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Dynamic aggregated building electricity load modeling and simulation

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A B S T R A C T

In order to support the growing interest in demand response modeling and analysis, there is a need for physical-based building load models. This work presents a new approach for simulating electrical power flow in buildings. The new approach handles the power flow capacity shortage in existing building simulation programs, which have been used for the past few decades by building energy communities. The suggested approach represents the building as a group of electrical networks, organized in hierarchical levels. On the top level, the user defines key parameters such as rated power and power factor of existing loads. The power cables are modeled by their equivalent PI model. Accurate simulation models are developed for solving the building network equations where building loads are integrated into building network. Smart meters are implemented at different locations for power quality and energy auditing. Two case studies of residential and commercial buildings are investigated to prove the capability of the introduced approach. A comparison with EnergyPlus, as verified building energy software, is introduced to prove the ability of the proposed Matlab-based model to evaluate the annual energy consumption of the building. All results show the accuracy and ability of the proposed approach for simulating the electrical power flow of the building and can be integrated with renewable and storage energy.

1. Introduction

The knowledge of consumer electricity consumption is essential for the development of smart grid integration strategies such as integration of electrical vehicles and distributed generation. Studies tend to fall back on the aggregated data when no detailed data is available. The use of aggregated data is not a problem if the focus is on aggregated results. Examples of this are total electricity demand, discrete load band and average load profiles [1–3]. However, when detail is important, data cannot be aggregated. Valid electricity profiles of building holds are required when simulating voltage problems due to electric vehicle charging at distribution level, when managing a micro-grid with photovoltaic (PV) systems or when estimating the potential for battery storage in a distribution grid [4–6].

In fact the prediction of power demand is more complicated than energy demand because of its random nature and its instantaneous acute fluctuating aspect, while energy demand is the integral of the former across time. On top of that, even if customers can have the same general characteristics (e.g. two domestic customers with the same building hold size, type of

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dwelling, building characteristics, appliances ownership, etc.) there is every chance that their corresponding power demands, so their load curves for selected days are completely different. Diversity that represents both the non-coincidence in energy use and an unlimited variety of customers' characteristics is responsible for this effect [7,8]. The human behaviors as a reflection of consumers' tasks have a great influence on the domestic power demand where there is every chance that two households with the same daily energy consumption may not show a similar load curve. That is the reason why modeling the power demand in a specific area for a specified target is also a hard task [9].

Modeling the electricity consumption of the residential sector is not a recent research topic. For a few decades authors have published their methods developed to anticipate the temporal evolution of the electric energy demand with different time and space scale considerations [10,11]. Among the motivations for developing such a model, the main one is the need of a tool to better predict, quantify and plan the future requirements of the whole energy supply/demand value chain. Other reasons are the electric network control and management or the impacts of various evolution scenarios that focus on technical, demographic, behavioral or economical aspect [12,13].

For such purposes the authors generally focused on the annual electric energy demand and the chosen methodologies are different depending on the finality, the scope, the input data and the output format of each model. Historically, the methods have been divided into two categories: top-down and bottom-up approaches [11,14].

Top-down methodologies consider situation on a whole (making use of national energy statistics for instance) and try to attribute electricity consumption to the studied building hold stock with regard to its characteristics. The input data for this type of model are very general information such as gross domestic product, unemployment rate and present statistics on the targeted population with possibly predicted evolution and appliance saturation rates [15,16]. Top-down customer models typically represent entire system loads or customer segments. These large groups are modeled in a synthetic manner based on historical load data records. For planning and load forecasting purposes these models are augmented with current weather conditions, calendar date information or economic indicators [17,18]. Traditionally, this demand modeling approach has successfully allowed maintaining short-term system stability and has provided guidance for long-term planning of grid resources. However, the aggregated nature of top-down models does not allow a detailed analysis of individual customer behavior. Therefore, they are less applicable for describing smaller scenarios where individual actions have a larger impact. Furthermore, their reliance on historical data complicates their usage for modeling novel load types in future electricity systems [14]. These limitations may necessitate the development of more expressive bottom-up models.

Whereas top-down customer models generate load profiles from historic aggregate load data; bottom-up models determine the load from individual devices and consumption activities.

Bottom-up models compute electric demand for a few modeled building holds which are either representative of a larger space scale or simply target consumers. The unitary results are then extrapolated to obtain the electricity consumption for the entire studied geographical scale. Here the required input data can be: the individual consumption of the selected domestic appliances; their technical properties; the geometrical and thermal properties of the modeled dwellings; weather information; electricity bills of building holds; human behavior [19–24].

Yet with this level of detail come two distinct disadvantages over top-down models; the computational complexity of individual bottom-up models is exponential in the number of load types considered [25]. Thus, for real-time evaluation of larger populations this modeling technique may become infeasible. Furthermore, high levels of model detail will require significant amounts of input data to avoid arbitrary modeling assumptions. However, with comprehensive load measurements from future metering systems such data should be more readily available [26].

Summarizing, the bottom-up technique seems to be especially relevant for modeling customer models that exhibit high levels of flexibility (e.g., EVs or smart homes). In these cases the action space as well as the relevant incentive schemes may be fairly complex and thus warrant a detailed analysis. Isolating specific load types may facilitate hybrid approaches where highly flexible loads are modeled bottom-up and other load types are modeled top-down.

Building power simulators play an important role in a wide variety of disciplines including energy conservation, energy auditing, and smart grid terminology. They estimate total energy consumption in facility buildings and enable predicting building energy demand as well. Energy demand is inevitable parameter for safe operation and power flow control of smart grid. In addition, the efficient use of energy, which would be built on power simulator programs, balances the energy equation [27,28].

This paper presents a novel Matlab-based buildings power flow simulator approach. In the suggested approach, the building is represented as a group of electrical networks, organized in hierarchical levels. The building loads, appliances, are modeled based on voltage dependent model. The electric parameters profile (voltage, current, active power, reactive power, apparent power, power factor and energy) in an aggregated form of bottom-up method starting from the appliance level is developed. On the top level, the user defines key parameters such as rated power and power factor of the building existing loads. The power cables are modeled by their equivalent PI model. Accurate simulation models are developed for solving the building network equations where building loads are integrated into building network. Smart meters are implemented at different locations for power quality and energy auditing. Two case studies are introduced to prove the ability of the proposed approach to simulate the building electricity power flow. One case is a residential building and the other is commercial building. A comparison between the proposed approach and EnergyPlus, the validated building simulation software, is presented to show the accuracy of the proposed approach.