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An energy systems engineering approach for the design and operation of microgrids in residential applications

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ABSTRACT

A distributed energy system refers to an energy system where energy production is close to end use, typically relying on small-scale energy distributed technologies. It is a multi-input and multi-output energy system with substantial energy, economic and environmental benefits. However, distributed energy systems such as micro-grids in residential applications may not be able to produce the potential benefits due to lack of appropriate system configurations and suitable operation strategies. The optimal design, scheduling and control of such a complex system are of great importance towards their successful practical realization in real application studies. This paper presents a short review and an energy systems engineering approach to the modeling and optimization of micro-grids for residential applications, offering a clear vision of the latest research advances in this field. Challenges and prospects of the modeling and optimization of such distributed energy systems are also highlighted in this work.

Keywords: Distributed energy systems; Energy scheduling; Energy supply chains; MILP; Unit Commitment Problem; CHP

1. Introduction

A distributed energy system refers to an energy system where heat, cooling and power are produced close to end use, which usually consists of various distributed energy resources and many modular and small-scale distributed energy technologies. There are a number of benefits that can be derived from distributed energy systems (Akorede et al., 2010; Bayod-Rújula, 2009; Pepermans et al., 2005). Firstly, distributed energy system can achieve cascade utilization of energy by tri-generation of heat, cooling and power, leading to a higher energy efficiency in contrast to traditional centralized energy systems. Secondly, on-site production of energy reduces the amount of power that must be transmitted from centralized plant, and avoids resulting transmission and distribution losses as well as the associated costs. Thirdly, it can increase the penetration of renewable energy resources, thereby reducing the consumption of fossil energy and building up a diverse energy portfolio. Due to the improved efficiencies, small transmission losses and increased penetration of renewable energy, greenhouse gas emissions as well as other noxious emissions such as oxides of sulphur and nitrogen (SO_x/NO_x) are minimized, therefore benefiting the environment. As an essential supplement of the power system, distributed energy systems can also improve the reliability of the grid, serve as backup or peaking systems and provide energy to remote areas without grid coverage.

Distributed energy system has plenty of potential advantages, however industrial experience indicates that it may not be able to produce the potential benefits due to lack of appropriate system configurations and suitable scheduling and controlling strategies.

From the design perspective, if the capacity of equipment is designed below the required level, the system may not be able to satisfy the peak loads. However, if the capacity is considerably larger than the optimal one, the economics of the system will be jeopardized by high investment costs.

The appropriate operation of distributed energy system is also a critical issue to achieve a robust and economically attractive performance under uncertainties and disturbances

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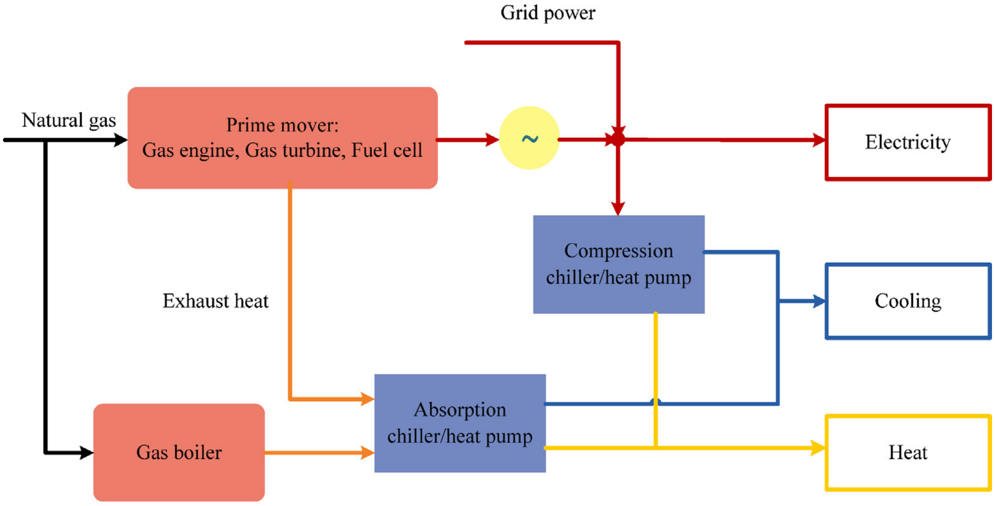

Fig. 1 – A typical CCHP system.

due to the availability of renewable energy sources and the rapid changes in the power/heat demand. Power/heat generation scheduling in distributed energy systems requires more decisions to be taken such as the power exchange with the upstream grid and the charging and discharging of energy storage systems. Furthermore, the operation of microgrids during isolated mode is a challenging task due to the limited resources available to meet the demand and the reserve requirement.

This paper presents a review of the current state of the art in the modelling and optimization of distributed energy systems, offering a clear vision of the latest research advances in optimal design and operation of distributed energy systems. In Section 2 we present the key challenges in the optimal design of distributed energy systems, such as diversity of distributed energy technologies, description of characteristics of different technologies, depiction of varying energy demands and uncertainties of input parameters. Existing works are compared according to how the key design issues are dealt in different studies. The subsequent section reviews state-of-the-art techniques related to the scheduling and operation of distributed energy systems and highlights key challenges from the Process Systems Engineering perspective. Finally in section 3 challenges and prospects of the modeling, design, scheduling and optimization of distributed energy systems are drawn up.

2. Optimal design of distributed energy systems

2.1. A generic description of the design problem

To address issues related to the optimal design of distributed energy systems, a number of mathematical models have been proposed. A common structure of these models is presented in Fig. 1. The required inputs of the model involve local resource constraints, energy demands and energy prices. The outputs of the models are combination of technologies and capacities of selected technologies. Technological parameters, e.g., efficiency, as well as financial parameters, e.g., investment cost, are pre-determined in the models. The objective function could be a scalar or a vector involving cost, profit, energy and environmental behaviours. At each point in time, following constraints must be met:

- Mass and energy should be balanced for each equipment
- Primary energy consumption should meet local constraints
- Energy production can satisfy demands of end users
- The sizes of equipment should be large enough to meet peak loads

The features of optimal design of distributed energy systems involve using binary variables to represent the selection of types of equipment and considering both design variables and operational variables. The design problem can be expressed generally as follows:

$$\begin{aligned}
\min_{b,d,x_t} \quad & f(b, d, x_t) \\
\text{s.t.} \quad & \phi^{dc}(b, d) = 0 \\
& \psi^{dc}(b, d) \leq 0 \\
& \phi^{oc}(b, d, x_t) = 0 \\
& \psi^{oc}(b, d, x_t) \leq 0 \\
& b \in \{0, 1\}^m,\ d \in \Re^1,\ x_t \in \Re^n
\end{aligned} \tag{1}$$

where,

- $\boldsymbol{b}$ is a vector of binary design variables, representing the selection (or not) of types of equipment
- $\boldsymbol{d}$ is a vector of continuous design variables, which represent continuous decisions to be made at the design stage, *e.g.*, the capacities of equipment, and the like
- $\boldsymbol{x}_t$ denotes a vector of continuous operational variables, representing quantitative decisions to be made at any point in time t
- $\boldsymbol{f}$ represents the objective function, which could be a scalar or a vector involving cost, profit, energy, and environmental behavior. If $\boldsymbol{f}$ is a vector, the problem becomes a multi-objective problem
- $\boldsymbol{\varphi}^{dc}$ and $\boldsymbol{\psi}^{dc}$ are equality and inequality design constraints, which involve design variables $\boldsymbol{b}$ and $\boldsymbol{d}$ only
- $\boldsymbol{\varphi}^{oc}$ and $\boldsymbol{\psi}^{oc}$ are equality and inequality operational constraints, which involve operational variables $\boldsymbol{x}_t$ and/or design variables $\boldsymbol{b}$ and $\boldsymbol{d}$

Although these models share a common structure, they are different from each other in several aspects. In the next section, different features of these models will be introduced.