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Impacts of Supply-Demand Characteristics on Optimal Configuration of Energy Storage System with Multiple Types of Batteries

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In this work, a model-based method to optimise capacity configurations of battery energy storage system (BESS) with multiple types of batteries based on considerations of power supply-demand characteristics is proposed, aiming to minimise the total cost of a hybrid power system (HPS). The effectiveness of the proposed method is demonstrated through a case study of a HPS with renewable energy generation and battery energy storage. Results show that the optimal capacity configuration of the BESS with the lowest total cost of the HPS can be obtained. The effects of the power supply-demand characteristics, including amplitude and period variations, on the optimal capacity configuration of the BESS with multiple types of batteries, are further analysed and discussed.

1. Introduction

To improve economic and environmental performances of hybrid power systems (HPS), it is crucial to balance intermittent power supply and fluctuating power demand by using battery energy storage systems (BESS) (He et al., 2017). Different batteries possess different performances and capacity fading dynamics (Wang, 2018). Design and operation of BESS with multiple types of batteries have been attached more importance in recent years (Ahmadian et al., 2018), aiming to determine the optimal capacity allocation, types of batteries and energy/power capacity of batteries (Günther et al., 2018). The optimal power scheduling that determines the best operating mode of the BESS is also determined to reduce the operational cost of the BESS (Wankmüller et al., 2017). However, most of these efforts were conducted with a fixed application scenario without considering the variation of the interaction between the power supply and the power demand, which significantly influence the capacity allocation of the BESS with multiple types of batteries. In other words, for the design and operation of a BESS, the characteristics of the power supply-power demand curves determine the configuration and scheduling of the BESS with given types of batteries if different power supply-power demand curves are given. The goals of this work are to develop a mathematical programming model to optimise the capacity configuration of the BESS with multiple types of batteries and investigate the effects of characteristics of the power supply-power demand curve on the design and operation of the BESS with multiple types of batteries.

2. Problem statement

A HPS consists of power supply side, power demand side, battery energy storage system and the grid. For the power supply side, the power is provided by renewable energy, such as biomass energy and wind power. The BESS is composed of *N* types of batteries. For the power demand side, the electricity is supplied by the grid, the power supply side and/or the BESS. The residual electricity generated by the power supply side is stored in the BESS or abandoned after the power demand is fully satisfied. In this work, the whole time horizon of interest is divided into *K* time intervals. The optimisation problem for the HPS can be described as follows.
Given are (1) power supply and demand curves, (2) electricity prices, and (3) parameters of the BESS including the capacity cost, the limits of state of charge (SOC) and charging/discharging efficiencies. For the HPS, the

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effects of characteristics of the power supply-power demand curves on the optimal capacity configuration of the BESS with multiple types of batteries are investigated when the total cost of the whole system is minimised.

3. Mathematical programming model of BESS with multiple types of batteries

3.1 Objective function

The objective is to minimise the total cost of the HPS, C^{tot}, which is the summation of the investment cost C^{inv} and the operating cost C^{oper}.

$$\min C^{tot} = C^{inv} + C^{oper} \tag{1}$$

In this work, the capital cost of the BESS is solely included in the investment cost of the HPS, which is determined by the rated energy capacity and the rated power capacity. That is

$$C^{inv} = \sum_{n\in\mathbf{N}} \left(C_n^{B,EC} \cdot EC_n^{B,rated} + C_n^{B,PC} \cdot PC_n^{B,rated} \right) \tag{2}$$

Where $EC_n^{B,rated}$ is the energy capacity of the battery *n* at its rated state, in kWh. $PC_n^{B,rated}$ is the power capacity of the battery *n* at its rated state, in kW. $C_n^{B,EC}$ is the unit cost of the energy capacity of the battery *n*, in \$·kWh^{-1}, and $C_n^{B,EC}$ is the unit cost of the power capacity of the battery *n*, in \$·kW^{-1}. **N** is the set of battery type.
The operating cost of the HPS includes the operational cost, maintenance cost and electricity cost. It can be expressed as

$$C^{oper} = \sum_{n\in\mathbf{N}} f_n \cdot C^{inv} + \sum_{k\in\mathbf{K}} \rho_k \cdot (E_k^{GD} + \sum_{n\in\mathbf{N}} E_{k,n}^{GB}) \tag{3}$$

where *f* is the coefficient of the operation and maintenance cost. ρ is the electricity price, in \$·kWh^{-1}. E_k^{GD} means the electricity transmitted from the grid to the power demand side at the time interval *k*, whereas $E_{k,n}^{GB}$ represents the electricity from the grid to the battery *n* at the time interval *k*. **K** is the set of time intervals. In this work, the unit of the electricity is kWh.

3.2 Constraints

(1) Electricity balances
In a certain time, interval *k*, the electricity in the HPS should satisfy

$$\Delta E_k = E_k^S - E_k^D \tag{4}$$

$$\Delta E_k = \left(E_k^{SD} + \sum_{n\in\mathbf{N}} E_{k,n}^{SB} + E_k^{out} \right) - \left(E_k^{SD} - \sum_{n\in\mathbf{N}} E_{k,n}^{BD} - E_k^{GD} \right) \tag{5}$$

where ΔE_k represents the electricity difference between the electricity supplied and the electricity consumed, in kWh. E_k^S, E_k^D and E_k^{out} denote the electricity from power supply side, the electricity required by the power demand side, and the electricity exported to the external system at time interval *k*, respectively. E_k^{SD} stands for the electricity from the power supply side to the power demand side at the time interval *k*. $E_{k,n}^{SB}$ denotes the electricity from the power supply side to the battery *n* at the time interval *k*. $E_{k,n}^{BD}$ is the electricity from the battery *n* to the power demand side at the time interval *k*.
In a certain time interval *k*, the electricity balances of the BESS can be expressed as

$$E_k^B = E_{k-1}^B + E_k^{B.c} - E_k^{B,d} \tag{6}$$

$$E_k^{B,c} = \sum_{n\in\mathbf{N}} E_{k,n}^{SB} + \sum_{n\in\mathbf{N}} E_{k,n}^{GB} \tag{7}$$

$$E_k^{B,d} = \sum_{n \in \mathbf{N}} E_{k,n}^{BD} \tag{8}$$

where the superscripts *c* and *d* stand for the charging and discharging processes.
The electricity balances of each type of battery in the time interval *k* can be expressed as

$$E_{k,n}^{B} = E_{k-1,n}^{B} + \eta_n^c \cdot E_{k,n}^{B,c} - E_{k,n}^{B,d} / \eta_n^d \tag{9}$$

$$E_k^{B,c} = \sum_{n \in \mathbf{N}} E_{k,n}^{B,c} \tag{10}$$

$$E_k^{B,d} = \sum_{n \in \mathbf{N}} E_{k,n}^{B,d} \tag{11}$$

where η is the charging or discharging efficiency.
(2) The state of the BESS
The constraints of SOC for each type of battery can be expressed as

$$E_{k,n}^{B} = EC_{k,n}^{B} \cdot SOC_{k,n} \tag{12}$$

$$SOC_n^{\min} \le SOC_{k,n} \le SOC_n^{\max} \tag{13}$$

where the superscripts *min* and *max* denote the lower and upper limits.
For each battery, the charging and discharging electricity satisfy

$$E_{k,n}^{B,c} \le PC_n^{B,rated} \cdot t_k \tag{14}$$

$$E_{k,n}^{B,d} \le PC_n^{B,rated} \cdot t_k \tag{15}$$

where t_k is the elapsed time of the time interval *k*.
The constraints of charging and discharging of the BESS can be expressed as

$$z_k^c \cdot E^{\min} \le E_k^{B,c} \le z_k^c \cdot E^{\max} \tag{16}$$

$$z_k^d \cdot E^{\min} \le E_k^{B,d} \le z_k^d \cdot E^{\max} \tag{17}$$

$$z_k^c + z_k^d \le 1 \tag{18}$$

where z^c and z^d are binary variables that indicate the charging and discharging states of the BESS. Eq(18) denotes that the BESS cannot be both in charging state and in discharging state simultaneously.
The existences of the energy and power capacities of each type of batteries, and the relationship between the energy capacity and power capacity can be written as

$$z_n \cdot PC_n^{\min} \le PC_n^{B,rated} \le z_n \cdot PC_n^{\max} \tag{19}$$

$$z_n \cdot EC_n^{\min} \le EC_n^{B,rated} \le z_n \cdot EC_n^{\max} \tag{20}$$

$$EC_n^{B,rated} \ge PC_n^{B,rated} \cdot t_k \tag{21}$$

where z_n is binary variable to indicate the existence of the battery type *n*.
(3) Battery capacity degradation characteristics
The battery performance will deteriorate in the course of its charging and discharging. Thus, the battery capacity degradation characteristics should be taken into consideration to optimise the energy allocation and power scheduling of the BESS with multiple types of batteries. In this work, all batteries are assumed to be fresh. The battery capacity declines to 80% of its rated capacity when it is discarded. According to the Hesse et al., 2017, the percentage of capacity degradation of each battery used after time interval *k*, $\alpha_{k,n}$, can be calculated by

$$\alpha_{k,n} = \alpha_{k\text{-}1,n} + 0.5 \times \frac{E_{k,n}^{B,c} + E_{k,n}^{B,d}}{EC_n^{B,rated} + \varepsilon} \times \frac{1}{L_n} \tag{22}$$

where L represents the equivalent cycle number of battery in its total life time. ε is a small positive number. The residual energy capacity $EC_{k,n}^{B}$ of battery n after time interval k can be calculated by

$$EC_{k,n}^{B} = EC_n^{B,rated} \times \left(1 - 0.2\alpha_{k,n}\right) \tag{23}$$

To avoid the replacement of batteries in the time horizon, the constraints of the residual energy capacity can be expressed as

$$0.8EC_n^{B,rated} \le EC_{k,n}^{B} \le EC_n^{B,rated} \tag{24}$$

4. Case study

4.1 Fundamental data

In this work, ΔP is used to depict the power difference between the power supplied by the power supply side and the power required by the power demand side. As shown in Figure 1, a square type curve of ΔP, where the power supply side could be a biomass energy generation system (Rozali et al., 2013), and the power demand side could be pulse loads (Günther et al., 2018), is used to investigate the impacts of the supply-demand characteristics on the optimal configuration of energy storage system with multiple types of batteries. The BESS in this case consists of three different types of batteries, namely Lead-acid, Li-ion and NaS batteries. The parameters of each type of batteries are listed in Table 1. The electricity price is 0.16 $\$\cdot kWh^{-1}$. The electricity curtailment is not allowed in this work. The minimum and maximum rated energy capacities of each type of batteries are 200 kWh and 550 kWh.

In this case, one day is equally divided into 24 time intervals, and the time horizon of the HPS is four years. To facilitate the calculations, the power scheduling scheme of the HPS of each day in a month is assumed to be identical, and the ΔP curve of each day during the time horizon keeps unchanged.

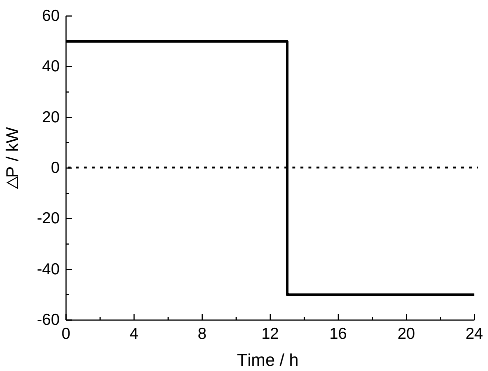


Figure 1: Power difference between the power supply side and the power demand side for one day

Table 1: The parameters of batteries

Parameters	Lead-acid	Li-ion	NaS	Reference
η (%)	91	94	88	(Mariaud et al., 2017)
L (cycle)	900	4,000	2,500	(Luo et al., 2015)
$C_n^{B,EC}$ ($\$\cdot kWh^{-1}$)	400	700	500	(Luo et al., 2015)
$C_n^{B,PC}$ ($\$\cdot kW^{-1}$)	600	1,400	1,500	(Luo et al., 2015)
$SOC^{\min}$ / $SOC^{\max}$	0.4/0.9	0.05/0.95	0.2/0.8	(Mariaud et al., 2017)
f (%)	1	1	1	

The proposed model is a mixed integer nonlinear programming model. All calculations in this work were implemented on the GAMS platform with the CPU of Intel(R) Core(TM) i5-8400 @2.80 GHz. DICOPT was selected for the mixed integer nonlinear programming problem, and CPLEX and CPNOPT were adopted for the mixed integer programming and non-linear programming sub-problems. The maximum relative errors of all calculations allowed were 5 %. In this example, there are 48,769 constraints and 24,907 variables, when the total cost of the HPS is taken as the objective. And the calculation time is about 15 min.

4.2 Optimal configuration of BESS with multiple types of batteries

When the proposed method is adopted for the optimization, the electricity cost of the system is $19,232. The lowest total cost of the HPS is $583,148, and the cost of the BESS accounts for 96.7 %, which means that the total cost of the HPS is mainly contributed by the cost of the BESS. In Table 2, the optimal configuration of the BESS with multiple types of batteries is presented. It can be seen that two types of batteries, namely Li-ion and NaS batteries, are selected for the BESS, when the total cost of the HPS is minimised. The Lead-acid batteries is not chosen. It means that Li-ion and NaS batteries have more advantages in the BESS in the HPS. Regarding the selected batteries, the energy capacity and the power capacity are 530 kWh and 40 kW for the Li-ion batteries, and they are 200 kWh and 10 kW for NaS batteries. It indicates that the capacity of Li-ion batteries is much higher than that of NaS batteries. This configuration mainly depends on their costs and performances including the capacity degradation characteristics, charging and discharging efficiencies and the allowed ranges of SOCs. In other words, the selection of battery type and the determination of battery capacity are a trade-off between the cost and performance under a given power curve.

Table 2: The optimal results with the lowest total cost of the HPS

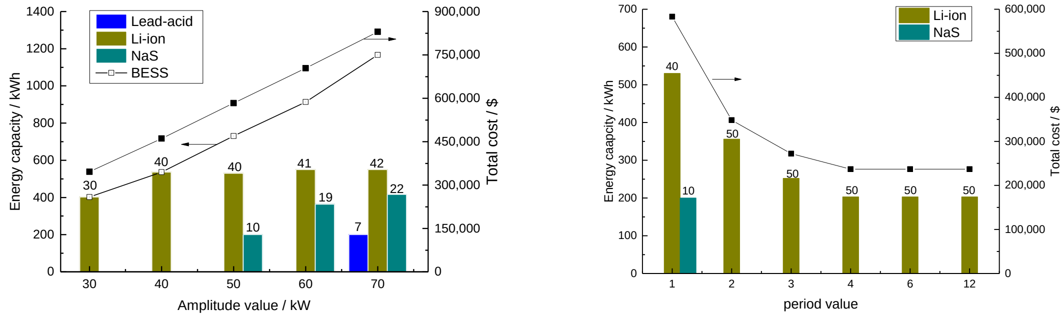
Parameters	Lead-acid	Li-ion	NaS
Energy capacity (kWh)	/	530	200
Power capacity (kW)	/	40	10
Remaining energy capacity (kWh)	/	498	187
Degradation rate (%)	/	6.1	6.4
Investment cost ($)	/	426,624	115,603
Operation and maintenance cost ($)	/	17,065	4,624

4.3 Effects of power curve variations on the configuration of BESS

In this section, the effects of the power curve variations on the configuration of the BESS are analysed and discussed. To facilitate understanding, for the style of the curve in Figure 1, the effects of the amplitude value and the period value of the power curve on the configuration of the system are investigated. The amplitude value refers to the power value of the power curve, whereas the period value represents the number of the same signal occurring in one day. For example, the amplitude value and the period value of the ΔP curve in Figure 1 are 50 kW and one. The effects of variations of the amplitude value and the period value of the ΔP curve on the capacity configuration for the BESS are presented in Figure 2, where the variation of the ΔP curve is represented by changing the amplitude value from 30 kW to 70 kW and the of period value changing from one to twelve. It should note that the numbers above the bars in Figure 2 are the power capacity of the corresponding type of batteries, and the units of these numbers are kW.

For the variation of the amplitude value, as shown in Figure 2a, only Li-ion batteries are selected in the BESS when the amplitude value is less than 50 kW, whereas Li-ion and NaS batteries are chosen for the amplitude value between 50 kW and 60 kW. When the amplitude value is greater than 70 kW, the three types of batteries are selected for the BESS. It indicates that the selection of the battery types depends on the amplitude values of ΔP. From Figure 2a, it can be easily drawn that the energy capacity of the BESS does not vary linearly with the increase of the amplitude value of the power curve. It indicates the differences of three types of batteries. This is a result of the nonlinear variations of the total cost of the HPS.

For the variation of the period value, as shown in Figure 2b, only Li-ion batteries are selected in the BESS, and the selection of the battery type keeps unchanged with the increase of the period value, when the period value is less than one. Figure 2b also shows that, when the period value of the ΔP curve is less than four, with the increase of the period value, the capacities of the BESS and total cost of the HPS decreases. In contrast, when the period value of the ΔP curve is greater than four, the capacities of the BESS and total cost of the HPS keep unchanged with the increase of the period value. It is worth noting that the degradation rates of the Li-ion batteries are all 20 % after four-years operation corresponding to the period values from four to twelve. This implies that the capacity degradation characteristics also have dramatic impacts on the capacity configuration of the batteries of the BESS. The design of the BESS without considering capacity degradation dynamics of batteries may fail to meet practical requirements. Therefore, it is critical to take the capacity degradation characteristics into consideration in the design and operation of the BESS with multiple types of batteries.



(a) Amplitude value variations

(b) Period value variations

Figure 2: Effects of the ΔP curve variations on the configuration of the BESS

5. Conclusions

In this work, a model-based method is developed to determine the optimal capacity configurations of the battery energy storage system with multiple types of batteries based on the consideration of the power supply-power demand characteristics, aiming to minimise the total cost of the HPS. The effectiveness and applications of the proposed method are demonstrated through case studies for a virtual HPS with renewable energy generations and battery energy storage. Results show that Li-ion and NaS batteries are selected in the BESS when the total cost of the HPS is minimised. The selection of battery types and capacities in the whole system is a trade-off between the performances and the costs of the batteries. Moreover, the variations the amplitude values and period values of the power difference curve affect the selection of the battery types and the corresponding capacities of the BESS. Based on the proposed model, the effects of the variations in other types of power difference curves, pulse and sinusoidal power curves, for examples, on the capacity configuration of the BESS should further be investigated.

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