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A profit sharing scheme for distributed energy resources integrated into a virtual power plant

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HIGHLIGHTS

- The reasons behind the surplus profit of integrated DERs are evaluated.
- A novel profit sharing scheme is provided for the integrated DERs.
- The proposed scheme has a significantly low computational burden.
- Energy and reserve markets are considered in the proposed scheme.
- The scheme can be used under both dual and single real-time pricing systems.

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ABSTRACT

Independent owners of distributed energy resources (DERs) can be integrated to form a coalition in order to trade in either retail markets (under predetermined tariffs) or wholesale markets using the virtual power plant (VPP) concept. The consequent coordinated operation of DERs entails a surplus profit in respect to the summation of their individual profits. In this paper, the reasons behind such a surplus profit are evaluated. The transactions virtually taken place inside the coalition are defined, classified and priced in order to provide a profit sharing scheme for the integrated DERs. The VPP dispatching center can implement this scheme for trading in both energy and reserve markets, as well as under both dual and single pricing systems in the balancing (real-time) market. This study shows that how the amount and price of the internal transactions in each class, and as a result, the allocated profits depend on the difference between sale and purchase prices in real-time and the risk-aversion level of DERs facing the uncertainties. The proposed framework is compared with the existing cooperative Game theory-based methods. The comparison shows that it has a much lower computational burden. It is also more comprehensible and more acceptable to DER owners.

1. Introduction

1.1. Coordinated operation of DERs

When the coordinated operation of small/medium-scale generators, loads and storage facilities is technically feasible, a heterogeneous coalition between them can be organized. Independent owners of dispersed generation units, storage facilities and flexible loads (known as distributed energy resources (DERs)) located in the same distribution grid can be integrated in order to have an adequate scale for participating in wholesale markets. This coalition is named virtual power plant (VPP) [1]. DERs located in a micro-grid can also be unified to benefit from the joint operation under a retail market structure. The concepts of VPP and micro-grid are compared in [2].

Since the trading framework in retail markets are dictated by distribution system operators and/or retailers, DERs and their coalition must comply with the regulations, irrespective of size, e.g., when DERs located nearby are unified to be connected to a distribution grid via a single meter, a coalition under the micro-grid paradigm is formed. This coalition needs to trade under predetermined fixed tariffs. In the context of VPPs, the integration of DERs, irrespective of location, forms a coalition to be large enough to participate in wholesale markets. From the standpoint of transmission grids, the difference between a VPP and other entities is that a VPP may consist of comparatively large number of units. Also from the viewpoint of distribution grids, VPP may be neither owner nor operator of the distribution grid in which its units have been

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dispersed, and hence it should take into account distribution grid limitations. A scalable wireless communication technology is presented in [3] to integrate geographically sparse DERs into a VPP. Ref. [4] proposes a method to form an optimal coalition of DERs in a VPP within a medium-term planning horizon. Considering the typical scale of coalitions of DERs such as micro-grids and VPPs, we assume that they cannot resemble monopolistic behavior, i.e., such coalitions have no considerable market power and thus they act as price-taker agents. The collusion issues related to price-maker agents are out of the scope of this paper.

1.2. Balancing markets

If the generation/consumption pattern of a large-scale producer/consumer deviates from that settled in the pool, an energy deviation takes place. There are several mechanisms to deal with the energy deviations of market participants around the world. As examples, participation in a balancing market (BM) with dual pricing system which is common in Europe, e.g., [5], trading in a balancing group that is operating in a few European countries, e.g., [6], and trading in a real-time market with single pricing system which is common in the US, e.g., [7]. All of these real-time exchange environments are called the BM in this paper, irrespective of imbalance settlement process. Participants need to sell/buy positive/negative deviations to/from the BM.

It is worth noticing that balancing groups are responsible for making sure supply and demand is balanced in various parts of the network. All market players are obliged to join a balancing group to trade their deviations. VPPs are much different from these groups. This stems from the combination of three facts. Firstly, VPPs are not in charge of the electricity grid. Secondly, DERs are not obliged to join a VPP. Thirdly, VPPs are not coalitions of large-scale agents.

It is also worth noting that, under single pricing system in the BM, the sale and purchase prices are the same, but under the dual pricing system, the sale/purchase price is lower/higher than or equal to the price in the day-ahead market (DAM) [8]. For this reason, dual BMs pose more risky situations to the DERs in comparison to single BMs. As a result, a higher surplus profit of VPP is expected under dual pricing system in the BM [9].

1.3. The origins of the surplus profit

Coordinated operation provides an opportunity to make a surplus profit in relation to the uncoordinated participations, e.g., for a wind power plant (WPP) and a pumped-hydro-storage plant (PHSP) [10–14], a photovoltaic plant and an elastic demand [15], small flexible nuclear reactors and a WPP [16], grid-enabled electric vehicles and a WPP [17], and dispersed generation units and demand response resources under the micro-grid [18] and VPP [19] paradigms. The electricity procurement cost reduction due to the integration of DERs trading under retail market tariffs are analyzed in [20].

The participation of VPP in wholesale electricity markets is subject to a great variety of uncertainties. The uncertainties involved in the optimal offering/bidding problem of VPP originate from the inherent randomness of the renewable resources and the volatility of the wholesale prices. Various techniques are provided in the literature to deal with these uncertainties, e.g., stochastic programming in [4,21], robust optimization in [1,22] and point estimate in [23,24].

The ability of a VPP to reduce the imbalance error of renewable generators is evaluated in [25]. The surplus profit of a VPP is discussed in [26] for trading in energy markets, and in [9] for trading in a joint market of energy and spinning reserve service. In these cases, a method should be implemented to fairly allocate the total profit/cost to the integrated DERs. The cooperative Game theory concepts are widely used in the allocation problems in power industry, e.g., [27–29]. Ref. [26] explains how these concepts can be used to allocate the profit of a VPP to its DERs. It also shows that the integration can be used as a tool to hedge against the risk of profit variability faced by DERs in electricity markets under uncertainty. Thus, the share of each DER in the surplus profit depends on its role in covering the risks. Since different types of DERs concern about different kinds of uncertainty, such integration reduces the cost of their risks and so a surplus profit is earned [9]. As explained in [26], DERs integrated into a VPP earn their individual profit at a minimum. This means that there is no reduction in the profit of a DER due to an increase in the profit of other DERs in the same VPP. This explains why a VPP is a cooperative game between its DERs and why the surplus profit of a VPP is always non-negative.

In retail markets, since there is no uncertainty on tariffs, the DERs do not face the risk of profit variability. Nevertheless, the aforementioned issue with respect to the surplus profits is also true for trading under predetermined tariffs that are not equal for generation and consumption [20]. It means that, in contrast with the equivalent tariffs for sale and purchase, the coalition expects a surplus profit under different tariffs. It should be noted that, the DERs for whom the unification of their output powers is not physically feasible (e.g., two DERs that trade at different distribution grids) exchange separately and so there is no surplus profit for their coalition. This is so because they cannot cover the risk of each other, e.g., positive or negative energy deviations (with respect to the amounts scheduled in the day-ahead energy and reserve markets) cannot be compensated by other DERs in the coalition.

The surplus profit of a VPP depends on the number and variety of its DERs, e.g., it is expected that the integration of a WPP and a PHSP earns more surplus profit in comparison with two similar WPPs. As another example, a higher surplus profit is expected for a higher number or variety of unified DERs trading in a retail market [20]. As a consequence, the share of each DER in the surplus profit of a VPP depends on the number and variety of other DERs existing in that VPP. This is the reason why a DER may prefer a VPP to another in a medium-term planning horizon, i.e., a DER may have an incentive to leave a VPP to join another coalition trading in either wholesale or retail markets.

1.4. Gaps in the literature and our contribution

The optimal participation of VPP in energy and reserve markets have been widely evaluated in the literature, e.g., in [1,9,21–24,26,30,31]. Nonetheless only one approach has been proposed to allocate the profit of VPP among its DERs in [26]. It is an important issue because the investment and the finance of each DER can be independent in the competitive environment of power industry, and so the control center of a VPP needs to have a fair and clear profit sharing procedure to respond to the DER owners.

On the other hand, the total and surplus profits of a VPP are fundamentally affected by the pricing system in the BM, the risk-aversion level of DER owners, and feasibility of providing the ancillary services [9]. For this reason, these issues should be included in the profit allocation solutions.

In [26], as the only proposed approach to allocate the profit of VPP, cooperative Game theory-based methods are implemented. This way, the proposed methods lead to a huge computational burden, especially if the number of DERs is large. Using the Game theory-based schemes, it is difficult to the DER owners to find out how their shares are determined by the control center of VPP. Moreover, the circumstances under the single pricing in the BM and the possibility of trading in the reserve market (RM) have not been taken into consideration.