Energy and Buildings 147 (2017) 188–199

Contents lists available at ScienceDirect

Energy and Buildings

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

Full Length Article

Energy management for voltage control in a net-zero energy house community considering appliance operation constraints and variety of households

Takuya Fujimoto*, Yohei Yamaguchi, Yoshiyuki Shimoda

Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

ARTICLE INFO

Article history:
Received 3 August 2016
Received in revised form 24 February 2017
Accepted 4 May 2017
Available online 5 May 2017

Keywords:
Energy management
Home appliance
Distribution line voltage
Operation constraint

ABSTRACT

A large-scale diffusion of photovoltaics (PVs) is expected to disturb the voltage control in an electric distribution network. When PVs generate more electricity than demand requires, the electric voltage may exceed its legal limit, and the PV generation is suppressed by the power conditioner. This paper evaluates the extent to which residential energy management resources (EMR) can contribute to controlling the distribution line voltage and reduce the amount of PV generation suppression while considering the variety among households due to family composition and appliance ownership and the operation constraints due to operation time restrictions, occupants' comfort and control method (manual control or automatic control). This paper estimates EMR that can be provided by a washing machine, clothes dryer, dishwasher, rice cooker, electric pot, air conditioner and heat pump water heater. EMR varies among households and accounts for 3%–63% of annual household electricity demand. Although 9.9% of PV generation is suppressed when all detached houses have installed PVs in the assumed residential community, the EMR is able to decrease to no more than 3.0%; this reduction potential decreases by 23% owing to the above-mentioned operation constraints.

1. Introduction

Photovoltaics (PVs) are thought to be among the key technologies for global warming mitigation in Japan. The Japanese government suggested the composition of renewable energy in 2030 to be 22–24% of electrical generation sources [1]. It also suggested the net zero energy house (ZEH) criteria for newly constructed public buildings by 2020 and the achievement of average net emissions of zero in newly constructed buildings by 2030 [2]. However, a large-scale diffusion of PV potentially makes voltage control difficult in local electric distribution lines because the distribution line voltage rises owing to local power generation. This might be severe in newly constructed residential communities with ZEHs because the installation of PV is a major method to satisfy the ZEH requirement. Hirabaru et al. [3] evaluated the effect of PV diffusion on a distribution line voltage serving a residential community and found that the electric voltage exceeded the legal voltage limit when 40% or more of the households in the community installed PV for their houses. When the electric voltage exceeds the legal limit, PV is automatically disconnected from the power system by the power conditioner attached to the PV, which results in a loss of generation opportunity. According to the simulation analysis by Baetens et al. [4], the PV generation suppression accounted for 9–42% of the annual PV generation when all detached houses in a residential community installed PV.

There have been several mitigation methods, such as the automatic voltage regulator (AVR) and static VAR compensator (SVC) implemented to control voltage in the electric power system [5]. The demand side also can provide resources to control voltage without investing in power systems. The electric battery, electric vehicle and electricity-driven water heater are devices that have been well studied as resources [6]. Ikegami et al. [7] optimized the operation of an electric battery and heat pump water heater (CO2HP) using mixed-integer linear programing (MILP). The result showed that these devices could contribute to reduce a considerable amount of electricity surplus. Kam et al. [8] revealed that electric vehicles are able to reduce electricity surplus by 30–70%. Fazeli et al. [9] analyzed the contribution of electric vehicles to control the distribution line voltage and revealed that the voltage could be kept within the legal limit even if 90% of the households in a community installed

* Corresponding author at: Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University M3 Building, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan.

E-mail address: fujimoto@ue.see.eng.osaka-u.ac.jp (T. Fujimoto).

http://dx.doi.org/10.1016/j.enbuild.2017.05.009
0378-7788/

PV. However, electric batteries and vehicles are still unpopular in Japan [10]. Thus, this paper focuses on home appliances and equipment that have already been installed in most households.

We refer to the electricity demand that can be utilized for distribution voltage control as an energy management resource (EMR). The EMR can be defined by considering two factors: 1) the specification of home appliances, such as power consumption and duration of operation 2) the flexibility in service between those produced by the appliances and demanded from the user. Occupants usually operate home appliances and equipment to satisfy their service demands, such as “want to eat rice” or “want to spend time in a comfortable room”. A rice cooker is used to prepare meals, and an air conditioner is used to improve thermal comfort. As long as a service demand is being satisfied, the operation can be flexibly changed. There are two ways to change the operation, i.e. to obtain EMR. The first one is to change the time at which the appliance produces service by using the flexibility in time between those to produce and deliver it. The other is to change the level of service delivered as far as the demand is satisfied. Thus, there are three kinds of constraint limiting the flexibility. The first constraint is related to the former way, which is the operation time restriction [11,12]. The operation time is restricted so as not to disturb the occupants' everyday life and expected time within which the service is delivered. The second constraint is the occupants' comfort [13], which is related to the latter way on the service level. Air conditioners are operated to satisfy thermal comfort in the home. Thus, the operation sacrificing thermal comfort is unacceptable. In other words, their operation changes are limited within the comfortable ranges of service level. The third constraint is related to the control method. There are two types of control methods: automatic and manual controls. The control method in which the changes in the operation of home appliances and equipment are implemented by the occupants manually are to be referred as Manual Control. Therefore, their operations cannot be altered if all occupants are absent. However, in Automatic Control Method, the appliances can be operated independent of the occupants' presence at home by automatic control, for example, a home energy management system (HEMS). Most of the previous researches assumed automatic control by HEMS, and there has been little evaluation of the effect on EMR considering differences in the control methods. Thus, the methodology to quantify EMR must be capable of dealing with the specification of home appliances as well as the constraints on the operation time restriction, occupants' comfort and control method that vary among households according to numerous factors including family composition, specification and ownership of home appliances, occupant behavior and appliance use [14,15]. Baetens et al. [16] evaluated the effect of the variety of occupant behavior on distribution voltage control and revealed that the voltage control potential varied from 88% to 130% owing to the difference in the occupant behavior. Further variety might be provided by home appliance ownership and specification. In addition to the demand, the impact of EMR operation constraints is different owing to the variety among households. Thus, it is necessary to evaluate the impact of EMR provided by home appliances and equipment with consideration of both the EMR operation constraints and the variety among households in the voltage control study.

In energy demand related studies, the methodology to quantify energy demand or flexibility can be divided into small-scale field measurement, large-scale demonstration and simulation. Small-scale field measurement is not effective because the number of sample is relatively small and the outcome cannot be extrapolated to residential communities with ZEHs, which electric voltage is expected to exceed the regal limit. D'hulst et al. [11] conducted a large-scale demonstration project in Belgium in which the authors distributed smart wet appliances equipping a function to automatically decide when the appliance is operated according to the price of electricity in a dynamic pricing market within a flexibility window defined by the user. Kobus et al. [17], Klaassen et al. [18,19] presented a similar demonstration project conducted in the Netherlands. The benefit of conducting demonstration is in reflecting behavioral reality. This is vitally important to quantify EMR. Vanthournout et al. [20] analyzed the result of the same demonstration project as D'hulst et al. [11] and revealed that due to the complexity due to from pricing schemes that require frequent price consultation, the dynamic pricing scheme did not change for the behavior of users tested with manual response, while such comfort deterioration was not observed for users with automated response. However, conducting demonstration is usually costly and only a limited number of appliances can be examined within a limited context.

Alternatively, energy demand simulation is available to quantify EMR that can be provided to a variety of appliances while considering the specification of home appliances and the three kinds of operation constraints. A number of bottom-up models have been developed to quantify energy demand of home appliances in recent years. The models can be divided into the empirical data based model and time use data based model [21]. In the empirical data based model, first, the number of switch-on event occurring on the simulated day is determined. Then, the time at which the switch-on events occur is determined by so-called time of use probability describing the distribution of time at which switch-on events occur developed based on measured data [22–24]. Time use data based models first generate activity of household occupants stochastically and then the activity is converted to the occurrence of switch-on event of home appliances [25]. Discrete time Markov chain is the most frequently applied methodology to simulate the activity of household occupants [26–28]. Nistor et al. [28] estimated the EMR that can be provided by wet appliances as operating reserves for the power system operator. The authors assumed that 20% of Great Britain's households own smart appliances that are operated automatically according to the electricity price after the activation time of appliances, at which the user presses the appliance ON button after clothes or dishes are loaded, within the user defined maximum delay. The operation of wet appliances is modeled by a time use data based model proposed by Richardson et al. [26]. The empirical data based models can analyze the energy demand with consideration of actual usage of home appliances. On the other hand, the time use data based models can quantify EMR provided by home appliances while addressing the behavior of household occupants and are appropriate to consider the effect of the operation constraints that cannot be evaluated by small-scale field measurement and large-scale demonstration. Although there are some applications of time use data based models to voltage control analysis, for example Baetens et al. [16] and Colin et al. [29], the effect of operation constraints on EMR has not been considered.

The aim of this paper is to evaluate the effect of EMR provided by home appliances on distribution voltage control and reduction of PV generation suppression while considering the specification of home appliances, operation time restrict, occupants' comfort, control method and the variety among households by using a time use data base bottom-up model.

In Section 2, the EMR operation constraints and the energy management cases are further discussed. In Section 3, the evaluation method and three simulation models used in this study are presented. These were designed to address the EMR operation constraints and the variety among households. In Section 4, the estimation results of the electricity demand, PV generation and EMR with consideration of the EMR operation constraints and variety among households are presented. The simulation results of the distribution line voltage and suppression of the PV generation in the community are then presented. Section 5 discusses the utiliza-