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Day-ahead stochastic economic dispatch of wind integrated power system considering demand response of residential hybrid energy system ☆

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HIGHLIGHTS

- Improving the utilization of wind power by the demand response of residential hybrid energy system.
- An optimal scheduling of home energy management system integrating micro-CHP.
- The scattered response capability of consumers is aggregated by demand bidding curve.
- A stochastic day-ahead economic dispatch model considering demand response and wind power.

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ABSTRACT

As the installed capacity of wind power is growing, the stochastic variability of wind power leads to the mismatch of demand and generated power. Employing the regulating capability of demand to improve the utilization of wind power has become a new research direction. Meanwhile, the micro combined heat and power (micro-CHP) allows residential consumers to choose whether generating electricity by themselves or purchasing from the utility company, which forms a residential hybrid energy system. However, the impact of the demand response with hybrid energy system contained micro-CHP on the large-scale wind power utilization has not been analyzed quantitatively. This paper proposes an operation optimization model of the residential hybrid energy system based on price response, integrating micro-CHP and smart appliances intelligently. Moreover, a novel load aggregation method is adopted to centralize scattered response capability of residential load. At the power grid level, a day-ahead stochastic economic dispatch model considering demand response and wind power is constructed. Furthermore, simulation is conducted respectively on the modified 6-bus system and IEEE 118-bus system. The results show that with the method proposed, the wind power curtailment of the system decreases by 78% in 6-bus system. In the meantime, the energy costs of residential consumers and the operating costs of the power system reduced by 10.7% and 11.7% in 118-bus system, respectively.

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1. Introduction

Wind power, which is a kind of clean energy, has received wide attention and support from the whole world. However, the stochastic variability of wind power output become increasingly significant as the growing wind power capacity. Since the ramping ability of thermal units cannot cope with such large power fluctuation, the power output of wind farm is limited in the power system scheduling [1]. According to the latest statistics of China's National Energy Administration, as of the first half of 2016, the total installed capacity of large-scale wind farms has been up to 137 million kilowatts. Whereas the average utilization time of wind power is only 917 h and the average wind power curtailment is 21% [2]. Therefore, the stochastic variability of wind power output is gradually becoming a bottleneck restricting the development and utilization of wind power [3]. It should be noted that this variability, which leads to the mismatch of demand and generated power, means the variable wind power output caused by

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Nomenclature

Δt	time step
T	set of time periods
$p_{ein,t}$	price when consumers imported electricity at time t
$p_{eout,t}$	price when consumers sold electricity at time t
$p_{gas,t}$	natural gas price
$g_{total,t}$	total gas used at time t
$e_{in,t}$	electricity imported at time t
$e_{out,t}$	electricity sold to the grid at time t
X	set of home smart appliances
$s_{x,t}$	on/off state of device x at time t
$p_{x,t}$	output power of device x at time t
P_x^N	rated power device x
P_x^{min}	minimum output power of device x at time t
P_x^{max}	maximum output power of device x at time t
T_x^{start}	the first time that device x can start up
T_x^{end}	the last time that device x must shut down
T_x^{last}	successive operation time of device x
T_x^{total}	required operation time of device x
η_x	efficiency of device x
$\theta_{in,t}$	inside temperature of the house at time t
$\theta_{out,t}$	forecasted outside temperature of the house at time t
θ_{in}^{min}	minimum inside temperature of the house
θ_{in}^{max}	maximum inside temperature of the house
ε_{air}	factor of inertia of air
κ_{air}	thermal conductivity
$\theta_{fr,t}$	inside temperature of the fridge at time t
θ_{fr}^{min}	minimum inside temperature of the fridge
θ_{fr}^{max}	maximum inside temperature of the fridge
ψ_{fr}	warming effect of the usage of the fridge per time
φ_{fr}	cooling effect of an ON state of the fridge per time
Ω_{fr}	warming effect of an OFF state of the fridge per time
$A_{fr,t}$	activity level of fridge at time t
$v_{prim,t}$	on/off state of the micro-CHP prime mover at time t
$v_{aux,t}$	on/off state of the micro-CHP auxiliary burner at time t
$u_{start,t}$	binary variable denoting start up of the prime mover at time t
$u_{close,t}$	binary variable denoting shut down of the prime mover at time t
T_{ref}	start-up time of the fuel cell
$e_{prim,t}$	electric power generated by the prime mover at time t
e_{prim}^{min}	minimum electric power generated by prime mover
e_{prim}^{max}	maximum electric power generated by prime mover
e_{prim}^{min}	minimum electric power generated by prime mover
e_{prim}^{max}	maximum electric power generated by prime mover
e_{ramp}	electric ramp capacity of the prime mover
$h_{prim,t}$	heat power generated by the prime mover at time t
$h_{aux,t}$	heat power generated by the auxiliary burner at time t
$h_{s,t}$	heat power stored by tank at time t
$h_{d,t}$	heat power needed by consumers at time t
η_e	electric efficiency of the prime mover
η_h	thermal efficiency of the prime mover
η_{aux}	thermal efficiency of the auxiliary burner
$g_{prim,t}$	gas consumed by the prime mover at time t
$g_{aux,t}$	gas consumed by the auxiliary burner at time t
g_{ref}	gas used for heating up the reforming unit during start-up
$\boldsymbol{d}_i$	demand curve aggregated from all consumers under node i
$\boldsymbol{p}_b$	benchmark price curve
Δp_e	unit price changes
N_{cus}	the number of HEMSs under a node
N_{tes}	the number of points for testing demand curve
G	the directed graph that reflect the grid structure
N	set of nodes
E	set of lines
N_G	set of thermal units
N_W	set of wind units
N_D	set of loads
$d_{i,t}$	electric load of load i at time t
$d_{i,t}^{min}$	minimum load of load i at time t
$d_{i,t}^{max}$	maximum load of load i at time t
$p_{i,t}$	generation dispatch of thermal unit i at time t
P_i^{min}	minimum capacity of thermal unit i
P_i^{max}	maximum capacity of thermal unit i
$w_{i,t}$	generation dispatch of wind unit i at time t
w_i^{max}	maximum capacity of wind unit i
$w_{a,i,t}$	actual available power of wind unit i at time t
$k_{un,i}$	underestimation cost coefficient of wind unit i
$k_{ov,i}$	overestimation cost coefficient of wind unit i
$P_{L,i,j}^{max}$	maximum transmission capacity of the line from node i to j
$r_{u,i,t}$	up regulation reserves provided by thermal unit i at time t
$r_{d,i,t}$	down regulation reserves provided by thermal unit i at time t
c_u	confidence level for having sufficient up regulation reserves
c_d	confidence level for having sufficient down regulation reserves

intermittence of wind energy. Many scholars have proposed the demand response technology using the regulating capability of load to balance the wind power variability [4,5]. With the micro-CHP and smart home appliances, residential users turn from passive energy consumers to elastic loads, and they gradually have the demand response capability. Since micro-CHP has the characteristics of gas and electricity coupling, users can build residential hybrid energy systems and meet their electricity demand from both the power grid and the natural gas network. Hence, the interaction between this kind of residential users and power system needs to be further analyzed.

At the level of power system, some existing research considers demand response in the scheduling problem. Ref. [6] presents an economic model of demand response, which explains the change of consumption pattern and cross-period shift of loads. Ref. [7] makes an integration of demand response programs and dynamic economic dispatch. A market clearing mechanism considering both demand-side and supply-side bidding is described in Ref. [8]. In addition, a bi-level optimization model of system-wide demand response management is presented in Ref. [9]. Some research also considers the coordination of demand response and wind power. Ref. [10] studies the bidding strategy of Load Serving Entities (LSEs), taking into account the stochasticity of wind power by probabilistic scenarios. In Ref. [11], a robust optimal dispatching model, which combines robust optimization and dynamic optimization, is constructed, considering demand response and its impact on wind power in various cases. Ref. [12] proposed a probabilistic unit commitment model with incentive-based demand response and high wind power, using an operational-cycle-based algorithm. A demand response market is designed in Ref. [13], and the quantity of residential demand response is optimized. In Ref. [14], the interruptible-load based and coupon-based demand

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