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Robust optimal design of distributed energy systems based on life-cycle performance analysis using a probabilistic approach considering uncertainties of design inputs and equipment degradations

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HIGHLIGHTS:

- A robust optimal method for distributed energy system (DES) design considering uncertainties is developed.
- The life-cycle performance of DES is used as the design optimization objective.
- Uncertainties of design inputs and equipment degradation are quantified.
- A probabilistic approach is adopted to perform the process of the robust optimal design.
- Advantages of this proposed design method in DES planning are provided.

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ABSTRACT

Uncertainties in design inputs (i.e. energy demand and energy price) and equipment degradations in operation result in that the actual performance of distributed energy systems (DESs) deviates from the design expectations significantly. To ensure that DESs designed can operate at high performance when the actual working environment and equipment performance change over a large range, a robust optimal design method based on life-cycle performance analysis is developed. This method adopts a probabilistic approach, which is based on quantifying the uncertainties of design inputs and equipment degradations, while Monte Carlo simulation method is adopted to model the uncertainty propagation and generate the probability distribution of the predicted DES performance in the design process. The "probabilistic" life-cycle performance of DES is therefore obtained and used for the robust optimal design. The method further identifies the optimum DES which has the best life-cycle performance expectation under the above conditions concerned. A case study is conducted on the DES design in a district in Hong Kong to test the application of this method. It is found that, compared with other schemes, the optimum DES has least life-cycle total cost and better robustness of performance under different operating conditions. The DES identified by this method achieves economic benefits and higher total system energy efficiency in the latter years of its life-cycle compared with the DES identified by optimal design method without considering the life-cycle performance. Conclusions of this study can be also used as references for DES life-cycle performance assessment for DES designers.

1. Introduction

Distributed energy systems (DESs) have been developing rapidly as kinds of high efficiency and high reliability energy system in the last decades [1]. Integrating the supply of electricity, thermal energy and gas, DESs are able to achieve the effective control of energy distribution, and energy cascade utilization [2,3]. Solar photovoltaic, wind power and other renewable energy technologies, which can reduce the primary energy consumption as well as the emission of greenhouse gas significantly in the process of energy generation, are adopted in DESs [4,5]. According to whether it is connected to the utility grid, DESs can be divided into grid-independence systems and grid-connected systems. The former can reduce the cost of establishing a long-distance power networks and the loss in power transfer in energy supply for remote districts [6]. The latter can improve the system reliability and achieve peak demand shaving by coupling with the utility grid [7,8].

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Nomenclatures

Abbreviations

ATSE	annual total system energy efficiency
DES	distributed energy system
DG	distributed generation
LTC	life-cycle total cost
PDF	probability distribution function

Parameters

C_d	cooling demand (kW)
C_{AC}	generated cooling of absorption chiller (kW)
C_{CAP}	cooling capacity (kW)
C_{EC}	generated cooling of electric chiller (kW)
C_{EM}	cost of carbon emission (USD)
C_{INV}	investment cost of the DES (USD)
C_{OPR}	annual operating cost of the DES (USD)
C_{PEN}	penalty due to cooling demand dissatisfaction (USD)
$CC_{equipment}$	capital cost of equipment (USD)
$CC_{CHW\_networks}$	capital cost of chilled water distribution network (USD)
$CC_{heat\_rejection}$	capital cost of heat rejection system (USD)
CEF	carbon emission factor (kg/kWh)
CM_{DG}	maintenance cost coefficient (USD/kWh)
COP_{AC}	COP of absorption chiller
COP_{EC}	practical COP of electric chiller
$COP_{EC,FL}$	full-load COP of electric chiller
$Cost_e$	price of electricity (USD/kWh)
$Cost_f$	price of natural gas (USD/kWh)
$Cost_{e,\ sell}$	feed-in tariff (USD/kWh)
CP_{DG}	capacity of distributed generation (kW)
CP_{AC}	capacity of absorption chiller (kW)
CP_{EC}	capacity of electric chiller (kW)
$E_{building}$	building base electricity demand
E_d	electricity demand (kW)
E_{EC}	electricity demand of electric chiller (kW)
E_{DG}	generated electricity of DG (kW)
E_{DNet}	electricity demand of chilled water distribution network (kW)
E_{grid}	imported electricity in the DES (kW)
E_{HRS}	electricity demand of heat rejection system (kW)
E_{sell}	exported electricity in the DES (kW)
$EC_{emission}$	carbon emission tax (USD/t Ce)
F_{DG}	fuel consumption of distributed generation (kWh)
F_{Plant}	fuel consumption of central power plant (kWh)
F_{trend}	trend factor
INC	annual income of the DES (USD)
Pen^C	penalty price (USD/kW)
Q_r	maximum recovered heat from distributed generation (kW)
$Q_{r,\ AC}$	recovered heat used by absorption chiller (kW)
UM^C	unmet cooling demand (kW)
r_P	part load ratio (%)
β	probability of demand satisfaction (%)
η_T	total efficiency of distributed generation (%)
η_{DG}	electric efficiency of distributed generation (%)
$\eta_{DG,FL}$	full-load electric efficiency of distributed generation (%)

The system design is one of important issues in the investigations of DES technologies [9,10]. A properly designed DES not only makes substantial economic benefits for investors, but also further improves energy efficiency of the system [11]. Due to the diversity of power generation technologies and the coupling between different equipment, DES design is a complex problem which needs to be solved at the beginning of the project [12,13]. Generally, the purpose of DES design is to identify the appropriate equipment capacities and associated operation strategies. Many studies on the DES optimal design which aims to improve the advantages of this system have been conducted. With given design inputs, for example, energy demands and energy prices, the DES optimal design is obtained by solving objective functions [14]. The optimal design is able to solve the problem of complex DES planning effectively. The study conducted by Ameri and Besharari indicated that the optimally designed DES, which integrates renewable generations and district thermal systems, can achieve considerable costs saving and CO_2 emission reduction compared with the existing energy system [15]. Studies on DES optimal design reveal the potentials of this technology in different climate regions. Some advices for DES development can be provided by analyzing the performance of this system [16,17]. Optimal design methods also be used for DES planning in large scale districts. Falke et al. developed an approach that integrates economic and ecological optimization for DES optimal design in a district of 150 buildings. They decomposed the optimization problem and denoted that this method is able to reduce computation complexity while guarantee sufficient accuracy [18]. However, those DES optimal design methods aim to maximize the system performance for the very early years, i.e., the new installations, and ignored the variation of system performance through life-cycle. In fact, the performance of DESs changes due to the variations of system operating conditions. Designing a DES which is able to operate with high performance in its life-cycle is an important issue. Huang et al. proposed an optimal design method for energy system in near-zero energy buildings based on the evaluation of life-cycle performance. Results proved that this energy system run with high energy efficiency through its operating years [19,20]. However, the DES design methods based on its life-cycle performance assessment cannot be found in literature.

Uncertainties are used to describe the possible variations of design inputs which cannot be reflected in conventional energy system design methods [21]. These uncertainties result in a situation that the DES performance has stochastic changes. Rezvan et al. adopted a probabilistic method to describe the uncertainty of energy demand in an investment of DESs in buildings [22,23]. They quantified the uncertain thermal demands of a building based on a random distribution, and estimated the system operation cost and proposed the appropriate design by means of stochastic programming. The uncertainty of energy price should not be ignored due to the impacts of energy markets [24]. Mavrotas et al. [25] investigated the impacts of uncertainties of the economic parameters such as the fuel costs and the interest rate on a hospital DES planning. It indicates that different probability distribution schemes of parameters lead to different probability distributions of DES annual cost. The DES robust optimal design method is proposed to identify the system which can run with high performance and robustness under variationally operating conditions [26,27]. This method usually quantifies the uncertainties of design inputs first, and obtains the optimization results by solving objective functions using some probabilistic approaches. The existing studies, however, only consider uncertainties in one operating year without considering uncertainties in the DES life-cycle. In fact, energy demands and energy prices cannot be kept at constants but vary following some trends in the life-cycle of DESs. Therefore, the trends of those variations should be considered in the quantification of uncertainty.

Degradation of equipment, which is defined as the reduction of its performance or outputs after a long time of operation, is inevitable for system operation in the real case. Studies on equipment degradation are conducted to prevent the energy system from operating in low