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Smart grid and smart building inter-operation using agent-based particle swarm optimization

L.A. Hurtado *, P.H. Nguyen, W.L. Kling

Department of Electrical Engineering, Eindhoven University of Technology, The Netherlands

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ABSTRACT

Future power systems require a change from a *"vertical"* to a *"horizontal"* structure, in which the customer plays a central role. As buildings represent a substantial aggregation of energy consumption, the intertwined operation of the future power grid and the built environment is crucial to achieve energy efficiency and sustainable goals. This transition towards a so-called smart grid (SG) requires advanced building energy management systems (BEMS) to cope with the highly complex interaction between two environments. This paper proposes an agent-based approach to optimize the inter-operation of the SG–BEMS framework. Furthermore a computational intelligence technique, i.e. Particle Swarm Optimization (PSO), is used to maximize both comfort and energy efficiency. Numerical results from an integrated simulation show that the operation of the building can be dynamically changed to support the voltage control of the local power grid, without jeopardizing the building main function, i.e. comfort provision.

1. Introduction

Being responsible for about one-third of the energy consumed in cities [1], commercial and industrial buildings play a central role in the emerging energy supply chain by offering their flexibility of energy use. Through Demand Response (DR) programs, operation of buildings with a proper Energy Management System (BEMS) can improve the performance of electric power grid, reduce investment costs, and increase Renewable Energy Sources (RES) penetration, without jeopardizing the demand side activities. However, there is a lack of functional interaction between Smart Grid and Building Energy Management System (SG–BEMS) to fully invoke flexibility from the built environment to achieve energy efficiency and sustainability goals.

Several attempts have been made to enable the inter-operation of these highly complex systems. However, buildings and the power grid have been treated as independent and unique control systems, operated based on their own information while oversimplifying interaction from the other. For instance, a model for load shifting has been developed from the SG's perspective with a DR solution while the building thermal capacity is simplified [2]. On the contrary, a model for the smart operation of Heat, Ventilation and Air Conditioning (HVAC) system is presented to optimize the system's energy efficiency with an abstraction of the power grid [3]. Thus, there is a clear need to have a comprehensive integration framework to fully address a wide range of variables in different physical environments, on all time scales of the inter-operation of the SG–BEMS [4].

To cope with the complexity of this integration framework, a shift is evident from a centralized energy management systems to a decentralized structure with the introduction of computational and distributed intelligence. By dividing the general control problem into a number of smaller control areas, distributed intelligence reduces the control burden, while improving the flexibility and efficiency of the control system [5]. For instance, in [6], a distributed control strategy is used to integrate Distributed Energy Resources (DERs) in the built environment. In [7], a distributed control methodology to optimize exchanged power flow and energy among smart buildings by means of the multi-traveling salesmen problem optimization method is proposed. This tendency based on a bottom-up architecture can invoke flexibility from different levels of the built environment towards the SG. Throughout the literature, one of the most popular decentralized control approaches is based on Multi-Agent Systems (MAS), which is now being applied in a wide range of applications in the power systems, e.g. condition monitoring, system restoration, market simulation, network control and automation [8,9]. MAS is also widely studied in the area of building automation, building energy management, and building control and operation [10–14].

* Correspondence to: Den Dolech 2, 5612AZ Eindhoven, The Netherlands. Tel.: +31 40 247 3297; fax: +31 040 2450735.
E-mail addresses: l.a.hurtado.munoz@tue.nl (L.A. Hurtado), p.nguyen.hong@tue.nl (P.H. Nguyen), w.l.kling@tue.nl (W.L. Kling).

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Furthermore, advanced optimization methods are required to guarantee a global optimal solution, maximizing the welfare of both the building and the power grid. For this decision-making step, the research trend seems to be moving away from deterministic gradient based optimization methods, e.g. Newton–Raphson, to stochastic ones, e.g. Particle Swarm Optimization (PSO), along with the increasing availability of data measurements. Currently, stochastic optimization methods such as PSO have been utilized in a wide range of power grid operation and control applications [15–18]. However, the application of advanced optimization techniques on the customers side to reveal their benefits in the smart grid environment is still limited [19]. We researched on making use of the building thermal buffers and storage systems to dynamically adapt with the power grid requirements, without significantly affecting the building's comfort levels [20].

This paper proposes a SG–BEMS integration framework including a MAS based control scheme to optimize both comfort and energy efficiency. Developed hierarchical agent structure will allow lower level agents abstracting the information of their immediate environment into the form of single value information blocks for the higher level agents. In this way, data management complexity is reduced at each agent level, in order to exploit the demand flexibility potential within the built environment to support the power grid with voltage control service. A PSO optimizer is proposed to improve the MAS's capability in exploiting the building's flexibility for the SG. Finally, the performance of the MAS based SG–BEMS platform is tested in a Low Voltage (LV) test feeder, and the system's potential for voltage control is demonstrated.

The remainder of this paper is divided into five sections. Section 2 presents the SG–BEMS framework, as well as the problem description for the integrated system. Section 3 formulates the optimization problem and introduces PSO as a suitable optimization technique. Section 4 describes the implementation of the distributed control methodology. Section 5 describes the test systems used and the simulation results obtained. Finally, Section 6 summarizes and presents conclusions from this study.

2. SG–BEMS framework

Development of an intertwined operation of the SG and BEMS needs a common framework to address critical involved control blocks for both two domains. This SG–BEMS framework is based on a reference of the Smart Grid Architecture Model (SGAM) [21], with an extension onto the building consumer domain, as shown in Fig. 1. Exchanging information within and between the two domains allows each system to operate towards its own goal, while reducing unnecessary information exchange. However, this interoperation framework requires a common ontology, to allow the exchanged messages to be understandable by both domains.

Both the power grid, i.e. the distribution grid, and building domains are formed by four different layers in this framework [21]. The "Operation" layer, which is linked directly to the SG–BEMS interaction, hosts the power system control, e.g. Distribution Management Systems (DMS), the Energy Management Systems (EMS), and the building controls, e.g. the centralized management systems (CMS), zone management system (ZMS), and the device management system (dMS). These systems have the main purpose of monitoring and controlling the distribution system equipment and the building equipment based on the information available. At the "Field" layer, the equipment to monitor, control and protect the power system and the building installation can be found. Such equipment are intelligent devices with communication enabled controller to monitor and control the automated devices.

In the following subsections, the two domains in the SG–BEMS framework will be described in more detail: their context, ultimate goals for each system operation, as well as their constraints.

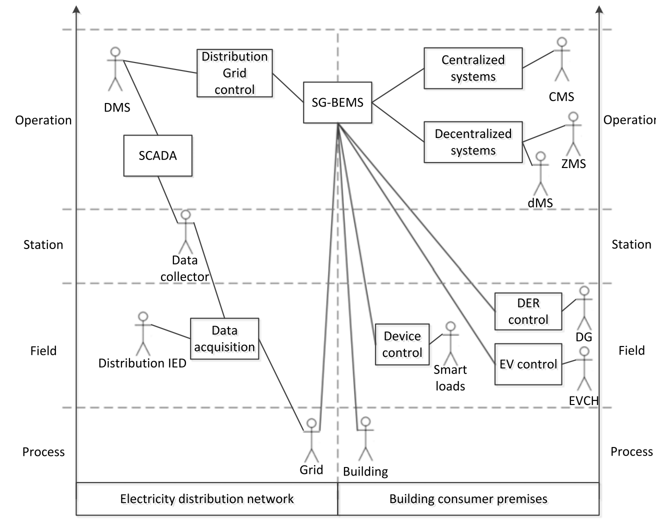

Fig. 1. SG–BEMS framework domains.

2.1. Distribution grid domain

The electric distribution grid is operated by the distribution system operator. Its main objective is to maintain reliable power supply to the customers. As the proliferation of RES and DER becomes larger, their intermittent and uncontrollable nature causes not only system balance issues, but also problems for the reliable operation of the distribution grid. Conventionally, the functioning block of distribution grid control must take place to support (a) prevention of overloading of assets; (b) regulation of voltage magnitude; (c) maintenance of the power quality and security.

Among them, voltage regulation is one of the biggest concerns of distribution system operators. Due to the high number and diversity of loads, voltage variations are higher in the LV networks than in the medium or high voltage networks. These voltage variations, $\Delta u\,[p.u.]$, over a network feeder are formulated as a function of the active power, $P[W]$, the reactive power, $Q\,[var]$, and the line impedance $Z[\Omega] = R + jX$, as described by the following equation:

$$\Delta u = \frac{(P \cdot R + Q \cdot X) + j(P \cdot X + Q \cdot R)}{u_{base}}, \quad (1)$$

where u_{base} is the base or reference voltage, e.g. $u_{base} = 240$ V for LV networks.

As shown in the equation, the voltage variation depends not only on the power flow in the feeder but also on the network impedance. The X/R ratio will define whether it is the reactive or active power which has a greater impact on the voltage level. In the LV network, the impedance is mostly resistive, which means that active power control has a bigger impact on the voltage variations along the feeder.

2.2. Building consumer domain

The two main aspects of the building consumer domain are comfort management and energy consumption. In buildings, the central objective is to provide the occupants with a comfortable environment. About 50% of the total electrical energy consumed is used for comfort management [22]. This strong correlation is crucial to reveal flexibility from the built environment to offer to the SG.

The following subsections describe more in detail these two aspects of the building consumer domain.