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A bi-level stochastic scheduling optimization model for a virtual power plant connected to a wind–photovoltaic–energy storage system considering the uncertainty and demand response

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HIGHLIGHTS

- Our research focuses on Virtual Power Plant (VPP).
- Virtual Power Plant consists of WPP, PV, CGT, ESSs and DRPs.
- Robust optimization theory is introduced to analyze uncertainties.
- A bi-level stochastic scheduling optimization model is proposed for VPP.
- Models are built to measure the impacts of ESSs and DERPs on VPP operation.

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ABSTRACT

To reduce the uncertain influence of wind power and solar photovoltaic power on virtual power plant (VPP) operation, robust optimization theory (ROT) is introduced to build a stochastic scheduling model for VPP considering the uncertainty, price-based demand response (PBDR) and incentive-based demand response (IBDR). First, the VPP components are described including the wind power plant (WPP), photovoltaic generators (PV), convention gas turbine (CGT), energy storage systems (ESSs) and demand resource providers (DRPs). Then, a scenario generation and reduction frame is proposed for analyzing and simulating output stochastics based on the interval method and the Kantorovich distance. Second, a bi-level robust scheduling model is proposed with a double robust coefficient for WPP and PV. In the upper layer model, the maximum VPP operation income is taken as the optimization objective for building the scheduling model with the day-ahead prediction output of WPP and PV. In the lower layer model, the day-ahead scheduling scheme is revised with the actual output of the WPP and PV under the objectives of the minimum system net load and the minimum system operation cost. Finally, the independent micro-grid in a coastal island in eastern China is used for the simulation analysis. The results illustrate that the model can overcome the influence of uncertainty on VPP operations and reduce the system power shortage cost by connecting the day-ahead scheduling with the real-time scheduling. ROT could provide a flexible decision tool for decision makers, effectively addressing system uncertainties. ESSs could replace CGT to provide backup service for the WPP and PV, to smooth the VPP output curve and to improve the WPP and PV grid connection by its charging–discharging characteristics. Meanwhile, IBDR and PBDR could smooth the load curve to the maximum extent, link the generation side with the demand side to minimize abandoned power value and reach the optimum benefit of VPP operation.

1. Introduction

Since energy and environmental problems become very serious, distributed energy resources (DERs), especially wind power and solar photovoltaic power, are playing increasingly important roles in the energy structure. However, constraints of small installed capacity, intermittence, uncertainty and other characteristics, make entrance and operation of the power market difficult for DERs [1]. Thus, the virtual power plant (VPP) was proposed as a new technology for DERs in the power market [2]. Without changing the DERs grid connection method, VPP integrates different types of DERs, such as distributed power sources, energy storage

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Nomenclature

Abbreviations

VPP	virtual power plant
DR	demand response
PBDR	price-based DR
IBDR	incentive-based DR
WPP	wind power plant
PV	photovoltaic generators
CGT	convention gas turbine
ESSs	energy storage systems
DRPs	demand resource providers
MILP	mixed integer linear programming model
DERs	distributed energy resource

Set

s, t	index for time
i	index for DPR
j	index for step
k	index for scenario
W	index for WPP
PV	index for PV
CGT	index for CGT
ESS	index for ESSs

Variable

π_t^{PB}	cost of DPRs participating in PBDR at time t
π_t^{IB}	cost of DPRs participating in IBDR at time t
L_t	load change after PBDR at time t
$\Delta L_{i,t}^{E}$	load reduction of DPR i
$\Delta L_{i,t}^{R,dn}$	up demand-side reserve of DPR i at time t
$\Delta L_{i,t}^{R,up}$	down demand-side reserve of DPR i at time t
$g_{CGT,t}$	power output of CGT at time t
$g_{ESS,t}^{dis}$	discharge power of ESSs at time t
$g_{ESS,t}^{chr}$	charge power of ESSs at time t
$g_{W,t}$	output of WPP at time t
$g_{PV,t}$	output of PV at time t
$g_{VPP,t}$	output of VPP at time t
$g_{GC,t}$	power output of system purchasing from generation company
$\Delta L_{PB,t}$	load change produced by PBDR at time t
Q_t	storage electricity of ESS at time t
$D_{CGT,t}$	startup–shutdown cost of CGT at time t
$T_{CGT,t}^{\mathrm{off}}$	continuous downtime of *CGT* at time t
$T_{CPP,t-1}^{\mathrm{on}}$	continuous operation time of CGT at time t – 1
$T_{CPP,t-1}^{\mathrm{off}}$	continuous shutdown time of CGT at time t – 1
$\Delta L_{IB,t}$	reserve capacity provided by DRPs
$g_{CGT,t}^{*}$	revised output of CGT at time t
$\Delta L_{i,t}^{*E}$	revised IBDR output plan participating in energy market
$\Delta L_{i,t}^{*R,dn}, \Delta L_{i,t}^{*R,up}$	revised IBDR reserve capacity participating in reserve market
H_t	system net load at time t

Parameter

e_{st}	demand-price elastic
P_t^0	electricity price before PBDR
L_s^0	load demand before PBDR
ΔL_s	electricity changes of demand after PBDR
ΔP_t	electricity changes of price after PBDR
$D_i^{j,\min}$	minimum acceptable load reduction of DPR i in step j
$D_i^{j,\max}$	sum of all deployed load curtailments of DPR i in step j
$\Delta L_{i,t}^{j}$	load reduction of DPR i in step j at time t
$D_{i,t}^{j}$	deployed load curtailment of DRP i in step j at time t
$D_i^{\min}$	minimum load reduction of DPR i
$D_i^{\max}$	maximum load reduction of DPR i
$\rho_{i,t}^{E}$	cost of DPR i participating in demand-side reserve scheduling
$\rho_{i,t}^{R,dn}$	cost of DPR i participating in down demand-side reserve scheduling
$\rho_{i,t}^{R,up}$	cost of DPR i participating in up demand-side reserve scheduling
$\rho_{W,t}$	grid-price of WPP at time t
$\rho_{PV,t}$	grid-price of PV at time t
$\rho_{ESS,t}^{dis}$	discharge price of ESSs at time t
$\rho_{ESS,t}^{chr}$	charge price of ESSs at time t
$\rho_{CGT,t}$	grid-price of CGT at time t
φ_W	power loss rate of WPP
φ_{PV}	power loss rate of PV
φ_{CGT}	power loss rate of CGT
v	wind speed
φ, ϑ	shape factor and scale factor
$P(v)$	probability of the wind speed v
v_a, v_b	wind speeds limitation of state v
v_{in}	cut-in speed of wind turbine
v_{rated}	rated speed of wind turbine
v_{out}	cut-off speed of wind turbine
v_t	actual speed of wind turbine at time t
g_R	rated output of wind turbine
α, β	shape parameters of *Beta* distribution
θ_t	solar irradiance at time t
u, σ	mean value and standard deviation of irradiance
θ_c, θ_d	solar irradiance limits of state θ
η_{PV}	efficiency of PV
S_{PV}	total area of PV
f_1	the objective function of the maximum VPP operation revenue
$R_{W,t}$	operation revenue of WPP at time t
$R_{PV,t}$	operation revenue of PV at time t
$R_{ESS,t}$	operation revenue of ESSs at time t
$R_{CGT,t}$	operation revenue of CGT at time t
γ_s	the weight of scenario s
$\pi_{CGT,t}^{pg}$	power generation cost of CGT at time t
$\pi_{CGT,t}^{ss}$	startup–shutdown cost of CGT at time t
$a_{CGT}, b_{CGT}, c_{CGT}$	cost coefficient of CGT power generation
N_{CGT}^{cold}	cold startup cost of CGT
N_{CPP}^{hot}	hot startup cost of CGT
$T_{CPP}^{\min}$	minimum allowable downtime of *CGT*
T_{CPP}^{cold}	cold startup time of *CGT*
$g_{CGT}^{\max}, g_{CGT}^{\min}$	upper and lower limitation of CGT
$\Delta g_{CPP}^{+}, \Delta g_{CPP}^{-}$	upper and lower limitation of CGT
M_{CPP}^{on}	minimum startup time of CGT
M_{CPP}^{off}	minimum shutdown time of CGT
Q_0	initial storage electricity of ESS
$\rho_{ESS,t}^{dis}$	power loss rate of ESS discharging at time t
$\rho_{ESS,t}^{chr}$	power loss rate of ESS charging at time t
$\bar{g}_{EV,t}^{chr}$	maximum discharging power of ESS at time t
$\bar{g}_{EV,t}^{dis}$	maximum charging power of ESS at time t
$\Delta L_{PB,t}^{\max}$	maximum load change at time t
$\Delta \bar{L}_{PB}, \Delta \underline{L}_{PB}$	pickup/drop off rate of load produced by PBDR
$\Delta L_{PB}^{\max}$	maximum load change
$g_{VPP,t}^{\max}$	maximum output of VPP at time t
$g_{VPP,t}^{\min}$	minimum output of VPP at time t
r_1, r_2, r_3	up reserve coefficients of load, WPP and PV