Renewable Energy xxx (2015) 1–11

Contents lists available at ScienceDirect

Renewable Energy

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

Adaptive building energy management with multiple commodities and flexible evolutionary optimization☆

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A R T I C L E I N F O

Article history:
Received 30 March 2015
Received in revised form
12 August 2015
Accepted 1 September 2015
Available online xxx

Keywords:
Energy management system
Building operation optimization
Battery storage
Trigeneration
Multi-commodity
Evolutionary algorithm

A B S T R A C T

To enable the efficient utilization of energy carriers and the successful integration of renewable energies into energy systems, building energy management systems (BEMS) are inevitable. In this article, we present a modular BEMS and its customizable architecture that enable a flexible approach towards the optimization of building operation. The system is capable of handling the energy flows in the building and across all energy carriers as well as the interdependencies between devices, while keeping a unitized approach towards devices and the optimization of their operation. Evaluations in realistic scenarios show the ability of the BEMS to increase energy efficiency, self-consumption, and self-sufficiency as well as to reduce energy consumption and costs by an improved scheduling of the devices that considers all energy carriers in buildings as well as their interdependencies.

1. Introduction

Nowadays, societies rely on ubiquitous and permanent availability of different energy carriers, such as electricity, hot water, and natural gas. Nevertheless, energy systems all over the world are currently in a phase of transition because of economical, political, and environmental reasons. The intermittent generation by *renewable energy sources* (RES) and the increasing power feed-in by *distributed generation* (DG) are already leading to problems in power grids, such as voltage problems and overloads of power lines [59]. Additionally, an efficient utilization of energy carriers is getting increasingly complex because generation does not longer follow consumption [40]. To tackle these problems, *smart grids* offer solutions: They allow for advanced management and optimization and provide the means for flexibility encompassing the grid as well as individual buildings. For instance, *demand side management* (DSM) is supposed to enable an economically efficient way of responding to intermittent and decentralized energy feed-in from RES [22,40]. In order to realize DSM and to ensure an efficient utilization of energy, sophisticated *energy management systems* (EMS) have to be introduced on all levels of smart grids [3,14], in particular in industrial, commercial, and residential buildings. The different setups of devices in buildings comprising heterogeneous devices, e. g., appliances, DG, storage systems, and electric vehicles, call for a flexible approach towards *building energy management systems* (BEMS).

A major contribution of this article is the comprehensive description and evaluation of a BEMS that is capable of optimizing the operation of devices typically found in commercial and residential buildings. This BEMS can be used in bottom-up simulations and in productive systems. New devices can easily be integrated as simulated devices or—in real buildings—be connected to the system using drivers and then be optimized using a modular, sub-problem based approach to optimization, which has been introduced in Ref. [3]. The approach respects interdependencies of the devices and the actual sub-problems for optimization are adapted to the particular global optimization problem at the runtime of the system, as originally described in Ref. [32].

Another major contribution is the integration of future hybrid household appliances and battery storage systems with novel encodings and mechanisms for optimization that combine scheduling and control logic. The capabilities of the BEMS are demonstrated using two scenarios: a *smart residential building* and a *smart*

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http://dx.doi.org/10.1016/j.renene.2015.09.003

Please cite this article in press as: I. Mauser, et al., Adaptive building energy management with multiple commodities and flexible evolutionary optimization, Renewable Energy (2015), http://dx.doi.org/10.1016/j.renene.2015.09.003

commercial building. Their operation is optimized with respect to energy costs, which often also increases self-sufficiency, self-consumption, and energy efficiency, using data from real buildings.

The following Section 2 provides an overview of architectures for complex systems, in particular EMS, and of optimization in such systems. Section 3 outlines the concrete scenarios and motivates the usage of EMS. Section 4 presents the *Organic Smart Home*, a modular BEMS with a generic architecture and a flexible approach to optimization. In Section 5, we specify the concrete setups for the simulation of the scenarios, before presenting and discussing the results in Section 6. Finally, the article is concluded in Section 7 with a summary and an outlook to further work.

2. Related work

There are several architectures for complex systems and for EMS in smart grids as well as approaches to optimization. This chapter outlines such architectures and approaches, showing that none of these is adequate to fulfill the requirement of resembling the multitude of entities in smart grids and their diverse capabilities, requirements, interdependencies, and complexity, while working in simulations and productive EMS in real buildings.

2.1. General architectures and principles for complex systems

The complexity of technical systems is constantly increasing because of a rise of interconnected devices. Typically, complex systems are prone to breakdowns and fatal errors caused by minor disturbances or emergent effects [36]. Smart grids, which are an example for complex systems, are still in development [6,18]: It is essential to design entities in smart grids with keeping in mind the upcoming complexity caused by many interacting entities, e. g., devices, buildings, and grid operators. Architectures and approaches used in the development of smart grids should facilitate appropriate methods for abstraction, optimization, and self-adaptivity of such systems [6].

The theory of *Autonomic Computing* [27] focuses on fully autonomic computer systems without any later user interaction after design phase. It provides a central design paradigm: the *MAPE cycle*, which consists of the four steps monitor, analyze, plan, and execute. In Ref. [20], it has been used in a control architecture for smart micro grids. Hierarchy, stigmergy, and collaboration are used to build an architecture with global and local optimization scopes by using rather simple models of power grids and their entities. In general, the *MAPE cycle* paradigm is suited to cope with complex distributed systems, although the particular control architecture in Ref. [20] lacks important concepts of device abstraction that are essential for productive systems.

Organic Computing addresses basic challenges of complex systems in dynamic environments, such as trustworthiness, flexibility, adaptivity, robustness, and effects of emergence [36]. Based on various scenarios in robotics [36], traffic [42], production [46], and energy [3,25], generic system architectures have been developed and evaluated. A particular example of an architecture for complex systems proposed by Organic Computing is the *Observer/Controller Architecture* (O/C Architecture), which serves as a generic framework comprising various components that are essential for designing systems showing organic behavior, i. e., an adaptive behavior similar to nature [43].

2.2. Architectures for energy management systems

First of all, EMS require appropriate architectures that provide the flexibility and modularity to adapt the system to the variety of different entities in energy systems.

The *Flexible Power Application Infrastructure* (FPAI) has been developed to exploit load flexibility in power grids by shifting the operation times of appliances and DG [54]. It comprises a centralized control structure for a BEMS called *Flexible Power Runtime*, which abstracts the flexibility provided by the devices. Nevertheless, the optimization aspect and its implementation are not precisely specified as it is provided by an external optimization service that is not part of FPAI. Similarly, components enabling interactions with external components, such as a distribution grid or an energy market, have been defined, though not yet realized.

In Refs. [38,58], an architecture for building automation and management is proposed that is named *Open Gateway Energy Management*. It uses a so-called *bidirectional energy management interface* to connect resources, which are abstracted using a graph-like structure, and applications that provide management functionality. Nevertheless, the architecture lacks an integrated approach, as the optimization of individual resources is provided by separate management applications.

2.3. Optimization in energy management systems

There are several approaches to optimization in energy systems and its various problems. Energy systems and their components may be optimized with respect to highly diverse objectives and on different abstraction levels. Usually, publications focus either on optimization of the technical setup of the system [2,26], or energy markets [56], or balancing groups [25]. Often, they do not respect interdependencies or non-linearities [12,21,26,55], or they perform a scheduling that is only exact to the hour [12,44,55], which is not practicable in concrete productive systems, because of averaging effects that hide load peaks, which have to be handled by a BEMS [49,57].

Often, optimization problems in the domain of EMS have been formulated in linear programming (LP) [35,44], mixed integer linear programming (MILP) [1,10,11,15,23,50], or mixed integer non-linear programming (MINLP) [4,7,21,47]. Modeling problems from the energy domain usually requires several thousand variables and constraints, even if the problem is reduced to an optimization based on time slots of five [11] or 15 min [10,15,23]. Solving such problems may lead to extensive computational requirements that are neither practicable nor reasonable for BEMS that should run on low-power, energy-saving computers with limited system resources.

Heuristic optimization has proved to optimize a wide range of optimization problems efficiently [34]. Advantages of heuristics are their low memory and time requirements. Consequently, *evolutionary optimization* has been used in the optimization of energy systems. Frequently, evolutionary optimization is used to optimize design parameters of devices in energy systems [2,26,55]. Only a fraction uses heuristics to solve scheduling problems [41]: uses *particle swarm optimization* to schedule devices in a smart residential building on an hourly basis. In Refs. [45], an *evolutionary algorithm* is used to schedule district heating and cooling plants. The approach of [48] is similar to the one presented in this article. Their encoding uses a string of integers in the evolutionary algorithm. Every integer determines the starting time of the operation cycle of one device exact to the minute. Nevertheless, the approach is limited to electrical loads and does not respect interdependencies of multiple devices and energy storages.

3. Scenarios and material

This article analyzes two scenarios: a *smart residential building* and a *smart commercial building*. Both require the optimization of multiple energy carriers, such as electricity and hot water, with

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