ARTICLE IN PRESS

Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Multiple energy carrier optimisation with intelligent agents

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HIGHLIGHTS

- Integrated technical and market-enabled approach to control of energy hub systems.
- Combination of flexibility of multi-agent systems with inclusivity of energy hubs.
- The methodology can address forecast errors with internal balancing mechanism.
- Cost and emissions reduction, reduction of balancing costs by more than 50%.
- Experimental validation of interface of agent platform with real micro-CHP equipment.

ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 12 September 2015
Accepted 20 October 2015
Available online xxxx

Keywords:
Multiple energy carriers
Energy hubs
Distributed generation
Microgrids
Multi-agent systems

ABSTRACT

Multiple energy carrier systems stem from the need to evolve traditional electricity, gas and other energy systems to more efficient, integrated energy systems. An approach is presented, for controlling multiple energy carriers, including electricity (AC or DC), heat, natural gas and hydrogen, with the objective to minimise the overall cost and/or emissions, while adhering to technical and commercial constraints, such as network limits and market contracts. The technique of multi-agent systems (MAS) was used. The benefits of this approach are discussed and include a reduction of more than 50% in the balancing costs of a potential deviation. An implementation of this methodology is also presented. In order to validate the operation of the developed system, a number of experiments were performed using both software and hardware. The results validated the efficient operation of the developed system, proving its ability to optimise the operation of multiple energy carrier inputs within the context of an energy hub, using a hierarchical multi-agent system control structure.

1. Introduction

It is expected that controllable loads and energy storage devices will be integrated in distribution networks of the future, in addition to distributed generation, thus increasing network complexity [1,2]. Combined Heat and Power (CHP) generation technologies are also expected to form part of this generation mix [2,3]. All these resources can be described as Distributed Energy Resources (DER).

CHP generators can utilise a number of different energy carriers as input fuels, such as natural gas or hydrogen. These carriers are delivered through different networks, which influence the overall efficiency and characteristics of a local energy system, including electricity networks. It has been proposed in [4–6] that these energy carriers should be included in the design and planning phases of an energy system. In [6], an infrastructure planning tool was proposed for the design of energy systems in which heat and electricity carriers are coupled. Combined network analysis methodologies have also been developed [7]. In [8], a tool for integrating economic dispatch and optimal power flows of electricity and gas at the Grid Supply Points of Great Britain has been presented. Electric vehicles can also play a role as mobile resources in multiple energy carrier systems, and this has been discussed in [9,10].

It is necessary to evolve traditional electricity, gas and other energy systems to more flexible, integrated energy systems [11], referred to as multiple energy carrier, or multi-carrier systems. The points of interaction between different energy carriers have been described as “energy hubs” [5,12], which present an

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http://dx.doi.org/10.1016/j.apenergy.2015.10.130
0306-2619/

integrated approach for optimizing systems with multiple energy carriers, such as electricity, hydrogen, or natural gas networks [13]. Devices are incorporated in an energy hub with the purpose of converting from one carrier to another, e.g. a CHP unit converting natural gas to electricity and heat. Storage elements such as batteries or thermal storage may also be considered. The energy carrier inputs to the energy hub are optimised and controlled in order to supply a given set of energy carrier loads/outputs, thus achieving whole-system optimisation [12,14]. In (1), the backward coupling matrix (D_{nm}) which links the inputs (P_m) with the outputs (L_n) is shown, as this is a formality that is used in Section 2.2. The elements of the D_{nm} matrix are constructed using the conversion efficiencies of individual devices in the energy hub [12]. Matrix dimensions are $M \times 1, N \times 1$ and $M \times N$, for P_m, L_n and D_{nm} respectively.

$$\underbrace{\begin{bmatrix} P_\alpha \\ \vdots \\ P_\xi \end{bmatrix}}_{\text{input } P_m} = \underbrace{\begin{bmatrix} d_{\alpha\alpha} & \cdots & d_{\alpha\xi} \\ \vdots & \ddots & \vdots \\ d_{\xi\alpha} & \cdots & d_{\xi\xi} \end{bmatrix}}_{D_{nm}} \underbrace{\begin{bmatrix} L_\alpha \\ \vdots \\ L_\xi \end{bmatrix}}_{\text{output } L_n} \quad (1)$$

A dispatch factor v is defined, which indicates the percentage of any given input that is being used by any given hub element in matrix D_{nm} [12]. For example, in (1), if $d_{\alpha\alpha} = v_1 \times \eta_1$ and $d_{\alpha\xi} = v_2 \times \eta_2$, then $v_1 + v_2 = 1$ where v_1 and v_2 are dispatch factors of conversion devices in the energy hub and η_1 and η_2 their conversion efficiencies. Therefore, (1) can be used to calculate the total energy inputs (P_m) required to satisfy a desired energy output [12]. Optimisation methods are used to minimise the total energy inputs (P_m) by varying the dispatch factors of the individual devices in the energy hub and consequently in the D_{nm} matrix. The problem is normally linear, but can become non-linear if generator part-load conversion efficiencies are taken into account, as their curves are non-linear.

Multi-agent systems (MAS) comprise multiple individual intelligent agents, e.g. installed on a controller of a DER. MAS are classified as a distributed control architecture and have been proposed as a promising technology for addressing control and co-ordination issues in the power industry, including DER [15,16]. In addition, MAS have been proposed for controlling CHP unit clusters [17] and for co-ordinating electric vehicle charging [18–21].

1.1. Related work

The concept presented in this paper combines the multiple energy carrier modelling approach of energy hubs, with the distributed control approach of multi-agent systems. The two concepts are inherently linked by the fact that they are both applicable mostly to distributed energy generation, i.e. local and small rather than central and large power plants. This link is thoroughly analysed in [22,23]. The comprehensive review of optimisation methods in multi-generation systems done in [22] reveals that a wide variety of centralised optimisation algorithms have been used. That includes traditional methods such as linear programming [24] and Lagrangian multipliers [25], as well as artificial intelligence (AI) algorithms such as evolutionary [26] and genetic algorithms [27]. Robust Optimisation (RO) techniques have also been proposed in [28].

On the other hand, a wider conceptual view of the use of multi-agent systems in a market-like structure with multiple layers has been proposed in [29]. Agent-based implementations are by definition market oriented, provided that they use cooperative or competitive negotiation and coordination techniques, and normally use market-like structures to reach an optimal or near-optimal solution [29,30]. Such market-oriented approaches have also been developed by the authors in previous work [18–21]. The key design considerations for agent-based implementations most frequently encountered in the aforementioned literature are:

(a) The need for a commercial interface, which enables access to markets (e.g. power, ancillary services) [18–21,29,31–33].
(b) The need for a technically-oriented supervisory structure, which is responsible for ensuring that the operation of the controlled/optimised resources adheres to technical limits of the infrastructure (e.g. voltage statutory limits, transformer ratings) [18–21,31].
(c) Agents typically possess cognitive abilities, such as complex communication and negotiation algorithms [15,16,29]. The responsive characteristics are very important in real-time power system operation, where time is often insufficient for high-level cognitive functions or communication (e.g. responding to faults).
(d) Hierarchical systems generally resemble the structure of power systems in terms of voltage levels, hence can be considered more suitable than their centralised or distributed counterparts [18–21,29,31].
(e) The need to address or compensate for planning errors, including operation forecasts [21,33,34].

The combined use of multi-agent systems and energy hubs was implied in [9,35], where the focus was on electric vehicles, as well as [36], where an agent-based optimal power flow (OPF) solution was proposed for multiple energy carriers. The use of an agent-based algorithm for economic dispatch of power systems with wind penetration has been proposed in [37].

1.2. Main contribution of the paper

This paper extends the current state of the art, as shown in the literature review, by proposing an integrated technical and market-enabled approach to the control of multiple energy carrier systems, using an agent-based implementation. The main contribution of this paper is the validation of a novel control methodology for controlling multiple energy carriers with multi-agent systems. This methodology was initially described in [10] and its unique contribution is that it enables interaction of the energy hubs with external markets for procuring energy carriers. An additional contribution of this methodology is that it can cater for forecast inaccuracies, by facilitating an internal collaborative balancing mechanism, thus preventing deviations from procurement contracts that may lead to monetary penalties. An implementation of the methodology is presented, as well as case studies, which verify its validity. The case studies include simulations as well as experimental work.

1.3. Structure of the paper

The paper is arranged as follows Section 2 describes the control approach; Section 3 presents the results of a simulated case study and Section 4 the results of an experimental study that validates the feasibility of the agents in real micro-CHP systems. Finally, the main conclusions and future work are discussed in Section 5.

2. Multiple energy carrier optimisation with intelligent agents

2.1. Agent-based control structure design

The proposed control structure includes a number of agents, with different roles. Agents are linked to each of the elements in the energy hub. These agents hold detailed information on the