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A new method for cost-effective demand response strategy for apartment-type factory buildings

Eunsung Oh [a], Youngmin Kwon [b], Sung-Yong Son [c,*]

[a] Dept. of Electrical and Electronic Eng., Hanseo University, Chungcheongnam-do, Republic of Korea
[b] Samsung C&T Corp., Seongnam-si, Gyeonggi-do, Republic of Korea
[c] Dept. of Electrical Engineering, Gachon University, Gyeonggi-do, Republic of Korea

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ABSTRACT

A demand response (DR) program for buildings is widely considered an effective way to improve energy efficiency using various potential resources, such as heating, ventilation, and air conditioning (HVAC) systems and distributed generators. This study presents a method for a cost-effective DR strategy for apartment-type factory buildings composed of individually owned cells. An apartment-type factory building has high energy density but there is limited control over the energy usage of each cell. To design the DR strategy, an energy response factor is defined, taking into account the energy consumption changes of each cell in relation to the outdoor temperature. Based on that, an optimization problem for the DR program participation is formulated by minimizing the total costs and an optimal DR strategy is proposed. The proposed DR strategy is based on the selection of the cells for the DR participants and their capacity. A case study using three apartment-type buildings in Korea shows that the proposed DR strategy can achieve the cost reduction of up to 67.4% on average compared to a conventional DR approach.

1. Introduction

Demand-side management is more important than ever in energy management [1] and it enhances not only the operational efficiency of energy systems on the power market but also reduces capital investment by deferring power plant construction and network upgrades [2]. The building sector is responsible for a major portion of energy consumption. It is estimated that 40% of the total energy consumption is attributed to residential and commercial buildings in the U.S. and the EU [3,4]. Various attempts have been made to reduce the energy consumption throughout a building's lifecycle from siting to design, construction, operation, maintenance, renovation, and demolition [5–7]. However, newly constructed buildings comprise less than 2% of total floor area annually [8]. Therefore, while an emphasis on greening in new building construction is important in the long term, a focus on existing buildings is required both in the short term and in the long term.

In countries with a high population density and high land prices, one of the trends in building construction is an apartment-type factory [9]. In Korea, 30.7% of all companies are located in apartment-type factories [10]. An apartment-type factory building consists of individually owned small factories and/or offices located in the building. The building supports a minimum of common utility services such as restrooms, aisles, elevators, and a lobby that represents a small portion of the energy consumption of the entire building. Therefore, most of the energy in the building is consumed by the individual factories. It is common to provide only electric power to the factories within the building while heating, ventilation, and air conditioning (HVAC) are the responsibilities of the individual factories. The benefit of the apartment-type factory is its ease of construction in an urban area. The apartment-type factory building is similar to a small industrial complex but everything is integrated into a single building. As a result, the building looks similar to a typical office building on the outside. However, the building has high ceiling clearance, fewer columns, a reinforced floor, and a high-capacity electric power supply, differentiating it from conventional office buildings. This type of building is usually preferred by factories with small assembly lines. From the viewpoint of energy management, the apartment-type factory has a high energy consumption density and low energy efficiency compared to conventional buildings, leaving room for improvement.

Demand response (DR) is widely accepted as an effective method to improve the energy efficiency of new and existing buildings [11,12] because there are various potential resources for DR control such as controlling HVAC systems and distributed generators [13] or adopting a pre-cooling process and shifting the

* Corresponding author.
E-mail address: xtra@gachon.ac.kr (S.-Y. Son).

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Nomenclature

T_c	Outdoor temperature at time t
d_t^c	Demand of cell c at time t
e_c	Energy response factor of cell c
d_{DR}	Requested DR capacity
α	Compensation cost factor
β	Installation cost factor
u_c	Compensation cost
u_e	Installation cost
C_{DR}	DR participant set
Δd_p	Demand change of participant p

operating hours of the equipment [14]. Several research studies have investigated the DR of buildings [15–20]. Motegi et al. [15] introduced DR control strategies and the results indicated that HVAC systems were an excellent means for DR-based savings by using global temperature adjustments of different zones. Yoon et al. [16] proposed a dynamic DR control algorithm based on the change of the set-point temperature to control the HVAC loads depending on the electricity retail price; this approach partially shifted some of the electricity load away from the peak. The DR rescheduling problem can be formulated as a reinforcement learning problem and solved by decomposing it over the device clusters [17]. DR strategy considering additional control equipment such as energy storage is proposed [18]. Case studies of DR control strategies based on an automated model calibration procedure with a real-time data monitoring system are presented in Ref. [19]. The work of Yin [19] has been extended to a DR framework for residential and commercial buildings using a combination of EnergyPlus^{TM} and two-state models for thermostatically controlled loads [20]. These research studies have shown that the energy efficiency of buildings is enhanced by a DR control. However, most of the conventional approaches for an effective DR control employ detailed information that requires additional processes for the accurate detection [21,22] and estimation [23] of the building occupancy.

In this study, a method is proposed that allows existing apartment-type buildings to participate effectively in a DR program. The main contributions of this paper are summarized as follows:

- *To propose an adaptive DR strategy for apartment-type buildings*

The proposed method does not require detailed information such as devices and equipment used by individual factories in the building to obtain the potential DR capacity. Instead, the aggregated demand measured for the billing is used. An individual factory in the building is defined as a 'cell', and an apartment-type factory building is defined as a "multi-cell building." Each cell has a different energy consumption level and sensitivity to the outdoor environment. To determine an effective manner of participation in a DR program for a multi-cell building, an energy response factor is first created based on the changes in energy consumption due to the outdoor temperature. Using that, an order-based DR strategy is proposed about the selection of DR participants and the allocation of the request DR capacity to the participants.

- *To assess the technical and economic sensitivity of the proposed method considering various factors*

Cost factors such as installation costs, operating costs to provide the DR services, and utility costs due to the inconvenience caused by participating in the DR services are considered. The benefit factors such as the energy cost savings and the peak reduction as well as incentives are considered. A case study is performed by simulating the effects of the DR program for three apartment-type buildings in Korea. Considering the cost and benefits simultaneously, the optimal number of participating cells for the DR service are determined to maximize the profit. Numerical result shows that the proposed method can reduce costs up to 67.4%. In addition, the results are analyzed based on the ratio of compensation and cost to generalize the proposed model.

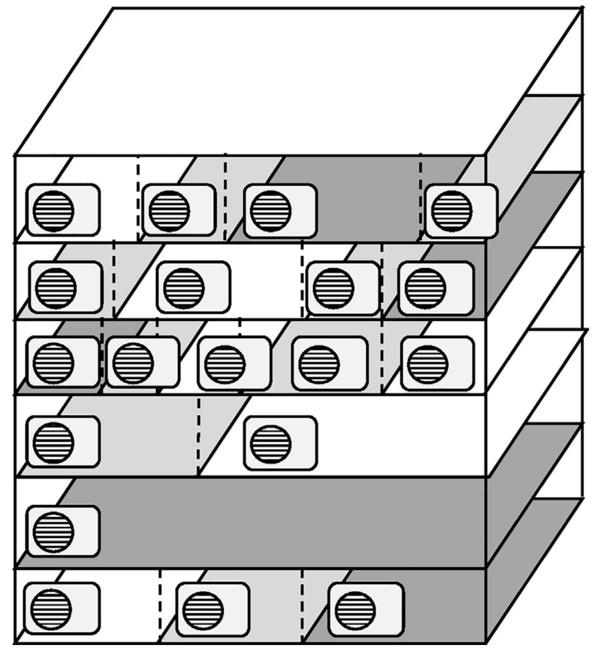

Fig. 1. Schematic diagram of a typical apartment-type industrial building.

2. System model

2.1. Characteristics of energy consumption in apartment-type buildings

Apartment-type buildings, also called industrial buildings, industrial tower, and flatted factory, depending on researchers and countries, are buildings constructed in urban areas to facilitate the attraction of a workforce and to reduce logistical costs [24]. From the viewpoint of energy management, apartment-type buildings described in this paper have certain characteristics as shown in Fig. 1. First, each factory, defined as a 'cell', occupies a different floor area depending on its contract. Second, HVAC is the responsibility of each company since the building does not have a centralized HVAC system or it is limited. Third, the indoor temperature of the space occupied by each factory is managed in a simplified way such as a single-point temperature control. Finally, HVAC is powered by electricity instead of gas or other energy sources.

2.2. Energy consumption response model

In general, introducing a demand response for a building entails a reduction of peak power rather than a reduction in the amount of total energy consumption, resulting in a decrease in the energy charge of an electricity tariff that usually consists of energy cost and usage cost. Different approaches are used when a demand response is adopted, such as changing the operation times of equipment, introducing alternative generators, and even altering production schedules [25]. In extreme cases, a plant shutdown can sometimes be used to meet government policies. However, there is usually a strong resistance to altering production plans in industries, and in