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Risk-based profit allocation to DERs integrated with a virtual power plant using cooperative Game theory

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A B S T R A C T

Distributed energy resources (DERs) play a key role in the deregulated power systems with environmental concerns. Their scales and the uncertainty pertaining to intermittent generation of renewable resources are the major challenges of participating in wholesale electricity markets. The concept of virtual power plant (VPP) makes their integration possible and also allows covering the risk due to uncertainties. It yields a surplus profit in comparison to profits made by uncoordinated DERs. In this paper, using a novel stochastic programming approach, the participation of a VPP in the day-ahead market (DAM) and the balancing (real-time) market (BM) is considered. The uncertainties involved in the electricity price, generation of renewables, consumption of loads, and the losses allocation are taken into account. The desired risk-aversion level of each independent DER owner is used to compute the conditional value-at-risk (CVaR) as a well-known risk measure. The role of each DER in covering the risk and making the total profit is evaluated. The Nucleolus and the Shapley value methods as the cooperative Game theory approaches are implemented to allocate VPP's profit to the DERs. The results of a numerical study are presented and concluded.

1. Introduction

1.1. Competition and distributed energy resources

Nowadays, distributed energy resources (DERs) including dispersed generation (DG), storage facilities (SFs), and demand response (DR) resources have a significant influence on the economic development of power systems. Although DGs and small- or medium-scale SFs seem highly successful in stimulating small investments, they face strong challenges of economic activities. Owners of these DERs will be limited to electricity price setting mechanisms considered by the distribution system operators (DSOs). Nodal pricing [1], locational marginal price (LMP) calculation [2], and contract pricing [3] are some of these mechanisms. On the other hand, small- or medium-scale consumers which are able to flexibly control their own loads are limited to DR programs offered by DSOs, and hence they are not at the advantage of competitive environment of wholesale electricity markets. Some of these programs are evaluated in [4–7].

The concept of virtual power plant (VPP) is a practical way of eliminating aforementioned limitations. According to this concept, dispersed generation and consumption units can integrate into a single market agent to be large enough for participating in wholesale markets. So they can trade at the wholesale price similar to large-scale producers and consumers. Centralized and distributed dispatches of VPPs are analyzed in [8,9]. In this paper, VPP is assumed to be centrally controlled. As smart grid infrastructure develops, the VPP concept becomes more practical, even for small DERs. Refs. [10,11] compare the concepts of VPP and micro-grid. It is important to emphasize that, in comparison to micro-grids, VPPs concept is much broader. This is so because it is not limited to geographical location of DERs and the ownership of the grid.

However, participation in competitive markets poses the risk of profit variability. For instance, there is no subsidy or fixed tariff in competitive markets. DERs must compensate energy deviations in respect of their scheduled generations or consumptions in the day-ahead market (DAM). Ref. [12] presents the procedure of including risk measures such as the shortfall probability, the expected shortage, the value-at-risk (VaR), and the conditional value-at-risk (CVaR) in the formulation of the stochastic programming.

In some cases, an imbalance penalty must be paid [13–15], and in a wider context, energy deviations shall be traded in competitive markets, namely the balancing (real-time) market (BM). Trading in the BM at a single price is the common practice in the US [16]. In European electricity markets, there is a dual pricing system for

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Nomenclature

Sets

(N)DL	set of (non-)dispatchable loads
(N)DP	set of (non-)dispatchable producers
(N)DU	set of (non-)dispatchable units
SF	set of storage facilities

Indices

b	index of net power injection blocks of DERs
f	index of combinations of the units, running from 1 to 2^{U-1}
h	index of combinations of the units except one of them, running from 1 to 2^{U-1}
t	index of time periods
u	index of units (DERs) integrated into a VPP, running from 1 to U
v	index of units expect one of them, running from 1 to $U-1$
ω, ω'	index of scenarios

Constants

c_u^m	marginal operation cost of DPs/SFs and marginal curtailment cost of DLs (\$/MWh)
c_u^f, c_u^s, c_u^d	fixed cost, start-up cost, and shut-down cost of DPs, respectively (\$)
$\underline{d_t}$	duration of period t (h)
$\overline{E_u^S}$	storage capacity of SFs (MWh)
k_{fu}	binary coefficient equal to 1 if unit u is available in combination f and 0 otherwise
k_{hv}	binary coefficient equal to 1 if remaining unit v is available in combination h and 0 otherwise
k_u	binary coefficient equal to k_{fu} or k_{hv}, pertaining to Nucleolus- or Shapley value-based methods
$\overline{P_{ub}}$	upper limit of net power injection associated with block b (MW)
$\overline{P_{ut}}$	upper limit of net power injection for unit u due to the generation capacity of DPs/SFs (constant during the time), hourly non-curtailable demand of DLs, and transmission/distribution limitations (MW)
$\underline{P_u}$	technical minimum of DPs and rated demand of DLs (MW)
$\underline{P_t^c}$	previously contracted power (MW)
$\overline{R_u}, \underline{R_u}$	respectively, up and down ramp rate limits for DPs (MW/h)
α, α_u	confidence levels of VPP and the owner of unit u, respectively
β, β_u	weighting factor used to materialize the tradeoff between the expected profit and the CVaR, respectively pertaining to VPP and unit u
ξ_u	whole efficiency factor of SFs (per unit)
π_ω	probability of occurrence of scenario ω
$\overline{T_u}, \underline{T_u}$	minimum up and down time limits for DPs, respectively (h)

Variables

$C_{ut\omega}$	operation cost of DUs (\$)
$E_{t\omega}^{B+}, E_{t\omega}^{B-}$	respectively, positive/negative energy deviation sold to/purchased in the balancing market (MWh)
$E_{ut\omega}^S$	energy stored by SF u at the end of time period t (MWh)
$\underline{L_{ut\omega}}$	loss allocated to unit u (MW)
$\widetilde{L_{ubt\omega}}$	forecasted loss allocation pertaining to block b of DUs (MW)
$P_{t\omega}^D$	power traded in the day-ahead market, positive values for selling and negative values for purchasing (MW)
$P_{ut\omega}$	net power injected by unit u (MW)
$P_{ut\omega}^+, P_{ut\omega}^-$	power generated and consumed by SFs, respectively (MW)
$\widetilde{P_{ut\omega}}$	forecasted power injection of NDUs (MW), positive values for generation and negative values for consumption
$s_{ut\omega}$	binary variable denoting on/off status of DPs, 1 for on and 0 for off
$z_{ut\omega}^s, z_{ut\omega}^d$	binary variables denoting respectively start-up and shut-down decisions for DPs
$\gamma_{ubt\omega}$	binary variable for selection of block b of DUs power injections. It is equal to 1 if block b is selected and 0 otherwise
ζ_ω	auxiliary variable for calculating the CVaR (\$)
η	value-at-risk (\$)
Π_f, Π_{hu}	profit of combination f, and combination h separating out unit u, respectively (\$)
Π_u, Π'_u	allocated profit to unit u and uncoordinated expected risk-neutral profit of unit u, respectively (\$)
$\Pi_{t\omega}$	profit realized in time period t and scenario ω (\$)
$\rho_{t\omega}^{B+}, \rho_{t\omega}^{B-}$	imbalance prices for positive and negative energy deviations, respectively (\$/MWh)
$\rho_{t\omega}^D$	day-ahead market price (\$/MWh)

the BM [17], i.e. the positive deviation (the generation surplus or consumption deficit) shall be sold to the BM+ and the negative deviation (the generation deficit or consumption surplus) shall be bought from the BM− [18–20]. The dual pricing system is considered in this paper.

1.2. Risk-hedging tools

The general mechanism for imbalance prices is described in [12,20]. It is shown that, in competitive environments, the DAM price is hourly equal to or higher than the BM+ price, and equal to or lower than the BM−. The owners of the non-dispatchable sources must cope with the generation intermittency. Decision-making of large-scale wind power plants (WPPs) under uncertainty are presented in [20,21]. These studies show that, as the risk aversion of non-dispatchable producers (NDPs) increases, the sale in the DAM decreases and in the BM increases at the expense of reducing the expected profit.

A joint configuration of a WPP and a pumped-hydro-storage plant (PHSP) is modeled in [13–15,18,19], and compared with an uncoordinated operation. These studies show that the joint operation results in a profit higher than the summation of profits uncoordinatedly obtained. In this paper, we call this added value "surplus profit".

The price volatility in competitive electricity markets is the source of uncertainty from viewpoint of dispatchable units (DUs), such as conventional power plants (CPPs), SFs, and dispatchable loads (DLs). Decision-making of large producers under uncertainty is discussed in [22,23], and energy procurement problem for large consumers is addressed in [24,25]. These researches show that the energy trades through bilateral contracts and the futures market (FM) grow as the risk aversion becomes more significant. It often leads to a reduction in the expected profit of producers and the expected cost of consumers.