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The design of a risk-hedging tool for virtual power plants via robust optimization approach

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HIGHLIGHTS

- A robust risk-hedging tool is proposed for the VPP's offering strategy.
- We have shown that the VPP acts as an arbitrager in some hours.
- This tool nullifies the risk of not meeting bilaterally contracted energies.
- The calculation time is suitable for the short-term scheduling and mid-term planning.

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ABSTRACT

This paper presents a robust optimization-based decision-making tool for the daily and weekly self-scheduling of Virtual Power Plants (VPPs) in the uncertain environment of electricity markets. VPP, as a heterogeneous coalition of distributed energy resources (DERs), is generally composed of intermittent renewable sources, storage systems, flexible loads, and small conventional power plants and thus, to ensure the commercial profit, it needs to negotiate some bilateral contracts in advance prior to participating in the day-ahead market. From the empirical point of view, most relevant decisions made by a VPP as well as its coalition members in short-term and mid-term energy transactions involve a significant level of data uncertainty. For this reason, an efficient MILP model based on robust optimization approach is proposed to enable informed decision making under different levels of uncertainty. The flexible feature embedded in this tool with respect to solution accuracy and computational burden would be advantageous to the VPP. The efficiency and applicability of the proposed method is illustrated and analyzed through different scenarios, and thereby conclusions are drawn.

1. Introduction

1.1. Background and motivation

The design and operation of the existing power grid are being changed due to the global warming and environmental concerns of coal-based power generation, hence the power industry is experiencing a gradual transformation which will have a considerable effect on the development of the infrastructure for generating, transmitting, and distributing power [1]. For a smart power system, renewable energy sources (RES) are supposed to supply electric power to the grid as much as they could. Moreover, due to the increasingly diminution of conventional fossil fuels and the associated environmental problems, RESs have been experiencing an outstanding growth during the last couple of decades.

Nevertheless, the government incentives impose a time limit after which RESs will become non-favorized agents in the market [2]. In Belgium [3], for example, investors could acquire green power certificates worth €450/MW h during the recent years. However, due to the large boom of solar plants, and thus rising subsidy cost, regulators are dropping this support (e.g. €450/MW h in 2009 to €90/MW h in 2012 [3]). The smart distribution system is expected to integrate distributed energy resources (DERs), including distributed generators (DGs) and energy storage devices, for promoting energy efficiency and reducing environmental pollution [4].

The forthcoming power system may have numerous distributed generators and intermittent power generation from renewable green energy resources. The challenges of designing a sustainable future power system with an integration of many distributed

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Nomenclature

Sets

T	set of time periods
DG	set of dispatchable DGs active in the VPP coalition
SG	set of stochastic DGs active in the VPP coalition
GSP	set of upstream grid supply points for transaction with the electricity wholesale market

Indices

t	index of time periods running from 1 to T
i	index of dispatchable DGs
j	index of stochastic/non-dispatchable DGs
k	index of upstream grid supply or transaction points
w	index for modeling of minimum up-time and down-time limits running from 1 to $(\mathrm{MUT}_i^{DG}-1)$ and, $(\mathrm{MDT}_i^{DG}-1)$ respectively

Constants

a, b	model estimation parameters for distribution network demand
α_0	the ratio of VPP customers' charge to the upper bound of the market price forecast
ζ_{total}	percentage of the total generation of dispatchable units and curtailment option of the flexible loads in the VPP coalition (%)
Δ_{BC}	allowed hourly discrepancy between bilaterally contracted and delivered energy

Parameters

$\mathrm{MUT}_i^{\mathrm{DG}}$	minimum up time of dispatchable unit i (h)
$\mathrm{MDT}_i^{\mathrm{DG}}$	minimum down time of dispatchable unit i (h)
$\lambda_t^{\mathrm{DSO,charge}}$	price that is charged to local VPP customers in time period t ($/MW h)
$\lambda_{kt}^{\mathrm{LMP}}$	day-ahead market price at the GSP k (as LMP) in time period t ($/MW h)
$\lambda_i^{\mathrm{DG,cost}}$	generation costs of dispatchable DG unit i ($/MW h)
$\lambda_i^{\mathrm{DG,startcost}}$	start up cost of dispatchable DG unit i ($)
$\lambda_i^{\mathrm{DG,shutcost}}$	shut down cost of dispatchable DG unit i ($)
$\lambda_j^{\mathrm{SG,cost}}$	generation costs of stochastic DG unit j (including installed capital cost, operation and maintenance cost) ($)
$\lambda_t^{\mathrm{FL,cost}}$	cost of a flexible load to curtail its demand in time period t ($/MW h)
$\lambda_t^{\mathrm{DA,max}}$	upper bound of price data (predicted price) in time period t ($/MW h)
$\lambda_t^{\mathrm{DA,min}}$	lower bound of price data in time period t ($/MW h)
P_t^{D}	total active power demand of VPP's customers in time period t (MW)
$P_i^{\mathrm{DG,max}}$	maximum DG capacity limit for active power (MW)
$P_j^{\mathrm{SG,max}}$	installed capacity of stochastic DG unit j (MW)
$P^{\mathrm{FL,max}}$	upper limit for curtailing on flexible loads (MW)
$P^{\mathrm{D,max}}$	maximum value of VPP's customers demand (MW)
$P^{\mathrm{D,min}}$	minimum value of VPP's customers demand (MW)
P_k^{SSmax}	the rating of the GSP k, for exchanging power with the main grid (MVA)
E_t^{Contract}	energy delivered due to bilateral contracts in time period t (MW h)
ζ_0	VPP surplus reserve (%)
α_k	the ratio of the LMP of GSP k to the upper bound of the predicted market price
Γ_0	uncertainty control parameter (Uncertainty Budget) in the robust optimization method

Variables

$P_{kt}^{\mathrm{Upstream}}$	VPP active power exchange with the day-ahead electricity market at the GSP k and in time period t (MW)
P_{it}^{DG}	generation of dispatchable DG unit i and in time period t (MW)
P_{jt}^{SG}	generation of stochastic DG unit j and in time period t (MW)
P_t^{FL}	the curtailment value of flexible loads in time period t (MW)
BC_t	bilaterally contracted energy delivery in time period t (MW h)
v_{it}^{DG}	0/1 variable which is equal to 1 if unit i is online in time period t
$y_{it}^{\mathrm{DG,start}}$	0/1 variable which is equal to 1 if unit i is started-up at the beginning of period t
$z_{it}^{\mathrm{DG,shut}}$	0/1 variable which is equal to 1 if unit i is shut-down at the beginning of period t
β, ζ_t	dual variables of the VPP's original (deterministic) decision-making problem
ω_t	an auxiliary variable used to obtain the corresponding linear expressions
X_t	the main variable corresponds to VPP active power exchanges with the day-ahead market

energy resources, especially renewable based units, are investigated in [5]. The concept of virtual power plant (VPP) is introduced to smartly utilize DERs with private ownership. As a matter of fact, the VPP, as a coalition of heterogeneous technologies, is an energy management system to aggregate the capacity of DGs, storage facilities, and flexible loads for the purpose of energy trading and/or providing system support services [6]. However, the economically optimal control of DERs included in the VPP is complicated by uncertainties, nonlinearities, and inter-temporal constraints [7].

VPP – from a black-box perspective – can be treated as a conventional dispatchable unit if the mix of its generating technologies can compensate for the intermittency of renewable generations [2]. In this case, VPP is operated as one unique entity from the point of view of any other agents hiding its inherent complexity, albeit, in reality, it represents a mixture of multiple DERs and small-scale conventional power plants. Therefore, the VPP is a flexible representation of DER commercializing energy at wholesale markets and/or ancillary services to any interested operator [8]. According to FENIX [5], the commercial VPP (CVPP) and technical VPP (TVPP) are two main types of VPP operation. The CVPP acts as a profit maker agent who economically optimizes its operating schedule in light of different electricity markets, whereas the response characteristics and obtained results are given to TVPP to implement them with the consideration of the local network constraints.

Since most relevant decisions to be made by a VPP and its coalition members in short-term and mid-term energy transactions involve a significant level of data uncertainty, this paper discusses the empirical application of Robust Optimization (RO) approach as a new non-probabilistic and non-possibilistic method for handling market price uncertainties in the risk-based decision-making tool of VPPs. To the best of the authors' knowledge, no research work has concurrently modeled electricity market prices for daily and weekly self-scheduling of a VPP in the RO framework, which is specific to this paper.