{ES} efficiency of the battery
$\bar{P}^{(.),j}, \underline{P}^{(.),j}$ maximum/minimum output power of (.) in H-MG j (kW)
$\bar{SOC}^{ES,j}, \underline{SOC}^{ES,j}$ maximum/minimum state-of-charge (SOC) limits of ES in H-MG j (%)

Parameters

$\pi_t^{i''-}, \pi_t^{i''+}$ offer price of retailer i″ at time t for selling/buying to/from H-MGs ($/kWh)
$P_{t,s}^{(.),j}$ output power of resource (.) under scenario s in the H-MG j (kW)
$\rho_{t,s}^{(.),j}$ probability of scenario s of resource (.) in the H-MG j

Functions

$\mathbb{C}_t^i, \mathbb{R}_t^i, \mathbb{J}_t^i$ cost/revenue/profit functions of generator *i* at time t ($) ($i \in \{1, 2, \ldots, n\}$)
$\mathbb{C}_t^{A,j}$ cost of producing power by (A) in H-MG j ($)
$\mathbb{C}_t^{i''}, \mathbb{R}_t^{i''}, \mathbb{J}_t^{i''}$ cost/revenue/profit functions of retailer i″ at time t ($) ($i'' \in \{1, 2, \ldots, n''\}$)
$\mathbb{J}_t^{i'}$ cost functions of consumer i′ at time t ($) ($i' \in \{1, 2, \ldots, n\}$)
$\pi_t^{H-MG,j}$ offer price of H-MG j at time t ($/kWh)

$EV_t^{(.),j}$ expected value of energy produced by (.) in H-MG j at time t
Z(x) optimum response function in NIRA
Φ_i pay-off function of each player i in NIRA
$\Psi(x, y)$ Nikaido-Isoda function

Decision variables

$P_t^{(.),j}$ output power of (.) in H-MG j during the time period t (kW)
X collective strategy set
x action of each player
$SOC_t^{ES,j}$ SOC of ES in H-MG j at time t (%)

large power systems and end-users. The proposed market should also be able to handle large number of players, as is likely to happen at the distribution level.

The application of H-MG energy management systems with (e.g., [1,3–5]) or without energy storage (ES) (e.g., [7–9,14,15]), and H-MGs interoperability (e.g., [10,11,16]) have been investigated in numerous research papers in the past. Developing general strategies for retail market operation have also been addressed in [17–25]. Colored Petri net technology [21], different game theory approaches using NIRA algorithm [22,24], Shapely value [24,26], and Cournot model [25] are among the methods which have been utilized for retail electricity market design. In [26], a retail market based on game theory was proposed for H-MG interoperability. In their proposed structure, all consuming participants were represented by a single player (i.e., aggregator) which does not appreciate different objectives and constraints among participants and the devices. Additionally, this formulation only allows one retailer in the proposed market which does not cope with the reality. Furthermore, using Cournot equilibrium model in [26], decision making is limited to only quantitative variables which is not desirable. In [27], a market structure was proposed as a part of an economic dispatch model for H-MG interoperability. Two types of players, including seller H-MGs as leaders and buyer H-MGs as followers, were introduced which essentially limits operational capability of the method. Moreover, the principles of Transactive Energy was used in [28–31] to develop optimal economic dispatch of H-MGs, charge optimization and optimal participation of electric vehicles. Only two types of players, namely electric vehicles and utility, were considered in [30,31]. In [30], the cost of electric vehicles' charging and power losses of the distribution network are optimized. Thus, the required functionality is not developed in this method for a large pool of players of different types.

To summarize, the following shortcomings can be identified in the existing literature related to the retail electricity market at the distribution level:

- Lack of a general framework for analyzing and modeling players' behavior in a deregulated competitive electricity market at the residential distribution level in [10,15,16,32–35].
- No investigation into the impact of prosumers on the economic operations of future residential distribution systems through probabilistic methodologies [18,20,21,25].
- No supply bidding mechanism for the players in the electricity market [15,16,22,24,26,25].
- No MCP calculation based on the Nash equilibrium point, market bids, and double-sided auction in [15–17,22,24–26].