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An operational optimization method for a complex polygeneration plant based on real-time measurements

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ABSTRACT

The combined production of electricity, heat and cold by a polygeneration system connected to a district heating and cooling network can provide high energy utilization efficiency. The inherent complexity of simultaneous production of different services and the high variability in the energy demand make combined cooling and heating systems performance highly dependent on the operational strategy. In this paper, an operational optimization method based on the moving average of real-time measurements of energy demands and ambient conditions is proposed. Real energy demand data from a district heating and cooling network close to Barcelona, Spain, are used to test the method. A complex polygeneration system is considered, consisting of an internal combustion engine, a double-effect absorption chiller, an electric chiller, a boiler and a cooling tower. A detailed modelling of the system is provided, considering partial load behavior of the components and ambient conditions effects. Results of the real-time optimal management are discussed and compared to traditional operational strategies and to the ideal optimal management achievable with perfectly accurate forecast of energy demands. Moreover, the optimal width of the window adopted for the moving average of real-time data is identified.

1. Introduction

Combined Cooling, Heating and Power (CCHP) systems are proven to be a reliable, competitive and very efficient alternative to separate production. CCHP is a common configuration for distributed energy systems where the end users are close to the energy generation point. These systems can be connected to a District Heating and Cooling (DHC) network [1], which is an energy efficient and environmentally benign solution compared to decentralized heat generation [2]. Nevertheless, the energy, environmental and economic performances of CCHP systems are strongly influenced by system synthesis [3], equipment selection and capacity [4] and operational strategy [5].

Different optimization techniques have been adopted over the years in order to identify the optimal design of polygeneration systems [6]. Arcuri et al. [7] presented a Mixed Integer Linear Programming (MILP) model for the determination of the design and the running conditions of a trigeneration plant for a hospital complex. Guo et al. [8] carried out a two-stage optimal planning and design method for a CCHP microgrid system, using both genetic algorithm and MILP algorithm techniques. Elsido et al. [9] and Arcuri et al. [10] proposed Mixed-Integer Non-Linear Programming models for determining the most profitable synthesis, design and annual scheduling of cogeneration systems.

Other works have focused on the optimal exploitation of the CCHP potential in existing plants. Franco and Versace [11] defined an optimal operational strategy for a cogeneration plant connected to a District Heating System. Li et al. [12] analyzed the effect of optimized operational strategy on a CCHP system for office and residential buildings. Ortiga et al. [13] presented a scenario analysis for economic, energetic and environmental performance assessment of a polygeneration system connected to a DHC network. Bischi et al. [14], Perez-Mora et al. [1] and Ünal et al. [15] investigated the optimal operating schedule of CCHP systems, with a given design.

Such works are usually based on an accurate load profile, while in practical applications an estimate of future load profile must be made [16]. Therefore, in order to implement optimal operational strategies in actual polygeneration systems, several methods have been proposed based on both demand forecast and real-time information. Fang and Lahdelma [17] developed a model based on weather and power price forecast and a sliding time window optimization. Luo et al. [18] provided a two-stage control for CCHP microgrid, including a Model Predictive Control (MPC) based on forecast information and a real-time adjusting stage to tackle power fluctuations. Cho et al. [19] and Yun et al. [20] tested real-time cost optimization algorithms on case studies.

Advanced control algorithms for real-time operations of CCHP

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Nomenclature

Acronyms

CFL	continuous full-load
EEPB	electric energy price based
FTL	following the thermal load
IOM	ideal optimal management
RTOO	real-time operational optimization
SP	separate production

Parameters

c	unit cost, €/kWh
COP	coefficient of performance, dimensionless
CR	part-load correction factor, dimensionless
EC	energy cost, €
f	electric energy consumption per unit of rejected heat, dimensionless
η	efficiency, dimensionless

Continuous variables

C	cooling energy, kWh
E	electric energy, kWh
F	energy content of the consumed fuel, kWh
L	load factor, dimensionless
Q	thermal energy, kWh
T	absolute temperature, K
t	temperature, °C
W	waste heat, kWh

Binary variables

δ	on-off state

Subscripts

AC	absorption chiller
boi	boiler
ICE	internal combustion engine
id	ideal
C	cold
CT	cooling tower
D	demand
E	electric
EC	electric chiller
ex	exergetic
F	fuel
G	generator
H	hot
HT	high-temperature level
LT	low-temperature level
min	minimum
nom	nominal (L = 1)
P	purchased
PEG	electricity purchased by the grid
Q	thermal
S	sold
SEG	electricity sold to the grid
W	wasted

systems have become a subject of great interest [21]. Uncertainties in energy demand forecast, non-linear part-load performances, multiple time-varying loads and various economical feature make the optimal management of polygeneration plants very challenging. In particular, savings resulting from real-time control are very dependent on the accuracy of the forecasts [17], while, in addition, accurate local weather predictions may be difficult to obtain [20]. Moreover, building simulation models are needed to estimate the thermal loads [19] and the calibration of the building model to the actual building may be an additional obstacle for real implementation of optimal control algorithms [20].

In this paper, an original operational optimization method based on real-time measurements of energy demands and ambient conditions is defined. The main novelty of this study is that the proposed method needs neither weather forecast nor a model for the estimation of future energy load demands, but only a monitoring system of the polygeneration plant. A moving average of real-time measurements of energy loads and current dry-bulb temperature and relative humidity are used to estimate energy load demands and energy system performance. On this basis, an optimal operational strategy is defined and, subsequently, a post-strategy design compensates for the gap between the estimated and the actual data.

The method is demonstrated by using real energy demand data from a trigeneration plant connected to a DHC network close to Barcelona (Spain). The energy system under investigation comprises an internal combustion engine, a double-effect absorption chiller, an electric chiller, a boiler and a cooling tower. An extensive modelling of the equipment is provided, considering partial load behavior and ambient conditions effects, to perform realistic and detailed simulations of the energy system.

The energy dispatch algorithm is designed to minimize the cost of energy (i.e. cost for purchasing electricity from the grid, income for selling electricity to the grid, cost of natural gas). To validate and evaluate the efficiency of the method, it is compared to conventional operational strategies and to the ideal optimal management achievable with perfectly accurate forecast of energy demands. Moreover, the effect of the width of the window adopted for the moving average on the performance of the method is analyzed and the optimal width is identified.

The rest of this paper is structured as follows. In Section 2 the methodological framework is described in detail. Section 3 presents the case study and the modelling of the energy system. An in-depth analysis of the results follows in Section 4, while the last section contains concluding remarks.

2. Methodology

A Real-Time Operational Optimization (RTOO) procedure based on measurements of energy demands and ambient conditions is proposed. The aim of this method is to determine an operational strategy that can be implemented in real-time to define the optimal energy input and flow inside the system. In this regard, a specific methodological framework has been developed, which is presented in this section.

The energy system under investigation is a typical CCHP system [4], consisting of an internal combustion engine, an absorption chiller, an electric chiller, a boiler and a cooling tower. The power plant feeds electricity to the grid, and heating and cooling to a DHC network. The energy system configuration is schematically shown in Fig. 4. Its operations are illustrated in detail in Section 3.2.

2.1. The objective function

The optimization problem consists in the determination of the scheduling that meets the energy demand with the lowest possible cost.