Energy storage economy research and sensitivity analysis applied to photovoltaic primary frequency modulation scenario

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Abstract. In practical engineering applications, the investment, income, subsidies and other costs of energy storage batteries have a certain impact on the overall economic benefits of primary frequency modulation. The larger the capacity of the configured battery energy storage system, the better the primary frequency modulation effect will be, but at the same time, the problem is that the cost of investment in the energy storage system will increase, which will offset the benefits of primary frequency modulation loss reduction of its auxiliary photovoltaic station from an economic perspective. Therefore, this paper will clarify the benefits and costs of the primary frequency modulation application environment of the energy storage system, and establish an economic analysis model from delaying the investment of photovoltaic station equipment, reducing the cost of light waste, environmental benefits, direct benefits, government subsidies, energy storage investment costs and other aspects. Finally, a photovoltaic station is taken as an example to simulate and analyse the sensitivity.

1. Introduction

With a large number of photovoltaic grid-connected, the primary frequency modulation capability of the power grid is increasingly weak [1,2]. Only relying on the traditional primary frequency modulation mode, the security and stability of the power grid will face huge hidden dangers. Therefore, it is imperative to turn on the primary frequency modulation function of the photovoltaic station [3]. However, the primary frequency modulation capacity of photovoltaic stations is limited.

With the development of power technology in China, energy storage technology is gradually introduced into the power system, and energy storage system has unique advantages. The energy storage system applied to the primary frequency modulation of auxiliary photovoltaic stations absorbs and stores excess energy when the grid frequency is higher than 50 Hz, and releases the stored energy when the grid frequency is lower than 50 Hz, effectively reducing the fluctuation of the grid frequency, thus solving the problems of the difficulty in the primary frequency modulation of the grid and the inability of photovoltaic stations to meet the primary frequency modulation assessment requirements. At the same time, the application of the energy storage system to the primary frequency modulation of photovoltaic stations can directly make profits by improving the qualification rate of the primary frequency modulation assessment of photovoltaic stations. At the same time, it can improve the utilization rate of power equipment, delay equipment investment, and promote the consumption of new energy, and at the same time, it can obtain economic benefits and achieve the effect of more with one stroke. However, the economy of the primary frequency modulation of the energy storage auxiliary photovoltaic station is the most concerned issue for the investment and construction of all parties. This paper first analyses the various factors that affect the economy of the primary frequency modulation of the photovoltaic station, and then establishes the economic analysis model. Finally, the sensitivity analysis is carried out from the perspectives of energy storage unit price, energy storage capacity and the frequency of primary frequency modulation examination.

2. Influencing factors of energy storage economy

2.1. Delay the investment in PV station equipment

Photovoltaic power generation is uncertain [4]. In order to improve the safety, stability and reliability of photovoltaic power generation, it is necessary to regularly invest in, upgrade and transform the photovoltaic station equipment. The application of the energy storage system to the primary frequency modulation of the photovoltaic station can delay the upgrading and expansion of the photovoltaic station equipment, further reduce the investment cost of the upgrading of the primary frequency modulation equipment of the photovoltaic station, and achieve the

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purpose of improving the power quality, improving the power supply reliability and reducing the cost [5].

The annual income generated by the energy storage system delaying the investment of primary frequency modulation equipment in photovoltaic stations is shown in formula (1):

$$S_{delay} = \frac{C_{inv}(1-(\frac{1+it}{1+id})^{N})}{N} \cdot P_i \tag{1}$$

Where, C_{inv} represents the investment in primary frequency modulation equipment of photovoltaic station; it is the inflation rate; id is the discount rate; N represents the operational life of the invested energy storage system; P_i represents the power of the energy storage system.

2.2. Reduce the cost of waste

In the process of responding to the primary frequency regulation of the grid, when the grid frequency is higher than the reference frequency and exceeds the dead band, the photovoltaic station can reduce the output, but when the grid frequency is lower than the reference frequency and exceeds the dead band, the photovoltaic station has no ability to increase the output [6]. The usual practice is to limit the PV output to provide sufficient margin for response to the primary frequency regulation of the grid. However, limiting the PV output will greatly affect its economy. The PV station is equipped with a certain capacity of energy storage to assist primary frequency modulation, which can not only meet the requirements of primary frequency modulation, but also reduce the economic loss of power limiting.

In order to meet the demand of primary frequency modulation under normal conditions, the power limit value of PV station is generally 10% of the rated power of the station, as shown in Formula (2):

$$S_a = 876 \times P_N \times e_a \tag{2}$$

Where S_a is the income from reducing the waste of light; P_N is the rated power of the photovoltaic station; e_a is the on-grid electricity price of the photovoltaic station.

2.3. Environmental benefit

At present, the primary frequency regulation of most power grids in China only depends on traditional coal-fired power generation units, thus increasing the unit coal consumption. Using the energy storage device to assist the primary frequency modulation of the photovoltaic station can replace the thermal power unit to complete part of the frequency modulation task, and then indirectly reduce and optimize the frequent increase and decrease of the output of the thermal power unit, so that it can basically operate stably in the high efficiency range. Its mathematical model is as follows:

$$S_{environment} = (\sum_{i=1}^{n} R_{re\_i}\rho_{re\_i} - R_{recycle}) \times \delta_{energy} \times E_i + (\sum_{1}^{365}\sum_{i=1}^{24} P_i)R_{tp} \tag{3}$$

In the formula, $S_{environment}$ represents the environmental benefits of the energy storage system, including two parts: the recovery benefits obtained after the energy storage system is decommissioned, that is, $(\sum_{i=1}^{n} R_{re\_i}\rho_{re\_i} - R_{recycle}) \cdot \delta_{energy} \cdot E_i$ and the coal saving benefits generated by the primary frequency modulation of the auxiliary photovoltaic station of the energy storage system replacing the primary frequency modulation of the thermal power unit, that is, $(\sum_{1}^{365}\sum_{i=1}^{24} P_i)R_{tp}$. In addition, R_{re_i} is the price of recyclable parts i, R_{re_metal} is the price of recyclable metal materials after battery scrap, R_{re_c} is the price of recyclable carbon materials, and R_{re_other} is the price of other parts such as engineering plastics; ρ_{re_i} represents the content of recyclable component i in each part of the unit weight energy storage battery; $R_{recycle}$ represents the production expenditure required to treat waste battery per unit weight; δ_{energy} is the energy-weight ratio of the energy storage system; R_{tp} represents the unit power supply cost of conventional thermal power units.

2.4. Direct income

The primary frequency modulation of the auxiliary photovoltaic station of the energy storage system is mainly to improve the qualification rate of the primary frequency modulation assessment, and the direct benefit is to reduce the primary frequency modulation assessment cost of the photovoltaic station, as shown in formula (4):

$$S_{income} = \sum_{i=1}^{n}\left(F \times \left(P_{p-i2} - P_{p-i1}\right) \times P_{kh-i}\right) \tag{4}$$

Among them, S_{income} is the income from reducing the primary frequency modulation assessment cost of photovoltaic stations; N is the number of primary frequency regulation assessment indicators of photovoltaic stations; F is the frequency of primary frequency modulation assessment of photovoltaic stations in the current year; P_{p-i2} and P_{p-i1} respectively represent the pass rate of the i test index before and after primary frequency modulation of the energy storage assisted photovoltaic station; P_{kh-i} is the single assessment cost of the ith indicator.

2.5. Government subsidies

The Notice on Several Policies for the Development of New Energy Storage (2022-2025) issued by the General Office of the People's Government of the Inner Mongolia Autonomous Region clearly pointed out that the establishment of a market-oriented compensation mechanism and the capacity compensation of independent new energy storage power stations included in the demonstration project of the autonomous region can be enjoyed, with the compensation ceiling of 0.35 RMB/kWh [7]. The mathematical model is established as follows:

$$S_{allowance} = \sum_{1}^{365} \sum_{i=n_1}^{n_2} 0.35 \times P_i \quad (5)$$

In the formula, n_1 and n_2 represent the start and end time of the energy storage system discharge.

2.6. Investment cost analysis of energy storage system

The investment cost of the energy storage system is mainly divided into two categories: one is the initial investment cost, including the cost of configuring a certain capacity of battery for the energy storage system, which is called the capacity cost in this paper; And the cost of energy conversion system, energy management system and other monitoring hardware facilities, which is collectively referred to as power cost in this paper. The second category is the maintenance cost that the energy storage system needs to spend in one year of operation [8].

2.6.1. Initial investment cost analysis

Combined with practical application, the initial investment cost of energy storage system is mainly composed of power cost and capacity cost. The capacity cost is related to the investment of energy storage battery, and the power cost is related to the investment of energy storage battery using PCS, BMS, etc. Its mathematical model is as follows:

$$S_{P,E} = C_{i\_p} \cdot P_i + C_{i\_E} \cdot E_i \quad (6)$$

Where, C_{i_p} represents the unit power cost of the energy storage system; C_{i_E} represents the unit capacity cost of the energy storage system; P_i is the power of the energy storage system; E_i represents the capacity of the energy storage system.

2.6.2. Annual operation and maintenance cost

The operation and maintenance costs of energy storage devices are mainly related to the size of energy storage batteries. The annual operation and maintenance costs of energy storage systems with different scales (capacities) are different, which can be expressed as follows:

$$S_m = C_{i\_m} \cdot E_i \quad (7)$$

Where, C_{i_m} represents the annual maintenance cost per unit capacity of the energy storage system.

According to the service life and benchmark rate of return of the energy storage system, the total investment cost of the battery energy storage system is allocated within the service life, which is superimposed with the annual maintenance cost of the energy storage system to obtain the annual cost of the energy storage system.

$$AC = (C_{i\_p} \cdot P_i + C_{i\_E} \cdot E_i) \times \frac{ie(1+ie)^n}{(1+ie)^n - 1} + C_{i\_m} \cdot E_i \quad (8)$$

Where, ie represents the return on investment of energy storage project; n is the service life of the energy storage system.

3. Establishment of general model for economic evaluation of energy storage system

The primary frequency modulation of the auxiliary photovoltaic station of the energy storage system involves the economic value evaluation, which is bound to be related to the cost of the energy storage device and the future income. In this paper, the models involved in various benefits have been introduced in detail as much as possible. Combined with the cost analysis of the energy storage system, the overall economic evaluation model of the energy storage system can be obtained as follows:

$$S = S_{delay} + S_a + S_{environment} + S_{reliablity} + S_{income} + S_{allowance} - AC \quad (9)$$

4. Simulation analysis of economy and sensitivity

Current research at home and abroad shows that energy storage system can greatly improve the pass rate of primary frequency modulation assessment in auxiliary photovoltaic stations, but its economy is the premise and key condition for the implementation of the project. Therefore, this paper takes the 200MW photovoltaic station as an example to conduct the economic analysis of primary frequency modulation of the energy-storage assisted photovoltaic station. The basic data required by the simulation is shown in the following table:

Table 1. Fixed parameters used in simulation

Parameter name	*Parameter value*
C_{inv}	3 million yuan
it	1.5%
id	4.5%
N	15years
e_a	290 yuan /MWh
R_{re_metal}	0.22 million yuan/ton
R_{re_c}	1040 yuan/ton
R_{re_other}	3000 yuan/ton
$R_{recycle}$	33000 yuan/ton
R_{tp}	350 yuan /MWh
C_{i_m}	100 yuan/MWh
C_{inv}	3 million yuan

In addition, it should be noted that Inner Mongolia Power Grid currently has no primary frequency modulation assessment requirements for new energy stations. The relevant parameters refer to thermal power units, that is, the primary frequency modulation assessment index number of photovoltaic stations n=3. Single index single assessment cost refers to thermal power unit.

4.1. Sensitivity analysis of unit price of energy storage

The size of the energy storage capacity will greatly affect the economic benefits of the energy storage system. When the energy storage capacity is large, part of the capacity will be wasted, thus affecting the economic benefits. If the energy storage capacity is small, the pass rate of primary frequency modulation assessment will be improved slightly, affecting the income. At the same time, the unit price of the energy storage system will directly affect the original energy storage investment cost of the energy storage system. The following curve describes the relationship between the economic benefits of the energy storage system and the capacity of the energy storage system under different energy storage costs.

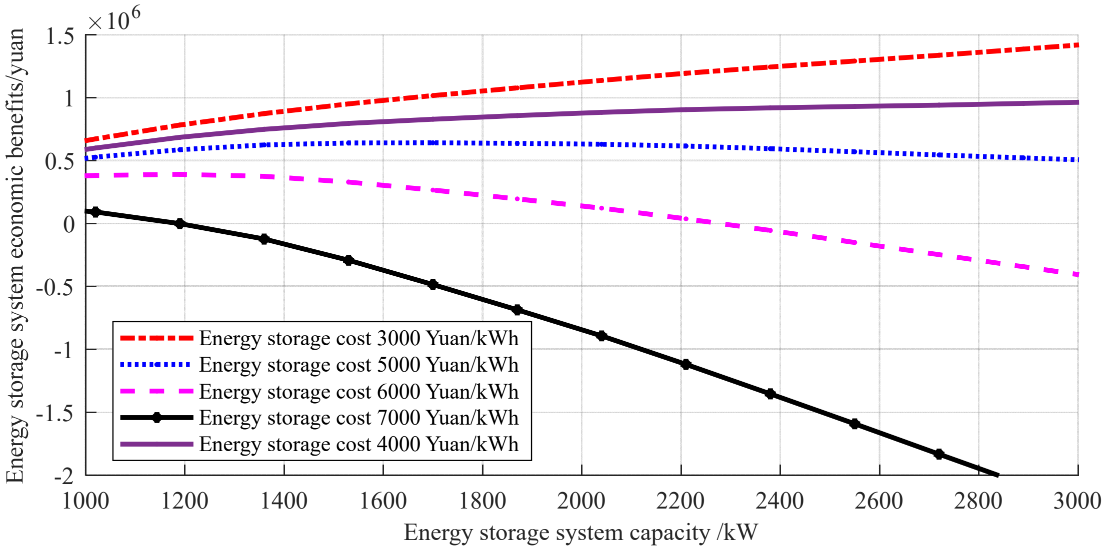

Figure 1. Relationship curve of economic benefit with energy storage capacity under different energy storage unit price.

As can be seen from the figure, no matter what the unit price of energy storage is, the economic benefits of energy storage will not increase indefinitely with the increase of energy storage capacity. When the unit price of energy storage is low, the economic benefit of energy storage gradually increases with the increase of energy storage capacity. However, when the energy storage capacity reaches a certain value, the economic benefit tends to be flat. When the unit price of energy storage is too high, the economic benefits will be very poor with the increase of the scale of energy storage. Only when the energy storage capacity is relatively small can there be some benefits, but in this case, the energy storage system basically cannot play the role of frequency modulation and has little impact on the pass rate of primary frequency modulation.

4.2. Sensitivity analysis of the number of primary frequency modulation

In addition to the unit price of energy storage and the scale of energy storage system, the frequency of a primary frequency modulation also has a great impact on the economic benefits of energy storage system. The following curve describes the economic benefits of the energy storage system under different primary frequency modulation times.

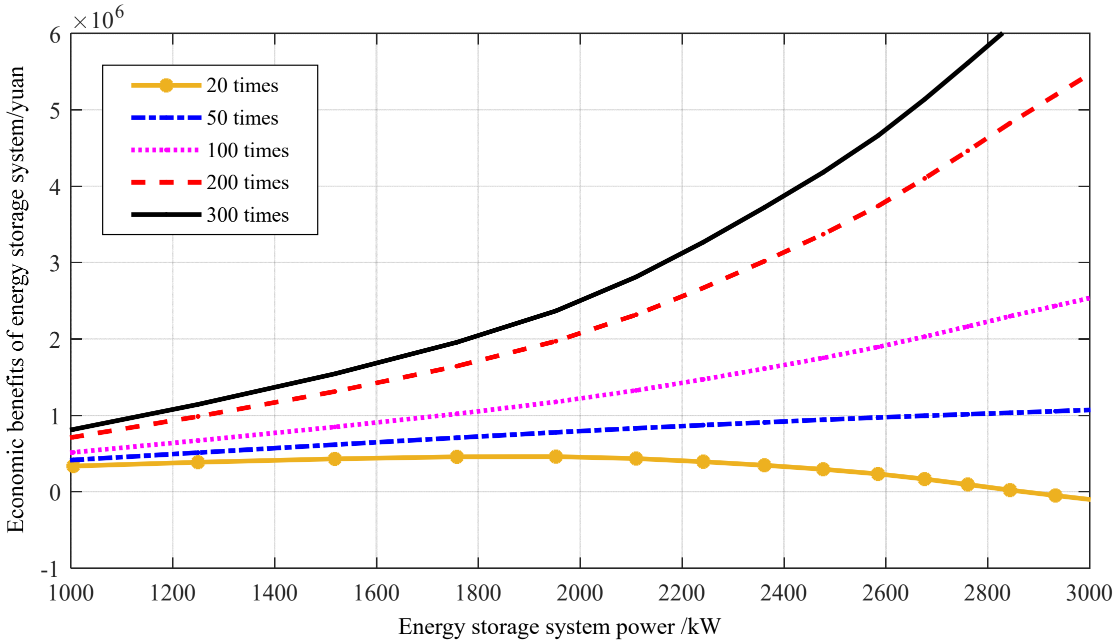

Figure 2. Curve of the relationship between economic benefit and energy storage capacity under different number of primary frequency modulation.

As can be seen from the figure, when the unit price of the energy storage system and the scale of the energy storage system are constant, the income of the energy storage system increases with the increase of the frequency of primary FM assessment. With the increase of the scale of energy storage, the benefits will increase more obviously.

5. Conclusion

In this paper, the economic benefits of the energy storage system are divided into the following aspects: delaying the equipment investment of the photovoltaic station, reducing the cost of light abandonment, environmental benefits, direct benefits, government subsidies, etc. In addition, the cost analysis of the energy storage system is taken into account, and the value evaluation model of the primary frequency modulation of the photovoltaic station assisted by the energy storage system is obtained. At the same time, taking a photovoltaic station as an example for specific economic analysis, it is concluded that:

1) Regardless of the unit price of energy storage, the economic benefits of energy storage will not increase indefinitely with the increase of energy storage capacity.

2) When the unit price of energy storage is low, the economic benefits of energy storage will gradually increase with the increase of energy storage capacity. However, when the energy storage capacity reaches a certain value, the economic benefits tend to be flat.

3) When the unit price of energy storage is too high, with the increase of energy storage scale, the economic benefits will be very poor. Only when the energy storage capacity is small can certain benefits be obtained, but at this time, the energy storage system can basically not play the role of frequency modulation, and has little impact on the qualification rate of primary frequency modulation assessment.

4) When the unit price of the energy storage system and the scale of the energy storage system are fixed, the income of the energy storage system will increase with the increase of the number of primary frequency modulation examinations;

5) The more the frequency of primary frequency modulation assessment, the more obvious the increase of the income with the increase of the energy storage scale.

The research in this paper provides certain reference value for the investment and application of primary frequency modulation of energy storage auxiliary photovoltaic stations.

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