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Optimisation of multicarrier microgrid layout using selected metaheuristics☆

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ABSTRACT

This paper presents an efficient methodology of optimising the structure of a multicarrier energy microgrid. The term 'microgrid structure' denotes the type and parameters of energy microsources and storage devices with which a microgrid might be equipped. In order to represent a generation and storage structure of a microgrid, the use of a modified energy hub model has been proposed. An energy hub may be defined as an interface between energy demand/ generation and power supply infrastructure or available local energy resources. The process of planning a technically permissible and economically efficient microgrid structure entails the necessity of providing an adequate optimisation solution. This paper proposes for the first time a solution to the optimal planning problem with a novel energy hub model recently developed by the author. The main objectives for a given problem are set, and then a detailed mathematical model of a stated optimisation problem is described. Both the criterion function and a set of constraints has been presented in detail. Then, two independent metaheuristics - the evolutionary algorithm and particle swarm optimisation - have been proposed and substantiated as exemplary methods of solving the formulated optimisation problem. In the next part of the paper, a calculation example has been presented for the given optimisation problem. The obtained results have been widely analysed and discussed, and areas and topics of future research about the microgrid planning process have also been further presented.

1. Introduction

Power industry in mini- and micro-scale still remains a fundamental element of the public worldwide debate over renewable energy as well as energy effectiveness policies. In particular, the engagement of energy consumers in the power delivery process is widely discussed. Extensive literature indicates a technical and economical opportunity for individual energy consumers and producers to organise themselves into structures referred to as 'microgrids'.

The microgrid concept has been created as a result of the development and implementation of different 'smart grid' initiatives. A microgrid can be defined as a local system of power and energy delivery to individual consumers. Such micro power systems usually consist of small generation and storage units, including local demand response systems [1,2]. A significant feature of the microgrid paradigm is the availability of energy conversion between different carriers, including combined generation. Energy carrier conversion can be realised, among others, by:

- gas boiler (gas → heat),
- solar thermal collector (solar radiation → heat),
- internal combustion engines + generator (gas, liquid fuels → electricity + heat),
- gas microturbine + generator (gas, liquid fuels → electricity + heat),
- photovoltaic system (solar radiation → electricity),
- wind microturbine + generator (kinetic movement of air masses → electricity),
- absorption chiller (heat → cold),
- compression chiller (electric power → cold + heat).

The aforementioned list shows that in a set of locally available energy carriers, energy sources (e.g. electricity) are inherently considered as energy converters. Thus, a microgrid should be regarded as a multicarrier energy supply system [3,4].

An important element of a multicarrier energy delivery system is the so-called 'energy hub'. It is a virtual interface between power load or production, and an energy delivery infrastructure or available energy resources (e.g. renewables). From a system engineering point of view, an energy hub is a unit providing features such as: in- and output,

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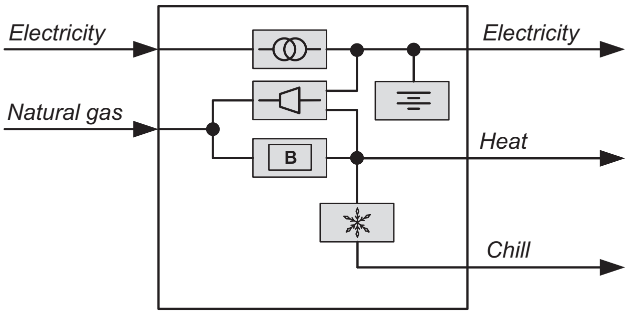

Fig. 1. Exemplary energy hub layout including conversion and storage subunits.

conversion and storage of multiple energy carriers [3,5]. An exemplary structure of an energy hub is shown in Fig. 1. The conversion equipment (looking at the top side of Fig. 1) comprises: an MV/LV electric transformer, a gas microturbine operated in the CHP mode, a gas boiler and an absorption chiller. The electrochemical battery ensures energy storage. It should be emphasised that the presented energy hub model does not represent a power transmission subsystem.

One can distinguish two approaches to the use of the energy hub model in multicarrier energy microgrids:

- microgrid represented by only one energy hub – all the aggregated energy generated and stored in one structure (Fig. 2a),
- microgrid represented by more than one energy hub – particular hubs represent e.g. buildings or settlements and are modelled together with an internal power distribution infrastructure (Fig. 2b).

The application of an energy hub model in multicarrier energy systems (including microgrids) has been a research topic raised in many papers. Most of the papers deal with optimisation research, which concerns both the energy hub structure or layout [6–8] and energy hub operation (power dispatching or scheduling) [6,8–16]. Optimisation problems pertaining to the energy hub model involve not only

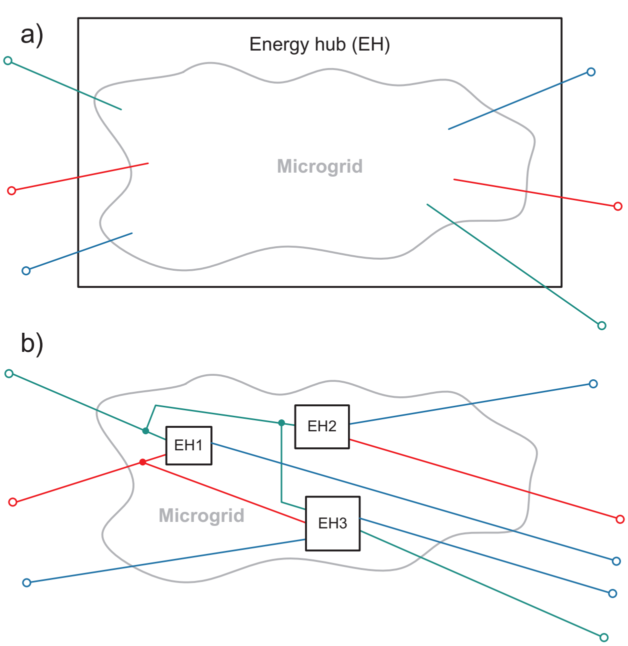

Fig. 2. Exemplary relationship between the terms 'microgrid' and 'energy hub': (a) one microgrid to one energy hub and (b) one microgrid to many energy hubs (particular colors mean different energy carriers).

deterministic, but also uncertainty conditions. The problem of the stochastic nature of renewables, energy prices and demand may be considered in the stochastic programming technique [10]. The probabilistic approach has also been applied solving economic dispatch problem for the energy hub [17].

The conventional model of an energy hub is represented by a 'black box' described by the matrix of coupling factors between input and output terminals. Particular coupling factors represent the efficiency of energy conversion and storage processes [5,6,9]. This model is simple and clear, although it has a number of limitations [3]:

- It is assumed that the power flow from the inputs to the outputs of the converters is unidirectional.
- Input and output terminals of the energy hub model are assigned to an energy delivery infrastructure (energy supply) and power load, respectively.
- Input and output are given *explicite*.
- It is not possible to connect two same-type terminals (two inputs or two outputs) with an energy converter.

Many modifications have been applied to the conventional energy hub model – important technical constraints have been introduces to the energy conversion and storage models within the hub [11]. An interesting modification of the conventional energy hub which resolves the drawback of single directional power flow is the so-called 'smart energy hub' [15]. This concept focuses on load flexibility in the form of a multicarrier integrated demand response. In order to consider the interaction between smart energy hubs, game theory techniques have been applied [16]. In the literature, other proposals of modified energy hub models may be found, e.g. [10,11,14].

Recently, the author has developed an original modification of the conventional energy hub based on the graph theory [3]. The proposed model avoids all the limitations identified for the original hub model. This paper presents for the first time a solution to the optimisation problem with a novel energy hub model recently developed by the author, with optimisation of a multicarrier microgrid layout being considered. The presented research assumes that a microgrid is modelled by one energy hub.

2. Modified model of energy hub

Mathematically, an energy hub model based on the graph theory may be defined as an ordered structure as follows [3]:

$$EH = \begin{pmatrix} \mathscr{E},\mathscr{C},\mathscr{D},c_1,c_2,d,\mathscr{N},\mathscr{A},g, \\ \mathbf{A}_{\text{node}},\mathbf{P}_{\text{node}},\mathbf{P}_{\text{arc}},\boldsymbol{\eta} \end{pmatrix} \tag{1}$$

where:

- $\mathscr{E} = \{1,2,...,|\mathscr{E}|\}$ is a finite nonempty set of indices of considered energy carriers in the energy hub;
- $\mathscr{C} = \{1,2,...,|\mathscr{C}|\} = \mathscr{C}_1 \cup \mathscr{C}_2$ is a finite set of converter indices in the energy hub ($\mathscr{C}_1$ is a set containing two-terminal converters (energy uni-generation) and $\mathscr{C}_2$ is a set containing three-terminal converters (energy co-generation)), $\mathscr{C}_1 \cap \mathscr{C}_2 = \varnothing$; additionally there is a $\mathscr{C}^{\text{rev}} \subseteq \mathscr{C}_1$ subset distinguishing reversible energy converters. It has been assumed that a reversible co-generation technology is not considered. A $\mathscr{C}^{\text{he}} \subseteq \mathscr{C}$ set is further assumed to represent indices of energy converters operating as heat engines related to additional starting cost;
- $\mathscr{D} = \{1,2,...,|\mathscr{D}|\}$ is a finite set of storage indices in the energy hub;
- c_1: $\mathscr{C}_1 \to \mathscr{E}^2$,$c_2$: $\mathscr{C}_2 \to \mathscr{E}^3$,$d$: $\mathscr{C} \to \mathscr{E}$ are functions assigning an individual converter or storage type to a particular energy carrier;