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Optimizing the configuration of the Battery Energy Storage System in Microgrid Considering orderly and non-orderly EV charging

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ABSTRACT

As energy issues become serious, the utilization of distributed energy resources in microgrid has become the most popular choice. At the same time, electric vehicles are growing fast and have been recognized as the most promising direction. However, the uncertainty of power generation and EVs charge/discharge will cause power grid fluctuation, which in further increases the control load. Under this circumstance, battery energy storage system is considered as the most effective way to overcome the instability and alleviate energy crisis. This paper evaluates the battery energy storage system optimal configuration in a residential area involving electric vehicles based on cost analysis includes the basic structure of MG and the model of electric vehicles. The BESS investment cost, environmental value and EVs subsidy are taken into account in cost analysis part. The Battery Performance and Cost model is used for the bottom-up design and calculation for unit capacity costs with different levels of rated capacity. The results in the case study show the system rated capacity and power decrease greatly when electric vehicles participate in frequency control with economical energy management strategy. And the using of Battery Performance and Cost could make the result more accurate, which benefits from unit cost changing value. Finally, the most optimal configuration is given by balancing the effect of the microgrid frequency control and the total daily cost.

Keywords: Battery Energy Storage System (BESS), Electric Vehicles (EVs), Optimal Configuration, Cost Analysis

NONMENCLATURE

Abbreviations	
BatPac	The Battery Performance and Cost model
BESS	Battery energy storage system
DER	Distributed energy resources
DG	Distributed generator
EMS	Energy manage strategy
ESS	Energy storage system
EV	Electric vehicle
HESS	Hybrid energy storage system
LFP-G	Lithium Iron Phosphate (batteries)
MG	Microgrid
NMC-G	Lithium Nickle Manganese Cobalt Oxide-Graphite (battery)
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
PG	Power grid
PSO	Particle Swarm Optimization
PV	Photovoltaic panel
REVB	Retired electric vehicle batteries
V2G	Vehicles to Grid
Symbols	
C_{BESS}^{inv}	Investment cost of BESS, $
C_{BESS}^{m}	Maintenance cost of BESS, $
C_d	Total daily cost of MG, $
C_{EV}	Payments for the frequency control of EV's users, $
C_{EV}^{N}	Whole daily cost of all (N) the EVs in the MG, $
C_p	Environmental cost, $

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C_{pu}	Punish cost of MG for failing to fulfill the need of frequency control, $
C_t^{ch}	Electricity price of charge at *t* time, $
C_t^{dis}	Electricity price of discharge at *t* time, $
E_{rated}	Rated capacity of BESS, kW·h
K_{BESS}^{inv}	Unit capacity cost coefficient of BESS, $/(kW·h)
K_{BESS}^{m}	Unit power maintenance cost, 0.001343 $/(kW·h)
K_{PCS}^{inv}	Unit power cost coefficient of PCS, 109.0893 $/(kW·h)
K_{PV}^{inv}	Unit power cost coefficient of PVs, 1745.4292 $/(kW·h)
k_i	Standard fee of the i_{th} contaminant, $/kg
k_{pu}	Penalty coefficient, 0.0149 $/kW
m_i	Unit capacity emissions of the i_{th} contaminant, kg/(kW·h)
n	Whole life of BESS, 10 years
P_{BESSt}^{ch}	Input of BESS at *t* moment, kW·h
P_{BESSt}^{dis}	Output of BESS at *t* moment, kW·h
P_{BESS}^{needed}	Theoretical power output of BESS, kW·h
P_{demand}^{t}	Total power load at *t* moment, kW·h
P_{EVs}^{t}	EVs load at *t* moment, kW·h
$P_{i,t}^{ch}$	Power of charge of i_{th} EV at *t* time, kW·h
$P_{i,t}^{dis}$	Power of discharge of i_{th} EV at *t* time, kW·h
P_{load}^{t}	Basic power load of the residents in MG at *t* moment, kW·h
P_N	Rated power of EVs, kW·h
P_{rated}	Rated power of BESS, kW·h
P_{rated}^{PV}	PVs rated power, kW·h
P_{supply}	Rated power output of distribution network set in advance, kW·h
P_{supply}^{t}	Power supply by the distribution network at *t* moment, kW·h
ΔP_i	Power shortage or surplus of MG in period *i*, kW·h
ΔP_t	Difference of power supply and load at t moment, kW·h
r	Discount rate, 8 %
s	Number of periods that power is unbalanced
$SOC_{i,min}$	Represent the lower limit SOC of EVs batteries, 0.2
$SOC_{i,max}$	Represent the upper limit SOC of EVs batteries, 0.9

1. INTRODUCTION

In the past few decades, energy consumption in global scope increased rapidly, from 28000 TW·h in 1950 to 153600 TW·h in 2017, almost 4.5 times increased [1]. There is still a long way to go to solve the problem of energy shortage and solar energy is recognized as one of the most popular renewable energies for its low cost and abundant reserves [2]. However, solar energy has a well-known instability issue [3]. The power outputs of PVs depend on the real-time climate, the sudden increase or decrease will affect the frequency of the power system and damage the generator eventually led to the collapse [4]. Moreover, the EVs are developing rapidly according to REVB, and if without any manage strategy, the uncertainty of docking rate in residential areas would aggregates the instability of the power system [5].

It is necessary to have an ESS in MG to stabilize PVs power output and the utilization of DG in MG brings many benefits such as lower cost of power consumption and huge environmental value [6]. The BESS has received wide attention for its small size, high efficiency, fast response and high capacity [7]. It is also necessary for the EVs charge/discharge management strategy to have a V2G system [8]. As the BESS plays a key role in MG, how to configure its optimal size is an important problem. In Liu et al. [9], HESS could not only reduce the cost of storage capacity, but improve the reliability of the whole system, and li-ion batteries are given priority over lead-acid batteries to charge/discharge. The demand-side management and EV charge/discharge manage strategy lead to the load curve becomes smoother and the lower cost of HESS. The PVs integrated EVs parking lot considering the significant growth of the electric vehicles market is studied in [10]. Huang et al. [10] proposed a reusing REVB model based on the capacity fading model of lithium batteries, which is solved with NSGA-Ⅱ.

Most of the papers studied the BESS of MG assumes the unit cost of BESS as a constant when calculating the total cost of MG. The model in [11] firstly took the real raw material price of lithium battery as the input and calculated through the Bottom-up method. In [12], The optimization model of battery power performance and production operation was established based on the technical-economic analysis of the design and manufacture of NMC-G square soft packet battery.

In this paper, the unit capacity cost coefficient changes with the total capacity of BESS is studied in detail. At the same time, the original configuration of BESS considering the EVs in MG when involving frequency control is discussed for the case presented.

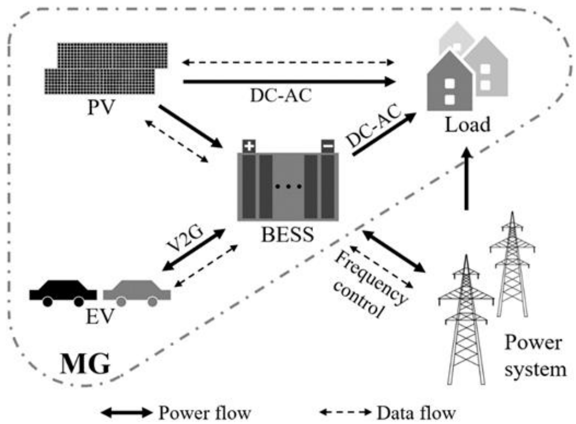


Fig 1 Structure of typical MG.

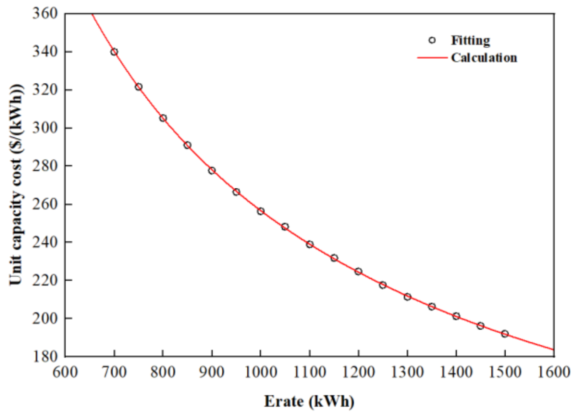


Fig 2 Unit cost changes with capacity

2. MATERIAL AND METHODS

2.1 The functions and configuration of BESS in Microgrid

The structure of the MG in residential areas in this study is shown as Fig. 1, MG consists of PVs, BESS, EVs, the converters and residents' basic electricity load. The BESS system mainly serves the following functions:

Firstly, BESS could store PVs power, serve as the 'alternative power source' for the whole MG at night when PVs could not work, interact with the power grid to stabilize its output in a certain interval in the long term, and keep the supplied power for EVs.

Secondly, EVs obey the EMS to charge/discharge with the use of BESS based on the electricity time-of-use price (V2G) to better control the system.

2.2 Cost modeling of BESS

The cost of BESS consists of the investment cost, operation and maintenance cost, interactive power cost with the power system, payment of frequency control by EVs and environment cost, etc. Here the power interactive cost is ignored and the cost function is:

$$C_d = C_{BESS}^{inv} + C_{BESS}^{m} + C_P + C_{EV} + C_{pu} \quad (1)$$

2.3 Material and methods

2.3.1 Investment cost

The investment cost includes manufacturing cost for lithium batteries, hardware cost and venue cost of BESS and is mainly determined by its unit capacity cost and the rated capacity, shown as:

$$C_{BESS}^{inv} = \frac{1}{365\times10}\left(K_{BESS}^{inv}E_{rated} + K_{PCS}^{inv}P_{rated} + K_{PV}^{inv}P_{rated}^{PV}\right)\frac{r(1+r)^n}{(1+r)^n-1} \quad (2)$$

This study studies different battery systems with different capacities based on BatPac. BatPac is developed by Argonne National Laboratory for lithium-ion battery packs used in automotive transportation. By inputting the parameters of cells, modules, battery packs and so on, the BatPac will calculate the cost with accounting for every step in the lithium-ion battery manufacturing process. Most variables in the calculation could be changed to make the bottom-up design [13]. According to GB/T 34013-2017, the parameters of cells are designed. LFP-G batteries are chosen for BESS since it is relatively cheaper. In module design, 4 cells in parallel with 7 cells in series (7S4P), 28 cells per module. In battery pack dimension, 4 series and 8 parallel (4S8P) of modules per pack, 32 modules per pack. Then, the cost analysis can be carried out in the cost calculation module. The final cost is mainly determined by two parts: first, the market price of selected battery electrochemical composition and related materials; second, the BESS final rated capacity.

The rated voltage of BESS is 367.6 V based on the above data, charge/discharge current set to 0.2 C. Fixing the number and arrangement of cells, modules and packs and changing the needed system power and capacity directly in BatPac, different unit capacity prices will be obtained in the results part in BatPac. The fitted curve of K_{BESS}^{inv} and E_{rated} is shown in Fig. 2.

The relation of the unit capacity cost coefficient (K_{BESS}^{inv}) and rated capacity (E_{rated}) is fitted:

$$K_{BESS}^{inv} = 6181.826e^{(-E_{rated}/36.437)} + 1222.7936e^{(-E_{rated}/233.444)} + 194.591 \quad (3)$$

In addtion, with the fixed number and arrangement of cells, modules and packs, the scales and hardware of BESS do not change with the need capacity means the total hardware fees of manufacturing the BESS is unchangeable. It is clear that smaller rated capacity input in BatPac increase unit cost, and greater rated capacity could decrease it. In addition, the unit cost of BESS changes about 150 \$/(kW·h) when the target rated capacity changes from 700 kW·h to 1500 kW·h, so assuming unit cost as a common value will bring a large

Table 1 EV parameters

parameters	values
rated power	7 kW
rated capacity	64 kW·h
SOC_{max}	90 %
SOC_{min}	20 %

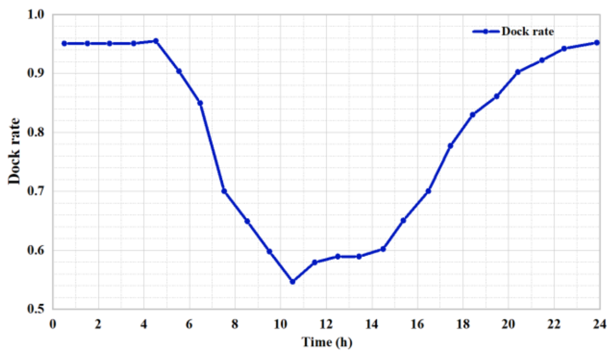


Fig 3 Dock rate of EVs

error when calculating the total cost of BESS. Moreover, for BESS's rated power and capacity is fixed, the number and arrangement of cells, battery modules and packs are all the ingredients affect K_{BESS}^{inv}, so how to arrange the cells, modules or packs to minimize the unit cost is worth to concern.

2.3.2 Maintenance and environment cost

The maintenance cost is linear to the rated power of BESS:

$$C_{BESS}^{m} = K_{BESS}^{m} P_{rated} \frac{r(1+r)^n}{(1+r)^n-1} \tag{4}$$

The environment cost involves the fees of dealing with the contaminant during manufacturing:

$$C_P = \sum_{i=1}^{4} E_{rated} m_i k_i \tag{5}$$

2.3.3. Punish cost of MG for power shortage

The MG will be punished when it couldn't supply enough power in peak and flat time or couldn't storage in off-peak time. The penalty cost is calculated by:

$$C_{pu} = k_{pu} \sum_{i=1}^{s} \Delta P_i \tag{6}$$

2.3.4. Payments for EVs and punish cost of MG for power shortage

The daily cost of all the EVs in an MG will be controlled by the EMS. The aim of EMS is to minimize the EVs cost include the difference of charging cost and the benefits of discharging to the power system to fulfill the peak load in the peak time. It is shown as follows [14]:

$$C_{EV}^{N} = \sum_{t=1}^{24} \sum_{i=1}^{N} \left(C_t^{ch} P_{i,t}^{ch} - C_t^{dis} P_{i,t}^{dis} \right), \ \forall i,t \tag{7}$$

Constraints include following equations:

1) Charge /discharge power constraint

$$0 \le P_{i,t}^{ch} \le P_N, 0 \le P_{i,t}^{dis} \le P_N, \forall i,t \tag{8}$$

2) State of charge (SOC) constraint of EVs

$$SOC_{i,min} \le SOC_{i,t} \le SOC_{i,max}, \forall i,t \tag{9}$$

3) Unidirectional power constraint

$$P_{i,t}^{ch} P_{i,t}^{dis} = 0, \forall i,t \tag{10}$$

Finally, the model is solved by the PSO algorithm. Dock rate and the initial SOC of EVs at *t* time could be obtained by Monte Carlo simulation in this study. The procedure will cycle per unit time, the electric energy eventually flows to grid, BESS, or from the grid and BESS flows to MG.

2.3.5 Frequency control effect evaluation

The evaluation of frequency control effect is expressed by:

$$\Delta P_t = \left| P_{supply}^t - P_{demand}^t \right|, \forall t \tag{11}$$

Details of P_{demand}^t are as follows:

$$P_{demand}^t = P_{load}^t + \sum_{t=1}^{N} \left(P_{i,t}^{ch} - P_{i,t}^{dis} \right) + P_{BESS,t}^{ch} - P_{BESS,t}^{dis} \tag{12}$$

EVs and BESS power are all calculated into the MG power demand to fulfill the power surplus and shortage of the power system whether charge or discharge. As a consequence, they all have the frequency control effects to guarantee the output of the power system within the setting range.

2.4 Results

To configure the optimal capacity and calculate the cost of BESS, an MG project with a 10-years lifetime is selected for the case study.

2.4.1 EV parameters

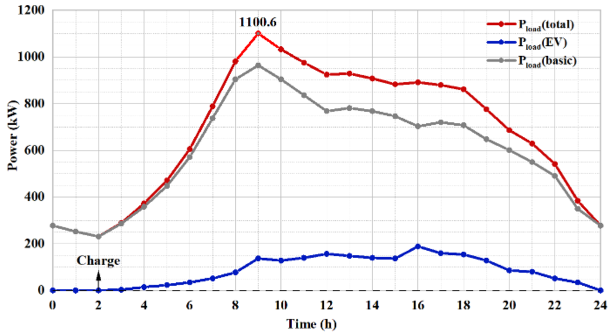
Assuming there are 500 EVs in the MG areas, and all the EVs obey the power schedule. The dock rate of EVs is shown in Fig. 3 and the time step is 30 min. Parameters of the EV battery are shown in Table 1. Initial SOC of EV could be obtained based on Monte Carlo simulation.

2.4.2 Power analysis

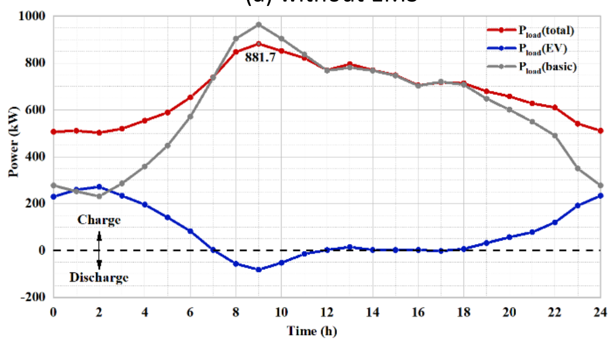
The charge/discharge power curve of EVs without/ with EMS and typical power load of MG are shown in Fig. 4. The power curve of EVs is obtained by the solving EVs model based on the PSO algorithm. It is clear that the total load on workdays involves EMS has a smaller fluctuation than without EMS, the power load without EMS is 1100.6 kW, while the value of deduces to 881.7 kW, about 19.9 % decline when considering EMS. In the near future, the power difference will be much higher and will be destructive for the whole power system when the number of EVs increases sharply and charging/ discharging disorderly or randomly.

Analysis of the rated power of BESS is shown in Fig. 5. The theoretical power output of BESS to fulfill all the requirements of frequency control is express as:

$$P_{BESS}^{needed}(t) = P_{supply} - P_{load}(t) - P_{EVs}(t), \forall t \tag{13}$$



(a) without EMS



(b) with EMS

Fig 4 Charge/discharge power of EVs

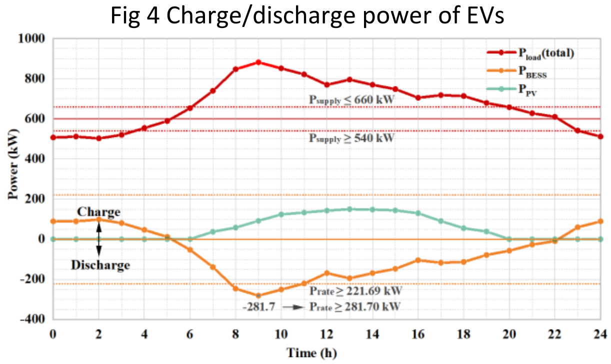


Fig 5 Power analysis of BESS

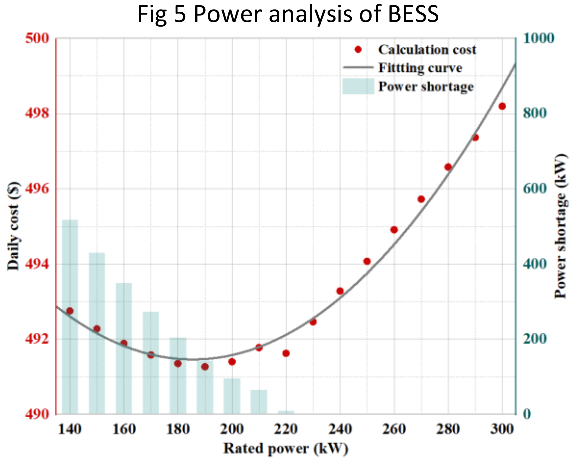


Fig 6 Daily costs and power shortage of different configurations of MG

Table 2 Time-of-use price in northeast power grid

time	price
peak: 7:30-11:30, 17:30-21:00	0.1741 $
flat: 5:00-7:30, 11:30-17:30, 21:00-22:00	0.1160 $
off-peak: 22:00-5:00	0.05804 $

where, P_{supply} taking a value of 600 kW according to the basic load of MG. 'Wonderful frequency control' means keeping the power output of power system at 600 kW all the time, the power shortage and surplus of the power system will be dealt with by EVs and BESS. Therefore, in order to fulfill the demand of frequency control, the rated power of BESS shouldn't be smaller than the maximum needed power (281.69 kW at 9 o'clock) in theoretical.

From Fig. 5, when considering the tolerance of the power system that the output changes 540-660 kW, the needed power of BESS could be decreased from minimum 281.7 kW to 221.7 (≈ 222 kW), it means that at any time, with its rated power upon 221 kW, the BESS could guarantee the safety range (540-660 kW) of power output of the power system, power shortage and power surplus are supplemented or eliminated by BESS. Setting the 0.2 C-rate in BatPac when designing the battery system in advance, the total energy of the BESS is $E_{rated} = P_{rated} \times 5 = 1110$ (kW·h).

Since it is too difficult and the cost is too high to realize 'wonderful control', considering the tolerance limit of operating frequency of the whole power system (50 ± 0.2 Hz), and this study is set the allowed fluctuation of supply power in MG to ± 10 % which could be changed. The allowed fluctuation of power supply is similar to the dead band in traditional frequency control, and the MG doesn't have to react to a small power fluctuation within this scope.

2.5 Discussion

2.5.1 Daily cost analysis

Based on the rated power, the total energy of BESS in *2.2.1* and Eq. 3, the unit cost is calculated in BatPac and the result is 205.12 $/(kW·h). The total investment cost of BESS is 227681.71 $, about 62.37 $ per day.

The time-of-use price of the northeast power grid in China is shown in Table 2. The daily total cost of BESS on workdays is calculated according to Eq. 1.

According to Eq. 4 and the charge/discharge strategy of EVs, the daily compensate of EVs C_{EV} is calculated as 467.998 $, the daily maintenance cost C^{m}_{BESS} and environment cost C_p of BESS are 0.05364 $ and 18.002 $, respectively. As the rated power and capacity of BESS are large enough to keep the power output of the distribution network within the power limits, the punish cost is 0. Therefore, the total daily cost of MG is: $C_d = 548.43$ $.

2.5.2 Optimal configuration

The whole power grid could accept a certain fluctuation of power output from the distribution network, although the rated power and capacity of BESS are less than the result as computed above, it is acceptable. Total daily costs and total power shortage of different configurations of BESS are shown in Fig. 6, and the fitted equation are as follows:

$$C_d = 510.4430 - 0.2046P_{rated} + 5.5141 \times 10^{-4}P_{rated}^2 \quad (14)$$

According to Fig. 6, the most economical rated power of BESS in the MG with 1000 households is 186 kW. And the corresponding daily cost is 491.46 $, with 56.97 $ reduction per day compared with the result of 548.43 $. Power shortage will be dealt with by the power system itself and the MG will pay the corresponding penalty.

2.6 Conclusions

The development and application of MG has attracted increasing attention due to the ability to connect different energy power forms to the grid and effectively improve utilization rate.

Firstly, the BESS unit cost based on BatPac with bottom-up design is discussed. The unit cost declines about 150 $/(kW·h) when the target rated capacity changes from 700 kW·h to 1500 kW·h. As a result, when designing a BESS, the effect of capacity on unit cost must be considered in the cost calculation.

Secondly, to obtain the V2G EMS strategy, a model of EVs in MG is proposed with the consideration of participating in frequency control based on the PSO algorithm. By comparing, the total load on workdays involves EMS has a smaller fluctuation than without EMS, the power difference (about 19.9 %) of peak time and off-peak time without EMS is 1100.6 kW, while the value of deduces to 881.7 kW when considering EMS.

Thirdly, the MG daily cost consists of the invest cost, maintenance cost and environment cost of BESS, the EVs interaction part and the penalty cost are considered. The rated power and capacity of BESS could be reduced a lot at frequency control, thus the cost could be cut greatly. And after balancing the cost of BESS and the power system stability, a most optimal configuration is chosen. The case result shows that the most economical rated power (or the lowest daily cost power) of BESS is existed, in the example with 1000 households is 186 kW, and the daily cost is 491.46 $, with 56.97 $ reduction per day compared with non-optimal configuration.

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