Applied Energy 96 (2012) 74–83

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation

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ARTICLE INFO

Article history:
Received 15 July 2011
Received in revised form 14 December 2011
Accepted 31 December 2011
Available online 8 February 2012

Keywords:
Zero energy building
Residential
Thermal demand
Electricity demand
Dynamic simulation
District

ABSTRACT

Recent European communications focus on the enforcement that by 2020 all new buildings are nearly Zero-Energy Buildings (ZEBs) and on the deployment of a European Smart Grid. The presented work focuses on assessing the electrical challenges at neighborhood level of an building stock evolving towards ZEBs, and identifying the resulting challenge in multidisciplinary dynamic simulation models required to perform this assessment.

A tool for Integrated District Energy Assessment by Simulation (IDEAS) is developed. This IDEAS tool allows simultaneous transient simulation of thermal and electrical systems at both building and feeder level.

Residential ZEBs show a self-consumption of locally generated photovoltaic (PV) electricity of 26 ± 4% at building level. Resulting feeder voltage fluctuations and possible transformer overload are quantified as bottlenecks. When all dwellings are intended to achieve a ZEB status, (i) a fraction of 14–47% of local PV supply is wasted by inverter curtailing depending on the feeder strength, while (ii) the peak transformer load is found to be 3.3 kVA per dwelling which may affect power security in existing feeder designs.

1. Introduction

World-wide 38% of the total energy use is used for operating the building stock [1]. To reduce its environmental impact and economical consequences, the European directive 2002/91/EC [2] on energy performance of buildings has been introduced stating energy benchmarks and goals at the level of individual buildings. A recent European recast 2010/31/EU [3] obliges all member regions to enforce that by 2020 'all new buildings are nearly Zero-Energy Buildings' (ZEBs). Although the definition of a nearly-ZEB is not elaborated within this recast, it aims to achieve a combination of energy efficiency and integration of local renewable energy sources. The non-simultaneity between local energy demand and supply may strongly affect the power quality at feeder level – i.e. neighborhood level – of an electricity distribution network. As such, large scale integration of ZEBs in particular and renewable electricity generation in general will require well developed solutions in the form of energy storage, demand side management or both: As such, with the recent communications of the European Commission on the deployment of a European Smart Grid [4] two crucial domains, i.e. climate change and security of power supply, become strongly linked.

Within this framework, the presented paper has a dual focus: (i) assessing the electrical challenges and impact at feeder level of an building stock evolving towards nearly-ZEBs and (ii) identifying the associated challenge in the development of dynamic simulation models at this level which are required to perform this multidisciplinary assessment.

2. Methodology

A tool for Integrated District Energy Assessment by Simulation (IDEAS) is developed and allows integrated transient simulation of thermal and electrical processes at neighborhood level. Related models have been developed in the last decade and two approaches can be distinguished in their development, i.e. (i) models using thermal Building Physics and Systems (BPSs) as starting point, or (ii) models using Electrical Energy Systems (EESs) as starting point.

BPS-based models at neighborhood level combine a dynamic simulation of the heating and cooling demand with a stochastic approach on occupant behavior. The main existing BPS-based models are *LT Urban* [5,6], *SUNtool* [7,8], *TUD-PS* [9] and the methodology

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doi:10.1016/j.apenergy.2011.12.098

by Yamaguchi et al. [10,11]. Each of these models have their specificities which can be attributed to their background: (i) the thermal load calculation for space heating and cooling generally relies on highly simplified building models, e.g. the *LT method* [12], a Radiant Time Series (RTS) or Weighting Factor (WF) method [13,14] or ISO 13790 [15] based models, while (ii) also system modeling is mainly simplified by performance curves. Furthermore, the main focus lies on (iii) the behavior of accommodated occupants [16,17] in offices and their interactions with lighting [18,19], shading [18,20,19], opening of windows [21], comfort [22] and appliances [8,23]. Also (iv) the urban microclimate and shade views for radiant exchanges [24,25] are a point of attention, while (v) the assessment of energy measures at aggregated level is mainly limited to the summation of energy loads [8,9,11].

EES-based models at feeder level combine a physical calculation of the electricity generation and distribution with a stochastic approach on power loads. The main existing EES-based are the models of *IEA-PVPS Task 10* [26], *PV-UPSCALE* [27], and the models of Conti et al. [28], Paatero and Lund [29], Thomson and Infield [30] and Widén et al. [31]. Each of these models have their specificities which can be attributed to their background: the main focus (i) lies on the appliance use of accommodated occupants in dwellings [32–34], and (ii) analysis shows the importance of a fine time resolution of simulation boundary conditions [35,31].

The IDEAS tool differs from existing BPS-based and EES-based models by (i) integrating the dynamics of the hydronic, thermal as well as electrical energy networks at (ii) both the building and aggregated level within a single model and solver as illustrated in Fig. 1. The transient thermal processes are expressed in detail based on the control volume method (CVM), whereas the electric models are expressed with static nodal and line models. The IDEAS tool integrates the (iii) the occupancy, appliance and lighting use of accommodated occupants in dwellings and (iv) includes a fine 1-min time resolution for the boundary conditions. Some aspects of pure BPS-based models will be added in the next stage of the IDEAS tool development, i.e. (v) the behavior of accommodated occupants concerning shading, opening of windows, and (vi) the urban microclimate and radiant exchange shade views. The tool is implemented in Modelica [36] which allows explicit symbolic declaration of each energy flow and system based on differential algebraic equations (DAEs). This DAE system is solved using Petzolds' Differential Algebraic System Solver (DASSL) [37]. Furthermore, Modelica is a pure object-oriented modeling language for component-based development allowing continuous development with limited implementation effort.

3. Model description

A model for a residential zero-energy neighborhood is developed in the IDEAS tool based on a representative set of architectural types, a feasible technology choices and stochastic residential occupant behavior. Their ZEB target is expected to be achievable by combining energy efficiency, heat pumps and building integrated photovoltaic (BIPV) systems covering the electricity consumption on an annual basis. It can be expected from the current strong increase in heat pump and BIPV systems on the domestic market [38,39] that new buildings with these technologies will become standard practice on the short to medium term. As such, this has been considered as a starting point for modeling ZEBs with feasible technology choices.

All simulations are performed for the typical moderate climate of Uccle (Belgium) and daylight saving time (DST) is taken into account [40]. Irradiance data with a time resolution of 1 min are obtained by Meteonorm v6.1 for the moderate climate of Uccle (Belgium) [41] based on the period 1981–2000.

3.1. Neighborhood description

The implemented residential zero-energy neighborhood consists of 33 detached residential buildings based on four different architectural types of detached dwellings, which are schematically shown in Fig. 2 and for which the main characteristics are listed in Table 1. The number of dwellings is determined in agreement with the topology of a radial IEEE 34 Node Test Feeder [42,43]. The architectural types were determined earlier as representative for the Belgian building stock [44] based on main building typologies in different periods and are implemented based on their national statistical spread [45]. All dwellings are modeled as a 2-zone model with the day zone (e.g. living area, kitchen) and night zone (e.g.

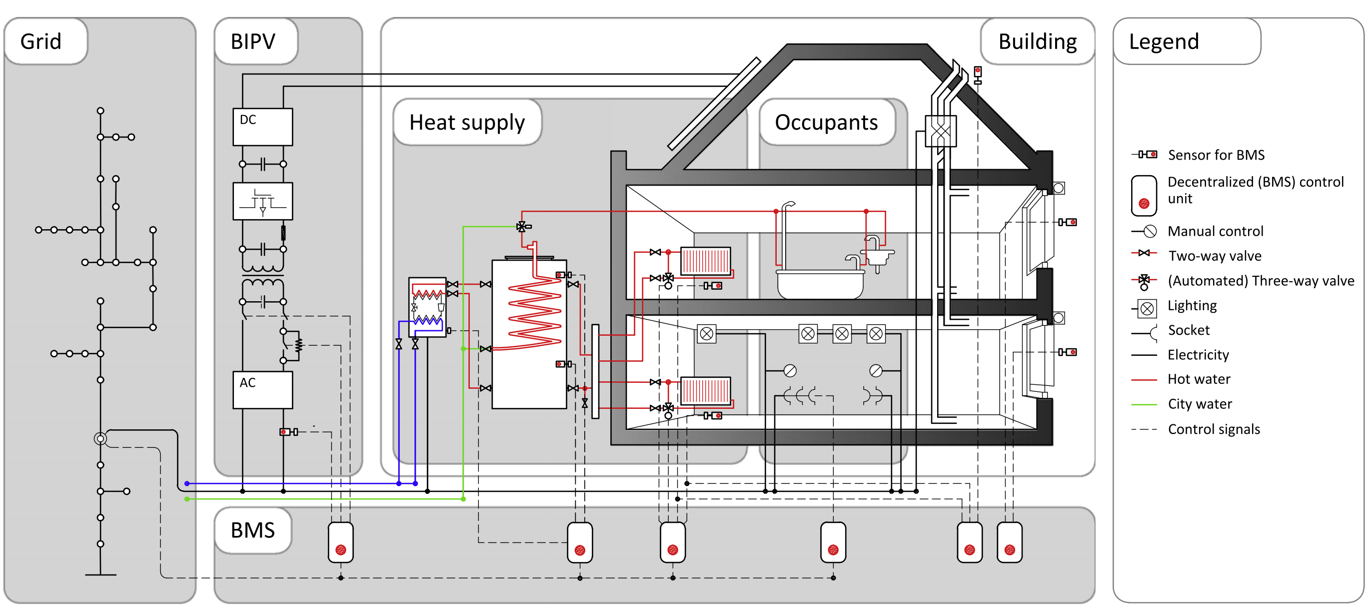

Fig. 1. Representation of the elaborated model in the IDEAS tool. At the level of an individual building, local electricity generation by means of building integrated photovoltaic (BIPV) systems, stochastic behavior of building occupants, the detailed thermal building response, the transient behavior of the heating, ventilation and air conditioning system, and the building management system (BMS). At feeder level, the transient response of the low-voltage electrical distribution grid is included for a residential neighborhood of 33 dwellings.