Applied Energy 160 (2015) 194–205

Contents lists available at ScienceDirect

Applied Energy

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

Advanced building energy management based on a two-stage receding horizon optimization

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HIGHLIGHTS

- Advanced building energy management based on a receding horizon strategy.
- Two-stage optimization approach using mixed integer linear programming (MILP).
- Emulation of power scenarios in a microgrid testbed using power hardware-in-the-loop.
- Validation of energy management strategies under realistic conditions.

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form 10 August 2015
Accepted 10 September 2015

Keywords:
Building energy management
Receding horizon optimization
Power hardware-in-the-loop
Microgrid testbed

ABSTRACT

The continuous increase in energy demand and the integration of a large number of renewable energy sources with intermittent production require an advanced energy management to guarantee an uninterrupted supply. Deployment of smart meters in wide areas of power networks and availability of affordable storage systems encourage development and implementation of local energy management systems. Local energy management is considered a feasible and inexpensive approach to reduce the impact of load variations and intermittent generation. Demand response and load shaping techniques provide customers with the facility to contribute to system balancing and improve power quality. This paper presents a building energy management which determines the optimal scheduling of the components of the local energy system. The developed two-stage optimization is based on a receding horizon strategy and minimizes the energy costs under consideration of the physical system constraints. The proposed building energy management has been implemented and tested with a medium-size hotel emulated in a microgrid testbed using power-hardware-in-the-loop techniques. The obtained results underline that energy management strategies can be validated under realistic conditions using flexible power scenarios.

1. Introduction

In modern societies, economic growth critically depends on the continuity of energy supply and the associated costs. Utilities and transmission network operators permanently supervise production facilities and grids and immediately compensate any mismatch between generation and consumption [1]. The traditional load-following approach has to ensure energy quality, grid stability and security of the infrastructure. The increase of energy demand and the integration of renewable energy sources convert energy management in a complex task. The transition from a centralized energy production towards a decentralized and distributed generation can only be achieved with advanced control and monitoring systems. Energy management will play a crucial role in the transformation of the classic business model with few key players towards a more open system with a large number of market participants.

The enormous potential of local energy management attracts the interest of companies and scientific communities. Deployment of smart meters and availability of affordable storage systems encourage development and implementation of local energy management [2]. The building sector, which in some countries accounts up to 45% of the primary energy consumption [3–5], is a good candidate for energy management. Advanced techniques such as demand response and load shaping can improve grid stability and energy quality [6]. Real-time pricing enables retailers to pass on the actual costs of generation, transmission and distribution to the customer [7,8]. Dynamic pricing is a common element in demand management and incentives customers to partially shift

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http://dx.doi.org/10.1016/j.apenergy.2015.09.049
0306-2619/

their energy consumption to off-peak periods. Local energy management permits a closer tracking of generation and facilitates the reduction of the mismatch between production and consumption.

1.1. Research aim

The main objective of this paper is to propose an advanced energy management algorithm with the optimal scheduling for a building energy system. The limited computational power of devices frequently used in building management systems (BMS), such as smart meters or low-cost embedded systems, restricts energy management algorithms to those of low mathematical complexity. Another important aim is the experimental validation of the proposed energy management scheme by using power-hardware-in-the-loop (PHIL) technology. The use of power electronics converters provides a flexible environment and allows testing with realistic power dispatch scenarios.

1.2. Paper overview

This paper presents a building energy management based on a two-stage optimization. The developed receding horizon strategy is implemented and tested with a medium-size hotel emulated in a microgrid testbed. The validation of the building energy management under realistic conditions using power-hardware-in-the-loop techniques represents the main contribution.

The paper is organised as follows: Section 2 reviews the state of the art in energy management algorithms for buildings and microgrids based on power-hardware-in-the-loop technology. Section 3 presents the building energy management and the associated optimization problems. The experimental setup, including the microgrid testbed and the power dispatch scenario, is described in Section 4. The results obtained in experiments are presented in Section 5 and the conclusions are drawn in Section 6.

2. Research background

A large number of local energy management strategies have recently been developed, including demand response (DR) and demand side management (DSM). Research studies on the impact of building energy management presented promising results regarding criteria such as energy efficiency and cost savings [6,9,10]. Despite the intensified efforts by the scientific community and industrial sector only a few of the developed strategies have been tested under realistic conditions.

Hardware-in-the-loop simulations (HILS) provide an opportunity for a rapid development and real-time testing of control algorithms [11]. Experimental validation of energy management systems can be carried out on flexible platforms based on power-hardware-in-the-loop technology [12].

2.1. Building energy management

A variety of advanced strategies for building energy management schemes can be found in the scientific literature. A usual practice is the minimization of energy costs under consideration of energy system's limitations and time-varying retail prices. The scheduling of an energy system is determined by using optimization methods and control schemes such as model predictive control (MPC) [13–15], linear programming [8,16], mixed integer linear programming [17–19] and mix-integer nonlinear programming [20]. Other strategies for building energy management include multi-agent systems [21,22], game theory [23], particle swarm optimization [24–26] or adaptive tuning [27].

Dynamic interaction between building energy management and main grid can improve the grid stability, energy efficiency and power quality [28]. The building demand management in [29] employs an iterative strategy and bidirectional communication for grid optimization. The minimization of energy costs motivates customers to readjust their power demand after changes in electricity price and consequently enables grid operators to use dynamic pricing to reduce grid imbalance and maximize economic benefits. The demand bidding program for hotel energy management in [30] maximizes the reward obtained for a temporal reduction of the amount of energy drawn from the electric grid. The customers may respond to the bid and reduce their costs or operate as usual without any monetary savings or other benefits.

Several multi-objective strategies for building energy management have been developed in the last years. The load management for smart buildings in [31] uses a layered structure for admission control, load balance and demand response and includes long-term performance optimization, stability enhancement and energy trading. The genetic algorithm in [32] minimizes the residential electricity costs and appliance operation delays. The reduction of the power peak-to-average ratio consequently increases grid stability and power quality. The energy management systems presented in [33,34] consider the energy costs and the thermal comfort of the occupants in the optimization procedure. The operation of distributed energy systems in [35] includes total energy costs and environmental impact (CO_2 emissions) and computes the set of Pareto optimal solutions.

2.2. PHIL technology and microgrid testbeds

Energy management strategies have been typically tested in simulation [36] or field demonstration [37,38]. However, the first method suffers from a lack of realism while the second has limited capacity to test power scenarios. Power-hardware-in-the-loop technology combined with real-time simulation offers a controlled, realistic and reconfigurable test environment.

Authors in [11,12,39–41] proposed hardware-in-the-loop (HIL) platforms to test energy management controllers and strategies. In these proposals, the microgrid and the distributed resources are simulated using a Real Time Digital Simulator (RTS) [42]. This method offers flexibility but requires complex simulation models to obtain realistic results.

Some authors [43,44] proposed PHIL architectures based on RTS and real power systems. The microgrid and most of the distributed elements are simulated using the RTS. The RTS is connected to a real power system. This solution is flexible and, to certain extent, more realistic than the HIL simulation, but the proposals are focused on analysing the grid integration of specific devices rather than testing energy management strategies.

Other authors proposed microgrid laboratories based on real system installations. A microgrid laboratory equipped with wind turbine and photovoltaic panels, passive and active loads and grid voltage, sag and impedance emulators based on power converters has been presented in [45,46]. The environment in [47] is organized in two microgrids that integrate distributed generators, storage systems and loads and controlled by a hierarchical control structure. These microgrids allow obtaining realistic results at the cost of a reduced demand and generation flexibility.

The approach in this paper seeks a flexible configuration and a high degree of realism. A similar proposal, presented in [48,49], employs a microgrid that consists of AC/DC/AC power electronics converters used as emulators and a 3-layered control system based on the IEC 61850 standard. However, the microgrid does not allow real-time dynamic simulation of distributed resources.