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Optimal online operation of residential μCHP systems using linear programming

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ABSTRACT

Environmental pressures have resulted in an increased importance being placed on the efficient production and consumption of energy. Micro combined heat and power (μCHP) technology has the potential to make an important contribution to make the transition to more sustainable energy systems since it is a highly efficient technology for generating both electricity and heat from a single fuel source. The conventional operation strategies for these technologies are pre-determined and either heat-led or electricity-led. This paper presents an optimal online operation strategy for μCHP systems, which is more efficient than the aforementioned conventional pre-determined operation strategies. A generic optimal online linear programming (LP) optimiser has been developed for operating a μCHP system. It is generic since it is applicable for any μCHP technology or demand profile. This optimiser is capable of minimising the daily operation costs of such a system. Three different simulation scenarios have been investigated: the new feed-in tariff (FIT) scheme; the trade of electricity; the introduction of a carbon tax. In all three investigated scenarios, the results show that the optimiser significantly reduces operation costs when compared to the conventional pre-determined operation strategies. As such, it is suggested that the optimiser has the potential to deliver significant energy savings in practice.

1. Introduction

International drives towards increased energy efficiency have led to increased interests in μCHP technologies since they have the potential to deliver both electricity and heat from a single fuel source in a highly efficient manner. Many companies are developing this technology for residential applications based on either an internal combustion engine (ICE), a Stirling engine (SE) or a fuel cell (FC) [1]. For instance, Ceres Power is developing a 1.0 kWe solid oxide fuel cell that is expected to be ready for mass production by the middle of 2011 [2].

Recent research conducted by the authors [3] has shown that relying on a single strategy for the operation of a μCHP system is not always the optimum choice whereas a hybrid strategy could achieve improved performance, which could save approximately €150 per year. Furthermore, it is well known that both residential electricity and heat demands fluctuate daily and seasonally, which makes the use of a pre-determined operation strategy less beneficial due to not being responsive to such dynamic fluctuations. For example, using an electricity-led strategy could lead to a waste of heat when there is little heat demand and the thermal storage device is fully charged. Instead, using an appropriate optimal online operation strategy, which aims for the most efficient operation of the μCHP system, is expected to outperform conventional operation strategies [1]. As a result, this study is concerned with developing an effective tool for optimal operation of residential μCHP systems.

LP techniques are principally used for determining the best allocation of limited resources either by maximising the profits or minimising the costs [4]. These techniques, which have the advantage of rapid calculation even with large problems containing a significant number of variables and constraints, are widely used for solving decision making problems. Conversely, in non-linear programming, the significant number of variables makes solving the problem more difficult and time consuming [5,6].

LP has been used for the optimisation of energy systems with different purposes and applications as summarised in Table 1.

Previous research has not developed a generic online LP optimiser for residential μCHP systems that accounts for a back-up heater and thermal storage device. In addition, the influence of some emerging energy policies, such as FIT and carbon tax, has not yet been considered. In this paper, a generic optimal online LP model for the operation of a μCHP system, which is named 'optimiser', is presented and has been developed, using the Matlab [13]. It has been formulated in a generic form to allow its use for any μCHP system and any demand profile. Importantly, in contrast to earlier work related to single run optimisation to determine the size of μCHP systems [4], this optimiser operates continuously online

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Table 1
Summary of CHP applications investigated using LP.

CHP application investigated using LP
1. Sizing of μCHP systems [4]
2. High-level system design and unit commitment of a micro grid (μG) [7]
3. Optimising the decision-making to manage CHP systems [8]
4. Determining the optimal strategies of a gas turbine-based CCHP system [9]
5. Studying the effect of fuel price on cost-minimised operation of CHP plants [10]
6. Evaluating the influence of uncertainties in energy demands on the optimal size of a FC-based CHP system used for an office building [11]
7. Optimising the CHP system for industrial sites [12]

with the aim of optimising the efficient operation of the μCHP system. Further, the developed online optimiser minimises the daily operation costs (c_{DO}) of such a system. Uncertainties in electrical and thermal demands have been considered by generating random errors for each individual value. Three simulation scenarios with different incentive mechanisms for installing μCHP technologies have been investigated: the FIT scheme recently adopted in the UK [14]; the trade of electricity; the introduction of a carbon tax. Sensitivity analyses have been performed to gain an understanding of the influence of key parameters on decision making regarding the operation of residential μCHP systems.

The remainder of this paper is organised as follows. Section 2 describes the conventional pre-determined operation strategies for μCHP systems. In Section 3, an online LP optimiser is presented and developed for online operation of μCHP systems. Section 4 presents results and a discussion based on the savings achieved through the application of the developed online LP optimiser in three different simulation scenarios. Finally, Section 5 draws conclusions regarding the strategies and the implications of the results obtained.

2. Conventional operation strategies for μCHP systems

An operation strategy for μCHP systems is a strategy for activating, deactivating or turning down/up the μCHP unit. In other terms, an operation strategy is the way of operating the μCHP unit and managing the flow of thermal and electrical energy within and to/from the system. The operation strategy aims to achieve specific targets, beneficial to the householder. Consequently, the operation strategy of a μCHP system has to answer the following important timing questions taking into consideration the need to achieve certain goals [1]:

- When should the μCHP unit be activated/deactivated/turned down/ramped up or ramped down?
- When should the thermal storage device be charged/discharged and at what rate?
- When should the back-up heater be switched on/off?
- When should electricity be exported/imported and how much?

These questions are difficult to answer since operating the system is complex due to a range of factors: different μCHP units and different sizes for each type with different thermal and electrical outputs; energy losses from both electrical and thermal storage devices to be considered; seasonal and in-seasonal variation in thermal and electrical demands according to climate, occupants and type of building; variation in prices of gas, imported and exported electricity; technical constraints of operating the μCHP unit and other components of the system such as ramp-up and ramp-down rates [1].

There are several operation strategies described in existing literature [1]. However, heat-led and electricity-led operation strategies are the prominent operation strategies for residential μCHP technologies available in the market [1].

2.1. Heat-led strategy

This operation strategy is based on meeting thermal demand by operating the μCHP unit and then meeting any deficiency with a back-up heater [15,16]. Technical constraints should be considered during the operation of the system such as the ability for modulation to meet low heat demands. This operation strategy is the most prominent for operating the μCHP units available in the market, especially SEs since they have a high heat to power ratio [17]. However, when a heat-led operation strategy is used, a substantial amount of electricity will be exported during periods of high heat demand and low electrical demand. As a result, electricity would be exported even when the exporting price is not profitable [18].

2.2. Electricity-led strategy

This operation strategy is based on operating the μCHP unit, within the operating limits, to meet the maximum possible amount of the electrical demand while any deficiency can be imported from the μG [19]. The same strategy may also be implemented to meet the needs of the electricity supplier [20] by operating the μCHP unit via a smart meter for certain periods. The system in this strategy should be integrated with a thermal storage unit to store heat when there is no thermal demand or when thermal demand is less than the produced heat. In addition, it should also be integrated with a back-up heater to compensate any deficiency in meeting the thermal demand [15].

3. Online operation of μCHP systems using linear programming

3.1. Overview

The residential μCHP system consists of a μCHP unit, a thermal storage device and a back-up heater. The μCHP unit, which is driven by natural gas, is used to meet the electrical and heat demands. However, when the amount of electrical output from the μCHP unit is greater than the demand, the surplus electricity can be exported to the micro grid (μG). Conversely, the μG can supply the dwelling with any deficit in electricity. Any excess heat will be diverted to the thermal storage device and used when it is needed. However, if the thermal output does not satisfy the demand and there is not enough stored heat, a back-up heater is used. Fig. 1 shows the conceptual arrangement of the residential μCHP system, which includes a μCHP unit, a thermal storage device and a back-up heater and is integrated within a μG.

In this study, the operation of a residential μCHP system is formulated as an online optimisation LP model (LP optimiser) as described in the following sections. The optimiser is formulated in a generic form to allow its use for any μCHP system and any demand pattern.

3.2. Model assumptions

The main purpose of the model is to optimally operate a residential μCHP system, where the electrical output of the μCHP unit is daily determined on an hourly basis. As such, the model involves determining optimal values for 24 decision variables: the hourly electrical output of the μCHP unit (kWe) for a whole day. These decision variables will be determined according to an objective function to minimise c_{DO}.

It is assumed that the μCHP unit can operate anywhere between 0% and 100% of its capacity. In addition, the μCHP system is assumed