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ORIGINAL ARTICLE

Energy Storage System Capacity Sizing Method for Peak-Demand Reduction in Urban Railway System with Photovoltaic Generation

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Abstract
The recent increase in the number of passengers has led to an increase in the operational costs of urban railway systems. In particular, peak demand is notably increasing due to the high affluence of commuters during rush hour. In addition, the expansion of the renewable energies has led to the adoption of sources such as photovoltaic (PV) power generation into the urban railway system. Similarly, energy storage systems (ESSs) have been introduced to reduce the peak demand. However, given the current high costs of ESSs, it is essential to accurately determine their capacity considering peak-demand reduction target in urban railway systems. In this paper, we propose an ESS sizing method considering PV power generation for peak-demand reduction in an urban railway system. The ESS capacity is determined using binary search and a linear programming based daily ESS scheduling. A numerical example considering data from urban railway and PV power generation systems shows the suitable performance of the proposed method.

Keywords Capacity sizing · Energy storage system · Photovoltaic generation

1 Introduction

The number of passengers in urban railway systems is increasing with the continuous growth in the urban population. Similarly, the peak demand has been rapidly increasing as the number of passengers using urban railway systems considerably increases during rush hour. Though most electric systems for railway systems adopt time of use and peak demand charges, the peak-demand reduction is essential to lessen the operational costs in the cities' railway systems [1]. In particular, the peak demand charges in Korea are estimated from the highest power demand over the preceding 12-month period. Consequently, peak-demand reduction is essential for financially sustainable operations [1].

Renewable energy has been adopted into urban railway systems for energy saving. In above-ground stations, photovoltaic (PV) power generation systems can be installed on rooftops, where a large capacity can be installed given their large area. However, the time of highest PV generation does not coincide in general with the time of peak demand in urban railway systems. Therefore, PV power generators need to be connected to energy storage systems (ESSs) to enhance efficiency and supply power during the rush hour.

Several types of ESSs have been introduced in urban railway systems for different purposes. For instance, the fast response of flywheel storage [2] is primarily used for voltage regulation, whereas battery-based and hybrid ESSs are economical alternatives [3]. To improve cost saving, the ESS must be scheduled considering aspects such as load, renewable energy generation, and variation in the daily electric rate. An ESS scheduling method has been proposed in Refs. [4, 5]; however, it determines the optimal charging and discharging schedule considering a fixed-capacity ESS. Further, appropriately sizing an ESS before its installation can drastically reduce the usually high installation cost.

In this paper, an ESS sizing method is proposed for peak-demand reduction in an urban railway system considering PV power generation. The ESS capacity is determined by combining binary search and daily ESS scheduling for

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peak-demand reduction. This paper is organized as follows: Sect. 2 describes the configuration of the urban railway electric system considered in this study. Section 3 details both daily ESS scheduling based on the discussion of preliminary study in Ref. [4] and the proposed sizing method. Section 4 provides the results of a numerical example using the proposed method on railway load and PV power generation data. Finally, a conclusion is given in Sect. 5.

2 Urban Railway Electric System

Figure 1 shows the configuration of the urban railway electric system. Energy from an external power system is supplied to the station and train through a substation. The station has AC load and PV generators installed at its rooftop. The ESS has independent power conversion systems for simultaneously charging through the PV generator and external power system. It is assumed in this study that the generated energy by the PV system is preferentially used for charging the ESS. The train is connected to the urban railway electric system by a 1,500 V DC catenary. The electricity consumption is calculated at a transformer connected to the external power grid. Therefore, the demand of both the station and train are considered as a single load.

3 Scheduling and Sizing of ESS

3.1 Daily ESS Scheduling

For the ESS sizing problem, daily ESS scheduling is required. The daily ESS scheduling for peak-demand reduction and electricity cost saving in urban railway systems was proposed in previous study [4]. During capacity sizing, the daily

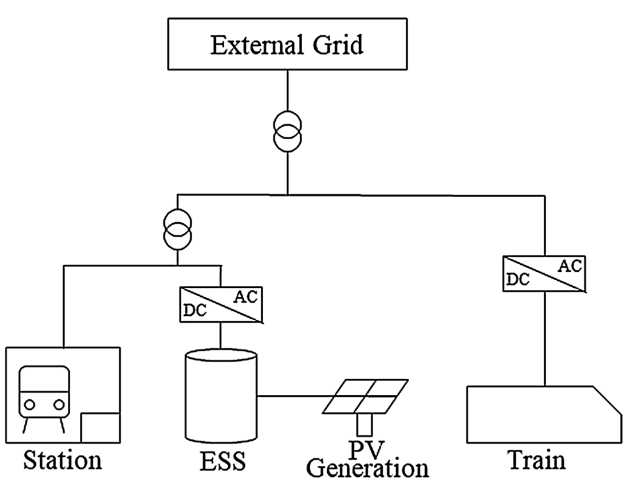

Fig. 1 Diagram of urban railway electric system

scheduling problem must be solved iteratively. Therefore, the scheduling algorithm proposed in Ref. [4] was modified into a linear programming (LP)-based problem in this study. Since states on and off of the ESS were described as binary variables, the discharging cost is disregarded during relaxation.

The objective function of the LP-based daily ESS scheduling attempts to minimize the daily power charge:

$$Minimize \quad \sum_{t=0}^{T} c_t P_t^{buy}, \tag{1}$$

where c_t and P_t^{buy} are the electricity rate and amount of power purchased from the external power grid at time t, respectively. Next, the balancing conditions in the system are expressed as

$$P_t^{load} + P_t^{ESS} = P_t^{buy}, \tag{2}$$

where P_t^{load} and P_t^{ESS} denote the load of the system and power in the ESS at time t, respectively. If P_t^{ESS} is positive, the ESS is charged, whereas a negative value indicates that it is discharging. For the peak-demand reduction, P_t^{buy} should be lower than target peak-demand power P^{Peak}, which is expressed as

$$P_t^{buy} \le P^{Peak}. \tag{3}$$

The power conversion system of the ESS has an output limit, which is given by constraint

$$P_t^{ESS} \le P_{\max}, \tag{4}$$

where $P_{\max}$ represents the power rating of the ESS. In general, the energy stored in an ESS is expressed by the state of charge (SoC), which indicates the percentage of energy remaining in the system with respect to its maximum storage capacity. The SoC can be calculated as

$$SoC_t = SoC_{t-1} + (P_t^{ESS} + P_t^{PV})/Cap_{ESS}, \tag{5}$$

where P_t^{PV} and Cap_{ESS} represent the power generated by the PV system at time t and the ESS capacity, respectively. Note that power P_t^{PV} is directly injected into the ESS to determine its SoC. Hence, the SoC must remain within a specific range for safe operation. This range can be defined as

$$SoC_{\min} \le SoC_t \le SoC_{\max}, \tag{6}$$

where $SoC_{\min}$ and $SoC_{\max}$ are the minimum and maximum SoC levels, respectively.

By solving the optimization problem described above, the daily schedule of the ESS can be calculated, and then the ESS sizing problem can be formulated.

3.2 Proposed ESS Sizing Method

Two major decision variables are related with peak demand reduction. The first one is the power rating of the ESS, i.e., the maximum output power, and the second one is the ESS capacity, i.e., the maximum energy that can be stored in the system. The power rating of the ESS allows to determine the maximum peak-demand power that can supplied by this system, whereas the capacity allows to determine the peak-demand reduction period. The power rating of the ESS can be calculated from the historical load data of the urban railway system:

$$P_{\max} = \max_{t \in H.L.} (P_t^{load}) \times (1 - PRR), \tag{7}$$

where *H.L.* represents the available load data from a given period and *PRR* denotes the peak-demand reduction ratio, which indicates the target peak-demand reduction.

After the power rating of the ESS is determined, the LP-based optimization problem described above can be reformulated as an ESS sizing problem, which is solved using binary search. Specifically, the LP-based scheduling problem with fixed capacity is iteratively solved using binary search while changing the capacity until the termination condition is satisfied.

The proposed ESS capacity sizing method is illustrated in Fig. 2. The capacity of the ESS varies according to infeasibility of daily scheduling. Except for the peak-demand constraint, no other constraint can be violated. Therefore, if scheduling is infeasible, it can be assumed that the capacity is insufficient for achieving the target peak-demand reduction. In this case, the capacity must be increased. If the problem is solved, it can be assumed that the capacity is excessive, and hence must be decreased. If both the problem can be solved and the difference between the ESS capacity at the current and previous iteration, ΔCap, is smaller than tolerance ε, the optimization process terminates by retrieving the current ESS capacity as the optimal solution. The proposed sizing method is applied by considering the same power rating over all the days in the calculation.

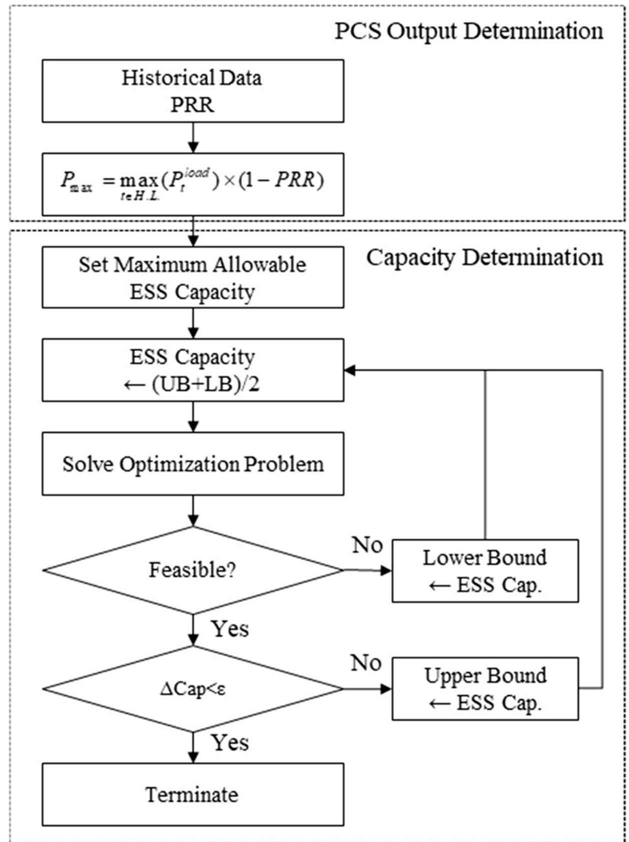

Fig. 2 Flowchart of ESS sizing method. *PCS* power conversion system, *UB* upper bound, *LB* lower bound, *PRR* peak-demand reduction ratio

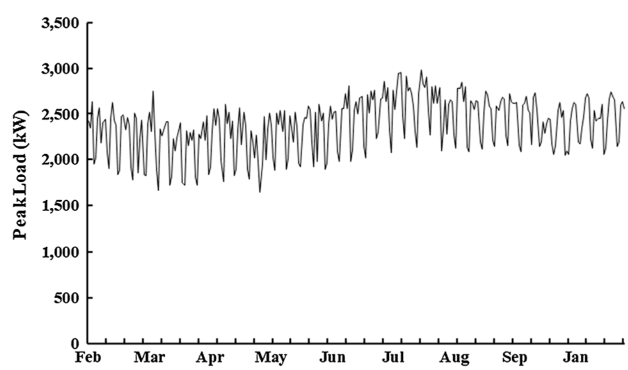

Fig. 3 Daily peak load of urban railway system

4 Numerical Results

This section presents numerical results of the proposed method using modified historical load data of the urban railway system in Korea and PV generation data. Since the peak charge is calculated with 15-min granularity of energy consumption in the Korean electricity billing system, the 15-min interval data are applied.

The PV generator installed in the station of the urban railway system is assumed to have 30 kW of capacity. In addition, load data acquisition starts at 4:00 instead of 0:00 for consistency of load pattern of the Korean urban railway system, which starts operating at 5:00 a.m. Figure 3 shows a typical load of the urban railway system over a year, with the highest peak of 2982.8 kW appearing on August 1st. Assuming a peak-demand reduction ratio *PRR* of 10%, the output of ESS is 298.3 kW according to (7). As a result, the capacity is determined to be 150.9 kWh at July 21st as shown in

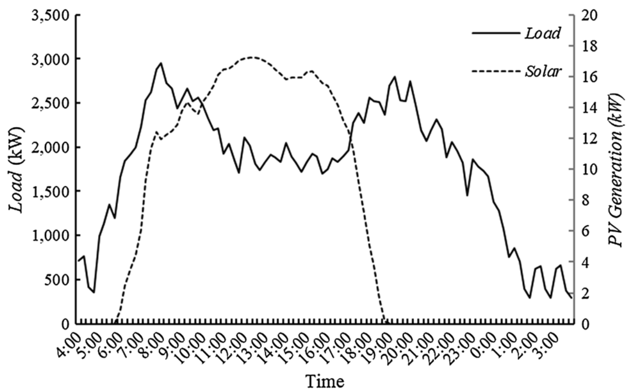

Fig. 4 PV generation and system load on July 21st

Table 1 ESS capacity with the corresponding lower and upper bounds per iteration of the proposed method

Lower bound (kWh)	ESS capacity (kWh)	Upper bound (kWh)
0	298.28	596.56
0	149.14	298.28
149.14	223.71	298.28
149.14	186.425	223.71
149.14	167.7825	186.425
149.14	158.46125	167.7825
149.14	153.800625	158.46125
149.14	151.4703125	153.800625
149.14	150.3051563	151.4703125
150.3051563	150.8877344	151.4703125

Fig. 4. Although August 1st has the highest peak demand, it turns out July 21st needs the largest capacity due to its peak-demand duration. The ESS capacity with the corresponding lower and upper bounds throughout the iteration process are listed in Table 1. In order to calculate a sufficiently large initial value, an average 1-h interval load on weekdays of 2017 was analyzed. As the morning peak power lasted for 2 h, the initial value of the capacity was assumed to be twice the output. The optimal ESS capacity was 150.9 kWh to sustain an output of 298.3 kW for approximately 30 min. As energy is continuously supplied to the ESS during the morning by the connected PV generator, it was able to discharge for a long time compared to the charged energy.

Figure 5 shows the peak-demand reduction through the ESS with output of 298.3 kW and capacity of 150.9 kWh. The daily demand from the external power system is minimized according to the objective function of the LP-based optimization by momentarily discharging the ESS after 8:00 and from 17:00 onwards, which represent the peak-demand hours.

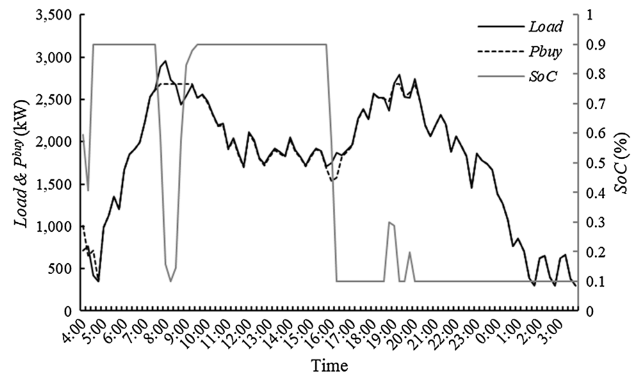

Fig. 5 Peak-demand reduction using ESS

5 Conclusion

In this paper, an ESS sizing method considering PV generation for peak-demand reduction of an urban railway system is proposed. The proposed method is based on daily scheduling and binary search to determine the appropriate ESS capacity. A numerical example with urban railway system and PV generation data illustrates the suitable sizing of the ESS using the proposed method. However, to further optimize ESS sizing, the installation cost should be considered in the future research. Hence, upcoming research will include the installation and other costs for optimal ESS sizing.

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