Optimal configuration and economic operation of energy storage system considering photovoltaic consumption rate

Yuguang Xie[1], Bo Gao[1], Jinzhong Li[1], Yang Zhou[2], Tianwen Zheng[3*]

[1]State Grid Anhui Electric Power Research Institute, Hefei 230601, China
[2]Anhui Lizhuo Smart Grid Technology Co., Ltd., Hefei 230601, China
[3]Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610213, China

Abstract: The outstanding photovoltaic (PV) abandonment problem can be effectively solved by configuring energy storage (ES). The capacity configuration and operation control strategy of ES are the main difficulty in the economic operation of the system. In this paper, a comprehensive evaluation model is established to evaluate the economics of ES to improve PV consumption. Further, an ES capacity configuration method based on double-layer optimization is proposed. The upper optimization uses PV curtailment rate to determine the feasible region of ES capacity configuration. The comprehensive economic benefits are used as the inner optimization indicator to optimize the capacity configuration of ES. The ES charging and discharging strategy used in the paper can realize the efficient use of PV power. The simulation result proves the effectiveness of the proposed method.

1 Introduction

With the increasingly serious fossil energy crisis and environmental pollution, building a clean, low-carbon, safe and efficient energy system is an inevitable trend in future development1. As a kind of clean and renewable energy, solar energy is widely used in photovoltaic power generation system. Improving photovoltaic consumption is a hot issue at present. Photovoltaic configuration ES is an important means to improve its consumption. The promotion and application of energy storage system (ESS) is subject to constraints such as investment costs and economic benefits. An ESS economy is directly affected by the ES capacity. A reasonable ES operation capacity allocation method has become the key to improving photovoltaic consumption.

The difference supplement method is to use the difference between the minimum power generation required by the power supply and the actual power generation under extreme conditions as the ES capacity 2-. The dynamic stability analysis method is based on the suppression of power fluctuations of new energy sources to optimize the operating capacity of ES 4-. Economic evaluation method is a method that has been studied more frequently6. In 7 , the benefits of photovoltaic power plants and ESS are jointly estimated, which makes it difficult to analyze the benefits of ESS. In 8-, a system benefit model was established to evaluate the economics of ES allocation, but it did not fully consider the time value of funds during the evaluation period.

To improve PV utilization rate consumption, this paper analyzes the ES capacity allocation configuration under different economic indicators. The economic operation

control and capacity optimization strategy of ES considering photovoltaic consumption are proposed. First, the feasible region of energy storage capacity configuration allocation is analyzed by PV curtailment rate. Then, through a comprehensive evaluation of multiple economic indicators, the ES operation capacity configuration is determined. Finally, the typical working conditions are simulated to verify the effectiveness of the proposed method.

2 Problems Description

The PV power has two operating modes: excess power and insufficient power. The available PV power and load curves are shown in Fig. 1. Area 1 indicates excess power and abandonment of light. Area 2 and Area 3 indicate insufficient power and the system needs external energy supply. The PV power has not been fully consumed.
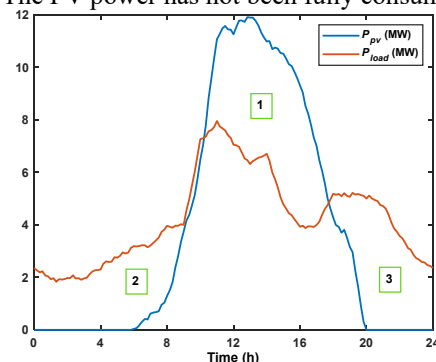

Fig. 1 A typical daily load and PV output curve

An ES charging and discharging can shift the time and

---

space of PV power, thereby improving PV utilization. The operation mode of ES is controlled according to the change of load and the output state of renewable energy 10. The allocation of appropriate ES capacity to increase PV consumption is an important problem that needs to be solved urgently.

3 Economic model of ES

3.1 Cost model

The total cost (C) of the ESS is composed of investment construction cost (C_1) and operation and maintenance cost (C_2) 12.

$$C = C_1 + C_2 \qquad (1)$$

$$C_1 = (C_p \cdot P_{bess} + C_E \cdot E_{bess}) \times \sum_{k=0}^{k} (1+r)^{-zk} \qquad (2)$$

$$C_2 = C_m \cdot Q \cdot \frac{(1+r)^n - 1}{r(1+r)^n} \qquad (3)$$

Where C_p is the installed cost per unit power. P_{bess} and E_{bess} are the power and capacity of ES. C_E is the installed cost per unit capacity. z is the life span of the ES battery. k is the number of battery replacement times within the ES life cycle. C_m is the annual operation and maintenance cost per unit capacity. Q is the annual power generation.

3.2 Revenue model

This paper comprehensively considers the benefits of investors, power grids, and society. I represents the comprehensive income of the ESS 14-

$$I = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7 \qquad (4)$$

(I_1) Electricity sales revenue

$$I_1 = N_1 \cdot \sum_{1}^{24} P_b(t) \Delta t \rho(t) \qquad (5)$$

Where N_1 is the number of days of ES operation per year. $\rho(t)$ is the time-of-use electricity price. $P_b(t)$ is the ES charge and discharge power.

(I_2) Peak shaving revenue

$$I_2 = N_2 \cdot \sum_{1}^{m_1} E_{pi} \cdot \rho_i \qquad (6)$$

Where m_1 is the number of times to participate in peak shaving per day. E_{pi} is the i-th peak shaving power. ρ_i is the i-th price. N_2 is the number of peak shavings involved per year.

(I_3) Grid frequency regulation 14

$$I_3 = 12 \cdot \sum_{1}^{m_2} (D_i \times \lambda_i \times K_i) \qquad (7)$$

Where m_1 is the number of trading cycles for monthly frequency adjustment. D_i is the rate adjustment amount provided in the i-th trading cycle. λ_i is the transaction price. k_i is the comprehensive performance index of the power generation unit.

(I_4) Battery recycling revenue

$$I_4 = C_{re} \cdot E_{bess} \times \frac{r}{(1+r)^n - 1} \qquad (8)$$

Where C_{re} is the recycling price of batteries per unit capacity.

(I_5) Delay power grid upgrades

$$I_5 = C_{inv} \left[1 - \frac{1}{(1+r)^{\frac{\log_{10}(1+\lambda)}{\log_{10}(1+\tau)}}} \right] \qquad (9)$$

Where C_{inv} is the cost of upgrading the power grid. r is the annual growth rate of load. λ is the ES consumption rate.

(I_6) Improved power supply reliability

$$I_6 = C_0 P_{bess} \frac{r(1+r)^n}{(1+r)^n - 1} \qquad (10)$$

Where C_0 is the investment cost of diesel unit per unit capacity. system. P_{bess} is the power of ES.

(I_7) Reduce carbon emissions benefits

$$I_7 = Q_c \rho_c N_{day} \qquad (11)$$

Where Q_c is the typical daily carbon emission reduction by configuring ES. ρ_c is the carbon trading price.

4 Capacity configuration of ES

4.1 Upper optimization method

The purpose of the upper-level optimization is to determine the feasible region of ES operation capacity with the abandonment rate as an assessment indicator.

(1) PV abandonment rate

The PV abandonment rate is an important evaluation target for PV. The smaller the PV abandonment rate, the higher the utilization rate of PV resources.

$$f = \left(1 - \frac{\sum\limits_{t=1}^{T} P_b(t) \cdot \Delta t + \sum\limits_{t=1}^{T} P_{TL}(t) \cdot \Delta t + \sum\limits_{t=1}^{T} P_{load}(t) \cdot \Delta t}{\sum\limits_{t=1}^{T} P_{pv}(t) \cdot \Delta t} \right) \times 100\% \quad (12)$$

Where f is the indicator of PV abandonment rate. $P_{pv}(t)$ is PV power generation. $P_b(t)$ is the ES power. $P_{TL}(t)$ is the tie line power. $P_{load}(t)$ is the local load. T is the duration of data statistics.

(2) ES operation capacity feasible region

Fig. 2 is a schematic diagram of PV output and load curves. In the figure, area 1 is the consumption of electricity by the local load. Area 2 is for sending part of the electricity to the Internet. Area 3 is the amount of waste light. After the system is configured with ES, the energy in area 3 can be reasonably utilized for profit.

The configured ES absorbs more electricity in area 3, the stronger the system photovoltaic energy absorbs. Assuming the system fully consumes photovoltaic output, the minimum power and capacity limits of the ESS are calculated as follows.
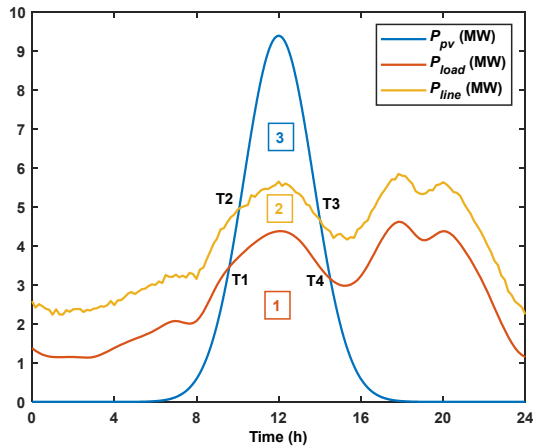
Fig. 2 The schematic diagram of PV and load curve

$$P_{b\min} = \max\left(P_{pv}(t) - P_{load}(t) - P_{TL}(t)\right) \quad (13)$$

$$E_{b\min} = \sum_{T_2}^{T_3}\left[\left(P_{pv}(t) - P_{load}(t) - P_{TL}(t)\right)\bullet\Delta t\right] \quad (14)$$

$P_{b\min}$ is the minimum configuration power of ES. $E_{b\min}$ is the minimum configuration capacity of ES. T_2 and T_3 are the start and times of area 3.

4.2 Inner optimization method

The inner optimization optimizes the capacity configuration of ES with the goal of the economics of the photovoltaic and ES combined operation system.

(1) Economic optimization target

The net present value (*NPV*) is the main dynamic evaluation target of the profitability of the project investor in the investment cycle 11.

$$NPV = I \cdot \sum_{1}^{n}(1+r)^{-n} - C \quad (15)$$

Where *n* is the lifetime of the system. *r* is the assets discount rate. *C* is the comprehensive cost of the ESS.

The dynamic payback time (P_t) is the time required for the net income of the project to offset the entire investment of the project.

$$\sum_{t=0}^{P_t}(CI - CO)_t(1+r)^{-t} = 0 \quad (16)$$

Where *CI* is the cash inflow of the projects. *CO* is the project cash outflow.

The internal rate of return (*IRR*) is the discount rate when the net present value is zero. It expresses the ability to recover from the initial investment.

$$I \cdot \sum_{1}^{n}(1+IRR)^{-n} - C = 0 \quad (17)$$

(2) Optimized configuration of ES capacity

Comprehensive economic indicators are used as the goal of the inner optimization algorithm. The capacity configuration of ES within the feasible range is calculated by the traversal algorithm. A double-level optimization method proposed in this paper not only considers the increase of photovoltaic consumption, but also considers the balance relationship between the capacity of ES and

economic operation. The concrete realization of the double-layer optimization algorithm is shown in **Fig. 3**.
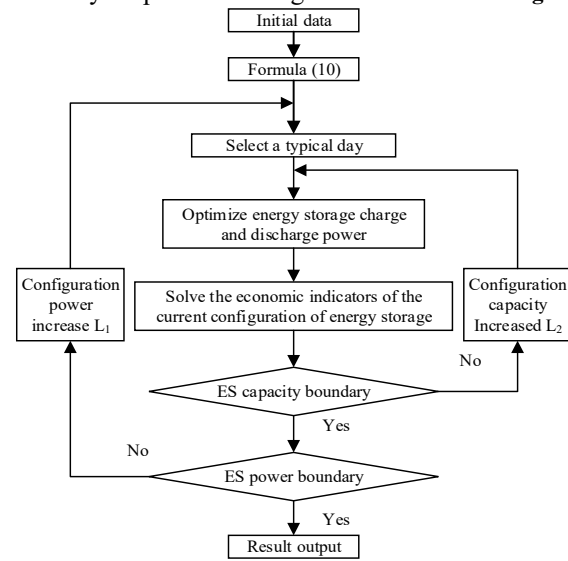

Fig. 3 Energy storage optimization allocation process

4.3 Restrictions

(1) System power balance

The transmission capacity of the tie-line is restricted by the line type and voltage level. The system tie line forward power flow (P_{TL2}) is usually greater than the reverse power flow (P_{Tl1}).

$$P_{pv}(t) + P_{TL}(t) - P_b(t) = P_{load}(t) \quad (18)$$

$$P_{TL1} < P_{TL}(t) < P_{TL2} \quad (19)$$

(2) ES charging and discharging power

$$-P_{\max} \le P_b(t) \le P_{\max} \quad (20)$$

Where $P_{\max}$ is the maximum discharge power of ES.

(3) State-of-charging constraint

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \quad (21)$$

$$SOC(t) = SOC(0) - \Delta t \sum_{t=1}^{T/\Delta t}\frac{P_b(t)}{E_{bess}} \quad (22)$$

Where $SOC(0)$ is the initial state of charge. E_{bess} is ES capacity. $SOC_{\min}$ and $SOC_{\max}$ are the minimum and maximum state of charge when ESS is working.

5 Operational control strategy of ES

Considering the influence of tie-line power, the ES charge ($P_{Cb}(t)$) and discharge ($P_{Db}(t)$) power is defined.

$$\begin{cases} P_b(t) = P_{pv}(t) - P_{load}(t) - P_{TL}(t), P_{pv}(t) \ge P_{load}(t) \\ P_b(t) = P_{load}(t) - P_{pv}(t), P_{pv}(t) \ge P_{load}(t) \end{cases} \quad (23)$$

To ensure the economy of the system, the ES should be discharged when the electricity price is high and charged when the electricity price is low.

Traditional droop power control (*P-U*) is applied by the ES charging and discharging, as follow.

$$U = U_0 - k_b(P_b - P_{b,0}) \quad (24)$$

Where *U* is the DC bus voltage. U_0 is the rated voltage

of the DC bus. k_{ES} is the droop control coefficient. P_b is the ES charge and discharge power. $P_{b,0}$ is the rated output power of ES.

6 Example analysis

6.1 Engineering example design

The example is designed based on a typical PV and ES combined power supply system. It assumes that all the surplus electricity of photovoltaics is consumed which means that PV abandonment rate is zero. It is designed with reference to Fig. 1. The simulation step is 10 minutes. The maximum output power of PV is 12MW. The local load peak is 8MW. The system operation is limited by the service life of other power equipment, so the ES service life is set to 15 years 14.The forward tie line transmission capacity is set to 8MVA and the reverse tie line transmission capacity is set to 3MVA. The time-of-use electricity price is the actual data of a certain place in 2019 in Table 1.

Table 1 The typical time-of-use electricity price

Types	Time period	Price (Yuan / kWh)
Peak	8:00-11:30; 15:00-16:00; 18:30-22:00	0.75
Level	7:00-8:00; 11:30-15:00; 16:00-18:30; 22:00-23:00	0.5
Valley	23:00-7:00	0.25

6.2 Analysis of the results

The relationship between *NPV, IRR*, P_t indicators and capacity configuration of ES is shown in Fig. 4, Fig. 5 and Fig. 6, respectively.
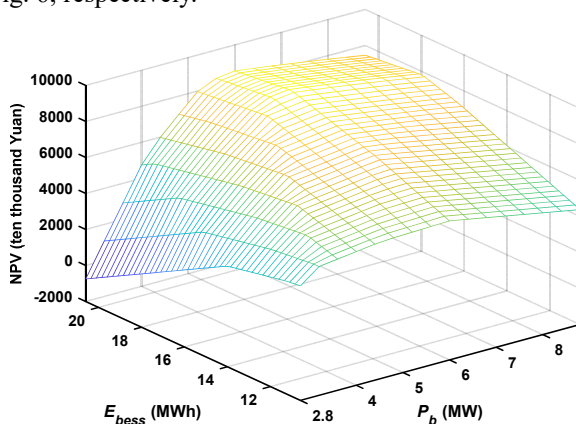

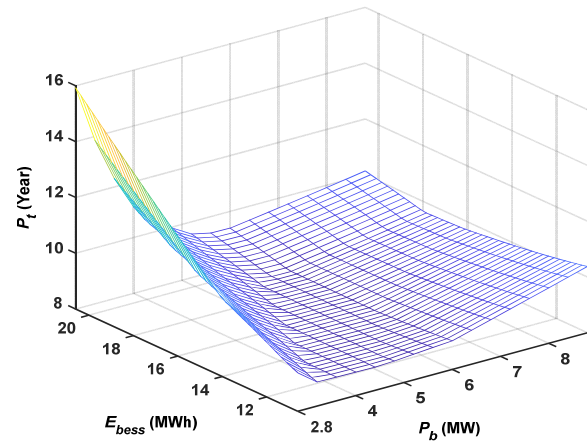**Fig. 4** The relationship between ES configuration and *NPV*

Fig. 5 The relationship between ES configuration and P_t
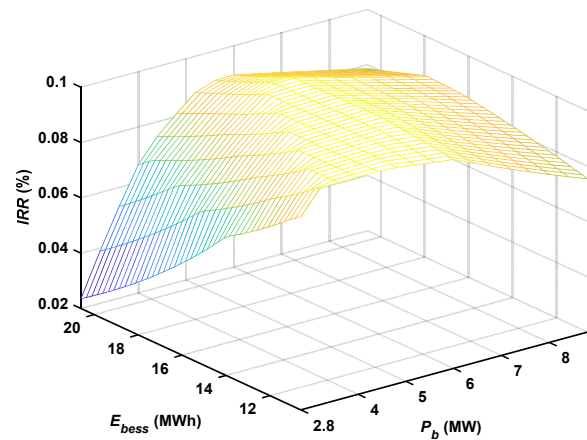

Fig. 6 The relationship between ES configuration and *IRR*

The system is not equipped with ES and the PV curtailment rate is 17.1% when considering the power delivery.

Upper optimization aims at the full consumption of excess PV power. It shows that the minimum power configuration for ES is 2.8MW and the minimum operating capacity configuration is 10.6MWh.

The inner optimization aims to achieve the best economic efficiency. The *NPV* achieved the maximum value of 89.21 million yuan, when ES configuration is 6MW/18MWh. The positive *NPV* is a necessary condition for the project profitability. P_t achieved the maximum value of 8.6 Years, When the ES configuration is 5.6MW/16.7MWh. Which is less than the 15-year life cycle of ESS, and the cost can be recovered in the early and mid-term of the project.

The simulation result of the control strategy of ES charging and discharging operation under the objective of system economic benefit is shown in **Fig. 7**.
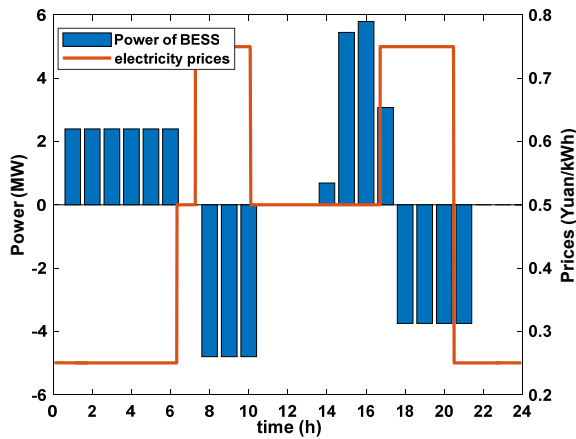
Fig. 7 ES charging and discharging simulation results

The simulation results show that ES can be discharged when electricity prices are high and charged when electricity prices are low. The system can be operated in a more economical mode.

7 Conclusion

To improve the utilization rate of PV, a method for optimal configuration of ES capacity and economic operation is proposed. The upper optimization control strategy takes the abandonment rate of PV as the target to solve the lower limit of the capacity configuration of ES. Under the boundary of the feasible region, the inner optimization considers comprehensive economic benefits to further optimize the capacity configuration of ES. The simulation results show that the optimal configuration of ES capacity improves energy utilization. The ES configuration and operation control strategy proposed in this paper provide references for the capacity configuration and operation of ES.

Acknowledgment

References

1. Wang, J., Zhong, H., Wu, C., Du, E., Xia, Q, Kang, C. (2019) Incentivizing distributed energy resource aggregation in energy and capacity markets: An energy sharing scheme and mechanism design. Applied Energy,252, 113471.

2. Wu S Y, Zhou F Y. (2018) Energy Storage capacity allocation principle and capacity ratio in DC Distribution Network [J]. Telecom Power Technology, 35(09):225-227.

3. Han T, Lu J P, Qiao L, Zhang H, Ding R, Zhao X. (2010) Optimized scheme of energy storage capacity for grid-connected large-scale wind farm [J]. Power System Technology, 34(01):169-173.

4. Asao, T., Takahashi, R., Murata, T., Tamura, J., Kubo, M., Matsumura, Y., ... & Matsumoto, T. (2008, September). Evaluation method of power rating and energy capacity of superconducting magnetic energy storage system for output smoothing control of wind farm. In 2008 18th International Conference on Electrical Machines (pp. 1-6). IEEE.

5. Zeng J. (2010) Simulation of battery energy storage system used for wind power regulation[J]. Southern Power System Technology, 4 (S1) :126-129.

6. Wang C M, Sun W Q, Yi Tao, Yan Z M, Zhang Y. (2013). Review on energy storage application planning and benefit evaluation methods in smart grid．Proceedings of the CSEE, 33(7): 33-41

7. He C, (2017) Optimal capacity allocation of large PV power station with battery energy storage system and its economical analysis [D]. North China Electric Power University.

8. Lunz, B., Walz, H., & Sauer, D. U. (2011, September). Optimizing vehicle-to-grid charging strategies using genetic algorithms under the consideration of battery aging. In 2011 IEEE vehicle power and propulsion conference (pp. 1-7). IEEE.

9. Ohtaka T, Iwamoto S. Possibility of using NAS battery systems for dynamic control of line overloads[C]. IEEE/PES Transmission and Distribution Conference and Exhibition, Yokohama, Japan, 2002:44-49.

10. Li Z J, Yuan Y. Smart microgrid: a novel organization form of smart distribution grid int the future [J]. Automation of Electric Power Systems, 2009, 33(17): 42-48.

11. Chen Q H, Yuan X J, He Y J, Guo L, Cai Y J, Chen Q X. (2018) Investment and optimization off-grid microgrid projects based on life-cycle cost/benefit analysis with open investment mode[J]. Power System technology, 42(08):2448-2457.

12. Zhang H. (2014) Research of economic evaluation for load shifting in distribution network based on energy storage system [D]. (Master's thesis, North China Electric Power University).

13. Xiang Y P, Wei Z N, Sun G Q, Sun Y H, Sheng H P. (2015) Life cycle cost based optimal configuration of battery energy storage system in distribution network [J]. Power System Technology, 39(01) :264-270.

14. Fan Y Q, Ding T, Sun Y G, He Y K, Wang C X, Wang Y Q，Chen T E，Liu J.(2021). Review and cogitation for worldwide spot market development to promote renewable energy accommodation [J]. Proceedings of the CSEE, 41(05):1729-1752.

15. Lou SH, Lv M X, Wang Y C, Wu Y W.(2019). Generation investment expansion planning for wind power accommodation considering investment risk. Proceedings of the CSEE (07), 1944-1956.