Energy xxx (2016) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Profit allocation analysis among the distributed energy network participants based on Game-theory

Qiong Wu [a], Hongbo Ren [a, *], Weijun Gao [b], Jianxing Ren [a], Changshi Lao [c]

[a] College of Energy and Mechanical Engineering, Shanghai University of Electric Power, 200090 Shanghai, China
[b] Faculty of Environmental Engineering, The University of Kitakyushu, 808-0135 Kitakyushu, Japan
[c] Clean Energy Technology Center, Innova Institute of New Energy, 518038 Shenzhen, China

ARTICLE INFO

Article history:
Received 28 April 2016
Received in revised form
11 October 2016
Accepted 26 October 2016
Available online xxx

Keywords:
Distributed energy network
MILP
Core
Game-theory
Profit allocation

ABSTRACT

To overcome the supply-demand imbalance problem within a conventional distributed energy system, the distributed energy network (DEN) based on electricity and heat interchanges is proposed. With rational design and operation, the DEN may achieve satisfied economic performance compared with the situation without energy interchange. However, the maximum of overall economic benefits does not necessarily lead to satisfied economic performance for each consumer. Therefore, to promote the consumers' participation in the DEN, an effective and fair allocation mechanism for the additional profit is necessary. In this study, firstly, a mixed-integer linear programming (MILP) model is proposed to deal with the optimal technique selection, lay-out of the energy transmission line and running strategy of the DEN. Then, a mathematical model for fair benefit allocation amongst the participants is presented based on the core method of the cooperative Game-theory. As an illustrative example, three buildings located in Tokyo, Japan have been selected for analysis. According to the simulation results, total annual cost is reduced by 14.5% thanks to the energy interchange within the DEN. Moreover, fair profit allocation mechanism is determined by employing the core method. In this way, a win-win solution is achieved for both group interests and individual interests.

1. Introduction

Distributed energy resource (DER) system has been widely recognized as an efficient alternative to the centralized energy generation, since it may avoid long-distance transmission loss and provide reliable power supply in case of blackout [1]. In addition, different from the traditional energy system, a DER system may employ various kinds of on-site technologies, e.g., combined heat and power units (CHP, such as gas turbine, gas engine and fuel cell, etc.), renewable energies (photovoltaics, wind turbines and geothermal energy, etc.), as well as some energy storage technologies (battery, thermal storage tank, etc.) [2–4]. Especially, in recent years, as a typical on-site energy generator, the CHP system with co-production of heat and power has attracted more and more attention [5,6]. However, the heat-to-power ratio of the CHP unit is not always in agreement with the fluctuating electric and thermal demands of the customers. In order to overcome the mismatching problem, the distributed energy network (DEN) based on electricity and heat interchanges among the customers has been proposed. Within a DEN system, by taking advantage of the diversified load profiles of various consumers, a complementary and interactive framework may be formed, so as to overcome the unbalance issue between demand and supply sides of a single consumer.

It is worth noting that, before establishing a DEN system, two key points should be paid enough attention. On the one hand, in order to realize the best performance of the DEN, appropriate selection of energy generators, optimal lay-out of energy distribution infrastructure, as well as optimal running strategy are essential. On the other hand, although the permission of energy interchange among the consumers may reduce total energy cost from the network level, the maximum of overall economic benefits does not necessarily lead to satisfied economic performance for each consumer which may belong to a specific stakeholder. For each consumer, the incentive to join in the energy network lies on increased profits through local energy interchange. However, from the viewpoint of the whole network, some consumers may produce more energy than its own needs. If the increased running cost of excess energy supply is not assessed and compensated in an

* Corresponding author.
E-mail address: tjrhb@163.com (H. Ren).

http://dx.doi.org/10.1016/j.energy.2016.10.117
0360-5442/

Nomenclature

Symbols

Bmax	maximum capacity of boiler (kW)
Bmin	minimum capacity of boiler (kW)
Capb	boiler capacity (kW)
Capc	compression chiller capacity (kW)
Capchp	CHP capacity (kW)
Capcmax	maximum capacity of compression chiller (kW)
Capo	capacities of generators other than CHP (kW)
Ce	equipment cost ($)
Cele	electricity cost ($)
Cgas	gas cost ($)
Cinv	investment cost ($)
Cl	cooling demand (kW)
Com	O&M cost ($)
COP	coefficient of performance
CRFchp	Capital Recovery Factor of CHP
CRFo	Capital Recovery Factor other than CHP
CRFp	Capital Recovery Factor of pipeline
CRFw	Capital Recovery Factor of wire
Csal	revenue from feed-in electricity ($)
Ct	annual total cost ($)
Ctrans	energy transfer cost ($)
Ctrs	transfer line cost ($)
D	days per month
Dist	distance (m)
Ebuy	electricity purchased (kW)
Echp	electricity from CHP (kW)
Edl	electricity delivered (kW)
El	electricity load (kW)
Eneo	energy output (kW)
Esal	feed-in electricity (kW)
Hb	heat from boiler (kW)
Hchp	heat from CHP (kW)
Hdl	heat delivered (kW)
Her	heat-to-power ratio
Hl	heat load (kW)
Irst	interest rate (%)
LifeN	lifetime (Year)
M	upper bond
n	index of participants
Omf	unit fixed O&M cost ($/kW)
Omp	O&M cost for pipeline ($/m)
Omv	unit variable O&M cost ($/kWh)
Omw	O&M cost for wire ($/m)
OR	visiting order of each node
Pe	price of electricity ($/kWh)
Pesal	electricity buy-back price ($/kWh)
Pg	price of gas ($/kWh)
UCchp	unit cost of CHP ($/kW)
UCo	unit cost of generator other than CHP ($/kW)
Ucp	unit cost of pipeline ($/m)
Ucw	unit cost of wire ($/m)
V(N)	profit of grand coalition ($)
V(S)	profit of part coalition ($)
x_i	distributed profit ($)

Binary variables

In,Out	0-1 variable
yb	selection of boiler
ychp	selection of CHP
yp	selection of pipeline
yw	selection of wire

Set

N	set of the participants
S	subset of players
X	profit vector

Subscripts

h	duration hours in a day
i,j	index of consumer (player)
k	index of CHP unit
m	months
p	index of distributed generator except CHP

Greek letters

η	efficiency (%)
γ	power efficiency of CHP (%)
σp	energy loss ratio of pipeline (%)
σw	energy loss ratio of wire (%)
$\mathcal{E}$	objective value

effective way, the conflict of interest may be formed among the consumers and the partnership will be broken. Therefore, in order to promote the cooperation of the consumers and insure the stability of the coalition, it is essential to balance and allocate the achieved profit gains among the participants in a rational and fair manner.

Several studies have been conducted on the DEN system. For instance, Casisi et al. [7] proposed an optimization model minimizing the annual cost of a district heating network and applied it to a real city centre. Bracco et al. [8] presented a multi-objective mixed-integer linear programming (MILP) model for the optimal design and operation of an energy system in a limited urban area connected by a heat distribution network. Weber et al. [9] proposed the Distributed Energy System Design and Optimization (DESDOP) tool for optimal generators selection and distribution network arrangement. Omu et al. [10] developed a MILP model for the optimal design of a distributed energy system including the determination of technology combination, unit size, unit location as well as distribution network structure, and applied it to a cluster of commercial and residential buildings. However, all of the abovementioned studies focused on the optimal design and performance analysis of the DEN from the overall viewpoint, without considering the profit payoff for each consumer participating in the DEN. Nevertheless, to maintain the cooperative relationship, the main issue is to find an effective way to allocate the benefits of a joint effort among the participants, while taking into account individual and group incentives, as well as various fairness properties [11]. This problem perfectly matches the cooperative Game-theory concept [12], which has a set of mathematical tools to deal with the profit allocation issues among independent rational players [13].

The concept of Game-theory has proved its success to deal with the conflict of interests in the energy fields. Specially, as to the local energy system, some attempts have been reported on the analysis of the cooperative relationship within a micro-grid [14,15]. Su et al. [12] applied the novel Game-theoretic algorithms to clear the retail electricity market price in future residential distribution systems