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Operation optimization strategy for wind-concentrated solar power hybrid power generation system

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ABSTRACT

This paper presents a new hybrid system to reduce wind curtailment and improve scheduling flexibility. This hybrid system includes a wind farm, a concentrated solar power plant with thermal energy storage, and an electric heater. The major role of the electric heater is to convert the redundant wind power into thermal energy, and the thermal energy is stored in the thermal energy storage of the concentrated solar power plant. The optimal scheduling of this hybrid system is formulated as a mixed-integer linear programming problem to maximize the profit subjected to technical constraints. The effects of the electric heater on the system are studied under different weather conditions. The test results show that the electric heater is helpful for reduction of the both deviation from generation plan and wind curtailment. The maximum relative deviation falls from 5.15% to 0% during the clear sky day, and 47.49% to 31.74% during the partial cloudy day. The wind curtailment rate decreases by 52.59% and 100% for clear and partial cloudy days, respectively. An annual simulation for the system shows that the overall daily cumulative deviations of the new system are significantly decreased, and the wind curtailment can be reduced by greater than 90% for 151 days, validating the effectiveness of the proposed system.

1. Introduction

Due to the challenges of global environmental problems, the installed capacity of wind power has been rapidly increasing. In China, the installed capacity of wind power reached 149 GW in 2016 [1], which contributes 34.7% of the global wind power capacity [2]. However, even with mature technology, China's wind power industry has faced difficulties in the wind farm dispatching and accommodation since 2010. The difficulties resulted in serious wind curtailment, which mainly refers to the phenomenon that the wind generations are not integrated into the grid and the wind turbines have to be shut down because of the reasons such as safety concerns, technology limitations, grid access management [3]. The wind curtailment decreases the utilization hours of wind power equipment and results in significant energy waste. In 2015, wind curtailment in China has reached 15% [4].

To improve the reliability of wind power and reduce wind curtailment, combining wind power with other forms of energy has been proposed. Sun et al. focus on the day-ahead optimal scheduling of wind-thermal generation considering the statistical features of wind speeds [5]. Laia et al. develop a stochastic Mixed-Integer Linear Programming (MILP) to coordinate the production of thermal and wind energy generation [6]. However, conventional thermal power plants use fossil energy, deviating from the efforts of energy conservation and emissions reduction. Pumped storage hydroelectricity is introduced to the wind farms to mitigate the intermittent behaviors of wind energy, and the design of the hybrid power system is formulated as a MILP problem in [7]. Papaefthymiou et al. focus on the dynamic behaviors of wind-pumped storage hydroelectricity hybrid generation system [8]. Genetic algorithms are applied for optimum sizing of wind-pumped storage hybrid power in [9]. Combining wind power with pumped storage hydroelectricity is an effective mode but is limited by the geography.

Solar energy is one of the most widespread renewable energy, and statistically negatively correlated with wind resource [10]. Therefore, solar energy is a potential resource to hybridize with wind resource. At present, photovoltaic (PV) power generation and Concentrating Solar Power (CSP) plants are the two major solar power techniques.

PV with batteries can not only smooth the power output, but also increase the overall system economic benefits. The techno-economic feasibility of implementing the wind-PV-battery system to supply power to a remote island is investigated in [11]. A method to simultaneously

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Nomenclature

Sets and index

T set of time periods, indexed by t

Constants

C_{SC} irradiation curtailment penalty factor
C_{WC} wind curtailment penalty factor
$E_{\min}$, $E_{\max}$ minimum/maximum storage level of TES
E_0 initial storage level of TES
g_t^{pw} forecasted power of wind farm for period t
L_{st} total load of the grid for period t
$P_{t,\min}^{SE}$, $P_{t,\max}^{SE}$ minimum/maximum power of PB
$P_{t,\min}^{th,H-T}$, $P_{t,\max}^{th,H-T}$ minimum/maximum thermal power of TES from CSP
Δt time interval
$P_{t,\min}^{w,W-T}$, $P_{t,\max}^{w,W-T}$ minimum/maximum power of EH
$P_{t,\min}^{th,T-H}$, $P_{t,\max}^{th,T-H}$ minimum/maximum discharge thermal power of TES
R_t average direct normal irradiation in period t
R_U^{SE}, R_D^{SE} upper and lower ramp rate of CSP plant
S_{SF} area of solar mirror field
T_{minon}^{PC}, T_{minoff}^{PC} minimum run-on/run-off time of CSP plant
γ heat dissipation factor of TES
η_{H-T} thermal efficiency from CSP to TES
η_{W-T} thermal efficiency from EH to TES
η_{T-H} discharge thermal efficiency of TES
π_t electricity price in period t
ω penalty factor for the deviation between system output and generation plan
η the ratio of wind-CSP hybrid power generation system with the total system load
η_{SF} the efficiency from irradiation to thermal
ε allowable deviation of storage level between the beginning and the ending periods in one day

Continuous variables

L_t generation plan in period t
E_t storage level of TES in period t
P_t^{WE} on-grid power from wind farm in period t
P_t^{SE} on-grid power from PB in period t
$P_t^{th,S-C}$ irradiation curtailment power in period t
$P_t^{w,W-C}$ wind curtailment power in period t
$P_t^{th,S}$ solar thermal power available in period t
$P_t^{th,S-H}$ solar thermal power input to the system in period t
$P_t^{th,H-T}$ thermal power of TES from CSP in period t
$P_t^{th,T-H}$ discharge thermal power of TES in period t
$P_t^{th,H-P}$ thermal power input into PB in period t
$P_t^{w,E}$ available wind power in period t
$P_t^{w,W-T}$ output thermal power of EH in period t
P_t^{in} total thermal power input into TES in period t
P_t^{out} total thermal power output into TES in period t
E_T storage level of TES in the ending period in period t

Binary variables

x_t^{PC} ON/OFF state variable of the CSP plant
x_t^{T-H} discharging state variable of TES
x_t^{H-T} charging state variable of TES from CSP
x_t^{W-T} charging state variable of TES from EH

Abbreviation

CSP concentrated solar power
TES thermal energy storage
MILP mixed-integer Linear Programming
HTF heat transfer fluid
PB power block
EH electric heater
SF solar field

optimize the battery capacity and operation strategy is proposed in [12]. A multi-objective optimization model is established for the wind and PV component capacity optimizing in [13]. An optimal scheduling model of wind-PV-battery systems is formulated as a two-stage stochastic programming problem in [14]. However, the lifetime of battery can be shortened by energy dispatches due to deep discharges [15], and is expensive for large-scale applications [16]

CSP is another promising technology to collect solar energy and produce electricity [17]. Unlike PV systems, Thermal Energy Storage (TES) is used in the CSP plant. The TES system is much economical than electromechanical or electromagnetic storages such as batteries and is easy to be implemented in large scale [18]. The storage efficiency can reach 95–97%, which is higher than the efficiencies of other frequently-used energy storage methods. The TES system allows CSP plants to cope with uncertainty in solar energy availability, mitigate short-term load fluctuations and shift/extend the energy supply period. Therefore, CSP is an ideal technology to hybridize with other intermittent energy technologies for power generation. Petrollese et al. proposed a hybrid power generation system based on CSP and PV plants to provide fully dispatchable power using only solar energy [19]. Zhai et al. propose a thermal storage PV-CSP system, in which the high-cost battery is replaced by low-cost TES [16]. Several researches have also been focusing on the integration of wind farms and CSP plants. Sioshansi et al. show that integrating CSP plants with wind farms can improve the capacity factor of the hybrid plants [10]. Pousinho et al. focus on the self-scheduling for the wind-CSP system under the considerations of the electricity price and the spinning reserve market [20]. Zhang et al. propose a day-ahead scheduling strategy for wind-CSP plants, and the schedule is based on a bi-level mathematical programming method [21]. Chen et al. propose an adaptive robust model for the scheduling of wind-CSP hybrid system [22].

However, the above studies still operate wind and CSP power systems independently and there are no additional measures when wind curtailment occurs. Therefore, in this paper, a new equipment called Electric Heater (EH) is introduced into the hybrid system. The EH converts the curtailed wind power into heat energy, which is then stored in the TES and can be used to generate power by CSP later. The EH can not only provide a way to utilize curtailed wind power, but also increase the flexibility of the hybrid system as an additional heat source to the TES.

The day-ahead scheduling of this hybrid system is studied in this paper. The MILP is very powerful for mathematical modeling and applied successfully to solve large-size scheduling problems in power systems, having binary variables for modeling start-up constraints [23]. Moreover, MILP has the advantage of having proficiency tested solvers which is not only able of reducing the computation time, but also is capable of finding a globally optimal solution [20]. MILP is used to optimally manage energy and heat generation, storage and demand for micro-grids in [24]. A stochastic MILP approach is presented for solving the self-scheduling problem of a thermal and wind power system in [6]. Xu et al. propose a stochastic optimal scheduling method based on scenario analysis, which uses MILP method to optimize the scheduling