Model and Feature Analysis of Energy Storage Participating in Interaction

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Abstract. The "the 13th Five-Year Plan for Energy Development" pointed out that it is necessary to actively carry out the construction of energy storage demonstration projects and promote coordinated operation of energy storage systems with new energy sources and power systems. The future prospects for energy storage development are considerable. Therefore, how to make full use of energy storage advantages to promote power system development is an important research topic. Based on the flexible and interactive characteristics of energy storage, this paper first studied the principle of energy storage equipment participating in the grid interaction. Then, taking the micro-grid system composed of "source-load-storage" under the condition of not being connected to the grid as an example, the specific modes and interactive features of the energy storage involved in the interaction under the system are studied.

1. Introduction
With the continuous development of energy storage technology, the disorderly access of large-capacity energy storage equipment to the power grid in the future will inevitably bring great influence on the operation of the power grid [1-2]. As a typical demand-side resource, energy storage equipment will play a major role in the distribution side in the future, including participation in demand-side response, balancing some peak-to-valley differences [3], providing auxiliary services such as system frequency regulation and pressure regulation [4], emergency power supply, improving power supply reliability, improving power quality and so on [5]. Because of the high flexibility of energy storage, studying its interaction characteristics in the power system will help realize the safe, economical and efficient operation of the power system [6].

2. The principle of energy storage equipment participating in interaction
As a kind of demand-side response resources, the interaction of energy storage participating in the grid mainly aims to stabilize some peak-to-valley differences, and the peak-valley price is used as the basis for interaction with distribution networks. Use the energy storage equipment to store electrical energy at low load period and delivering the stored energy at peak load period for use in other loads or release to large grids, thus the peak loads of the peak period are reduced, and the valley loads at low load period are increased. At present, the energy storage resources commonly used for peak shaving are mainly pumped-storage power stations. However, with the continuous development of technologies in the future, batteries, super-capacitors and other devices will also participate in demand-side
management. Combining the different characteristics of various types of energy storage devices, a hybrid energy storage system can be designed to participate in the interaction of the grid. The interaction pattern of loads with energy storage equipment and distribution network is shown in the figure below:

Fig. 1 The interaction model of loads with energy storage equipment and power grid

On the other hand, the relevant policies of energy-storage in the future and the continuous improvement of the auxiliary service market mechanism will further lay a good foundation for energy storage equipment to participate in the auxiliary service market \[7\]. In addition, the interaction of energy storage equipment in the power grid can provide auxiliary services such as frequency modulation and backup for grid operation, and also provide good support for the grid to accept large-scale new energy sources.

3. The interactive model and feature analysis based on "source-load-storage"

In the future, distributed power supplies, loads, and energy storage devices can form an independently operating micro-grid system, and there is a mutual interaction between the various devices in the system. This section mainly studies the interaction mechanism and interactive effects between distributed power sources, loads, and energy storage devices under the condition of not being connected to the grid.

3.1. The interactive model analysis based on "source-load-storage"

Micro-grid is a small-scale power generation and distribution system that is composed of distributed power sources, energy storage devices, energy conversion devices, associated loads, and monitoring and protection devices. It is an autonomous system capable of self-control, protection, and management and it can be operated either in parallel with the large grid or in isolation. The independently operated micro-grid system does not depend on the power supply of the large power grid, and it depends on the mutual interaction of various components within the system to form an orderly power consumption pattern. The basis for participating in interactions within the system is based on the sum of the electricity cost savings generated during the life cycle of the micro-grid system and the related benefits, which is greater than the sum of the construction and operation and maintenance costs of the micro-grid system. The specific interaction mechanism within the system is shown in the figure below:

Fig.2 The "source-load-storage" interactive model
It can be seen from the interactive relationship in the above figure that the interaction between subsystems of a micro-grid system that is not connected to the grid is relatively simple. Distributed power supply can provide power input for the system in the form of complementary wind energy and light energy. The energy storage system can store excess energy generated by the distributed power supply. When the distributed power supply is insufficient, the energy in the energy storage device can be released for the use of various types of loads. Dynamic energy storage devices such as electric vehicles can store the energy in batteries in static energy storage devices when the distributed power output is high. The use of the power provided by the distributed power source for charging can improve the utilization efficiency of the power.

3.2. The interactive feature analysis based on "source-load-storage"

Since the independently operating micro-grid system does not involve the grid, the interaction between the distributed power source, the electric vehicle, the energy storage, and the static load is mainly analyzed from the perspective of the user. From the perspective of users, the interaction is mainly reflected in the premise of meeting the reliability of the entire interactive system, which brings the best economic benefits, and achieves the optimal configuration of the energy storage system. In a microgrid system that is not connected to the grid, the direct economic benefits brought by energy-storage users participating in the interaction can be expressed by the following formula:

\[
minC = \sum_{i=1}^{n}(p_{i,Bat}^M \times Q_{Bat}) + \sum_{i=1}^{n}(p_{i,SC}^M \times Q_{SC}) \times \frac{1}{(1+\alpha)} + (P_{Bat} \times Q_{Bat} + p_{SC} \times Q_{SC})
\]  

where \(C\) refers to the cost in the life cycle of the energy storage device in a micro-grid system not connected to the grid, \(P_{i,Bat}^M\) refers to the unit cost of operation and maintenance of the battery for the \(i\)-th year, \(P_{i,SC}^M\) refers to the unit cost of operation and maintenance of the super capacitor for the \(i\)-th year, \(P_{Bat}\) refers to the unit cost of the battery, \(P_{SC}\) refers to the unit cost of the super capacitor, \(Q_{Bat}\) refers to the capacity of the battery, \(Q_{SC}\) refers to the capacity of the super capacitor.

Because it is a micro-grid system that is not connected to the grid and operates independently, its safe and reliable operation needs to meet the following constraints:

3.2.1. Charge and discharge current constraint. In the following, the hybrid energy storage system consisting of a battery and a super capacitor is taken as an example to illustrate the charge and discharge constraints of the energy storage module. Due to the power density of the supercapacitor, it cannot be used as the main energy storage unit in the hybrid energy storage system. Its role is to provide instantaneous maximum power when the load fluctuates greatly. The hybrid energy storage system is fully charged and discharged several times a year. The load will have a large current of size \(\omega \times I\) (\(\omega > 1\)) at a time, which is the discharge current \(I_d\) of the super capacitor. In addition, since the output energy of wind power generation and photovoltaic power generation is not stable, it is necessary to suppress the fluctuation of output power by using a super capacitor. Assume that the maximum ripple current is \(\eta \times I\) (\(\eta > 1\)), which is the charge current \(I_c\) of the super capacitor, that is:

\[
\begin{align*}
\eta \times I &\leq I_c \leq I_c^{max} \\
\omega \times I &\leq I_d \leq I_d^{max}
\end{align*}
\]

(2)

where \(I_c^{max}\) and \(I_d^{max}\) are the maximum charging current and the maximum discharging current of the super capacitor, respectively.

3.2.2. Maximum power surplus constraint. When wind and light are sufficient, wind power generation and photovoltaic power generation are greater than power consumption, in order to ensure that the energy storage system can fully absorb excess energy, select the \(t\)-period with the largest surplus of
power generation as the constraint condition, then that is:

\[ P_t(w) + P_t(s) - P_t(l) \geq Q_{bat} + Q_{SC} \]  

(3)

where \( P_t(w), P_t(s) \) and \( P_t(l) \) correspond to the wind power distributed generation output, the photovoltaic distributed generation output, and the load consumption, respectively, in t-period with sufficient wind and light. \( Q_{bat} \) refers to the capacity of the battery, \( Q_{SC} \) refers to the capacity of the super capacitor.

3.2.3. Maximum power loss constraint. When there is no wind or rain for a long time, wind power generation and photovoltaic power generation are less than power consumption. In order to provide continuous power supply to important loads and ensure the reliability of the power supply system, select the k-period with the largest amount of losses to generate power as a constraint, that is:

\[ P_k(w) + P_k(s) + Q_{bat} + Q_{SC} \geq P_k(l) \]  

(4)

where \( P_k(w), P_k(s) \) and \( P_k(l) \) correspond to the wind power distributed generation output, the photovoltaic distributed generation output, and the load consumption, respectively, in k-period with insufficient wind and light. \( Q_{bat} \) refers to the energy released by the battery in the k-period. \( Q_{SC} \) refers to the energy released by the super capacitor in the k-period.

4. Conclusion

Effective use of the flexibility of energy storage equipment can achieve the effect of reducing the peak-to-valley difference of the grid on the basis of ensuring the economic benefits of users. In the "source-load-storage" system, energy storage systems can be combined with distributed power sources to promote the absorption of renewable clean energy and improve the efficiency of the use of electrical energy.

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