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Electric energy storage design decision method for demand responsive buildings

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ABSTRACT

Electric energy storage is one of the most promising and convenient solutions for energy cost management of buildings by shifting electric loads. This paper investigates electric energy storage (EES) size planning to minimize the total electricity cost of buildings, including investment. This study discusses EES planning considering an EES operation, especially focusing on an economically optimized decision of EES capacity. We first formulate a general electricity cost minimization problem with the electricity bill of buildings and EES cost, and decompose the problem into two parts for EES planning and EES operations. The EES planning algorithm based on the iteration process is proposed considering an ESS operation. The simulation demonstrates that the proposed EES planning can perform close to the optimal exhaustive search algorithm.

1. Introduction

Residential and commercial buildings consume 40% of all energy and 70% of the electric energy produced in the U.S. It is also forecast that these buildings will take a 70% load increment until 2040 [1]. Related to the increasing the electricity energy usage, the pay for the electricity bill is significantly growing.

The cost of electric energy is usually composed of demand charge and energy charge that are determined by the peak demand and the entire energy consumed, respectively, during a given period.

To reduce peak load, various methods can be used, such as peak clipping and peak shifting. Setting room temperature higher or lower than normal and reducing lighting intensity are typical approaches for peak clipping [2,3]. In this case, customers usually experience inconvenience or productivity reduction [4,5]. Peak shifting is distinguished from peak clipping because somehow the shifted energy should be consumed at another time. Providing stored cooling energy that is generated during night time, adopting a pre-cooling process, and shifting working hours are examples of peak shifting [6,7]. Using a distributed generator is also a good approach to reducing peak load in the result by providing additional power. However, there are additional problems in using an emergency generator for demand response, such as pollution, noise, and low efficiency [8].

To reduce the energy costs of buildings, various building design and maintenance approaches have been studied, such as electronic ballasts, LED lighting, and green roofing [9,10]. It is reported that, on average, green buildings designed and constructed with an environmental perspective are 28% more energy-efficient than conventional buildings [11]. Energy operation with renewable sources such as solar and wind power are also discussed extensively [12,13]. However, these approaches have caused additional issues to be considered, because of the reduced operational reliability due to the intermittent energy production of renewable sources.

An energy storage system is one of the most promising solutions for demand response, owing to its ease of use and the environment-friendly characteristics of its operation. Energy storage systems are classified as mechanical, electrochemical, chemical, or thermal energy storage systems. Conventionally, thermal energy storage is widely used for improving thermal comfort and reducing energy consumption in buildings [14]. However, given the increasing importance of electrical energy and integrating renewable resources, mechanical (such as compressed air energy storage (CAES) and flywheel energy storage) and electrochemical storage (such as lead acid and Li-ion batteries) and their applied techniques [15,16] are more intensely studied. Therefore, electrical energy storage (EES) systems are the focus of this work.

EES stores energy during low-price hours and provides it during high-price hours, providing a load shifting effect. At the same

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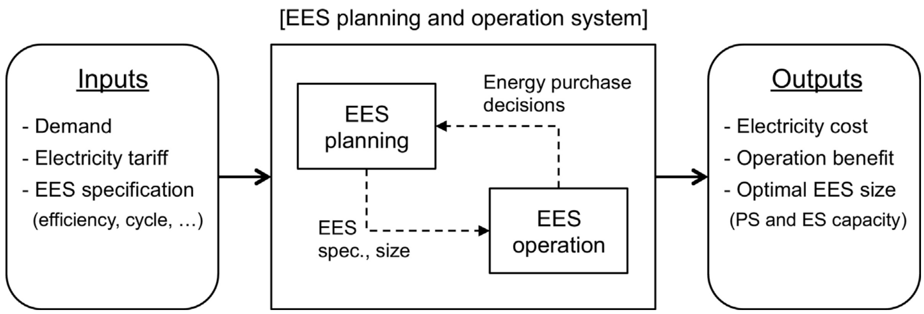

Fig. 1. EES planning and operation system framework.

time, EES can substitute for a conventional emergency generator using stored energy. Currently, the greatest drawback of using EES is its high cost. In Korea, attempts to reduce the impact of initial installation costs have included using EES to replace or complement emergency generators [17]. When considering the rapid decrement of EES cost, the cost issue would be resolved in the close future.

There are two main problems in using EES for buildings to save the electricity cost including peak shifting: appropriate sizing and optimal operation. Appropriate sizing means determining the EES installation size for a given building before operation, whereas optimal operation is a scheduling problem for a specific environment after EES installation. Although many studies on optimal scheduling have been performed, appropriate EES sizing is studied rarely. Makarov et al. studied an EES sizing issue to improve grid reliability [18]. Yan et al. studied appropriate EES sizing for buildings based on short-term load forecasting. However, the approach is limited in sizing to meeting a given shaving peak demand amount [19].

To maximize the utilization of EES, an optimized operation should be considered from the EES installation planning stage. In this paper, we propose an optimal EES size planning system to minimize the electricity cost of a building. The proposed system consists of a two-stage iterative regression process, including planning and operation. The system considers load, rates system, and component costs to determine the optimal combination of power subsystem (PS) and energy subsystem (ES) that define the EES.

The remainder of this paper is organized as follows: Section 2 describes an EES planning and operation framework and system parameters such as demand, electricity tariff, and EES specification considered in this paper. In Section 3, an electricity cost minimization problem is formulated, and an EES planning strategy is suggested. The performance of the proposed method is demonstrated in Section 4. Finally, conclusions are drawn in Section 5.

2. System description

2.1. EES planning and operation

The overall framework of the proposed EES planning and operation system is shown in Fig. 1. The objective of the system is to find optimal PS and ES sizes and the appropriate ES type to be installed that minimize both the total cost of the EES investment and the electricity cost. To operate the system, information such as demand, electricity tariff, and EES specifications should be modeled or provided by building owners, an electricity market, and EES manufacturers. With this information, the system looks for the best size combination of PS and ES as well as the type of ES. Once the type and size are tentatively determined, optimal EES operation simulation is performed to determine the impact on the electricity cost. The combination of PS and ES is altered until the result converges to an estimated optimal value with the iterative regression method.

2.2. Demand and electricity tariff

Demand and electricity tariff are the basic information for the EES planning and operation system. The aggregated occupants demand, d_t[kWh], from buildings, and the electricity tariff p_t[KRW/kWh],[1] from the electricity market, are periodically input to the system at time interval ΔT[h]. The time interval is determined by the time period that the demand and tariff are announced from buildings and electricity market, respectively. Consider an observation time duration T (e.g., 1 month). A set of decision times for the tool is defined as $\mathcal{T} = \{1, 2, \ldots, N\}$ where $N = T/\Delta T$, and t denotes the operation time indicator in $\mathcal{T}$. Throughout this paper, it is assumed that the duration of each operation is one hour, i.e., $\Delta T = 1$h, which is a reasonable assumption under an hourly tariff system.

For an effective operation of the system, demand and tariff predictions are required, as well as their current values. Many prediction techniques have been suggested, such as historical data set matching and customer baseline modeling; studies have shown that these techniques could pre-determine the demand and tariff within 1–2% estimation error [20,21]. To focus on the operation of the system, we assume that sequences of demand forecasts and tariff forecasts are perfectly provided.

2.3. EES specification

An EES is comprised of a PS and an ES. The PS controls the power input and output that electricity is converted to and from some type of stored energy. The ES stores the energy by mechanical, electrical, chemical, and thermal mechanisms. EESs are determined by the device power of the PS and the chosen ES mechanism's energy capacity.

The following key parameters characterize an EES:

- Power capacity, c_{PS} [kW]: the maximum power of the storage device, depending on PS. Power capacity restricts the charge and discharge power of EES.
- Energy capacity, c_{ES} [kWh]: the amount of stored energy of the ES. Energy capacity decides hours of storage coupled with power capacity.
- Efficiency, η[%]: the round-trip energy efficiency calculated as the product of the input and output energy efficiency; it affects the amount of charge and discharge power.
- Cycle life, θ [cycle]: the number of charge-discharge cycles that the system can experience before it fails to meet specific performance criteria. Cycle life limits the total amount of charge-discharge power per unit time because the replacement cost of an EES is extremely large.

[1] KRW is the currency of South Korea.