Capacity Optimization and Economic Analysis of Energy Storage Systems in Photovoltaic Power Generation

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Abstract. The rapid increase in the installed capacity of renewable energy generation has led to the phenomenon of "abandoned solar power" and "abandoned wind power." Some questions, for example, bidirectional power flow, three-phase unbalance, harmonics and voltage crossings can affect the safe operation of the grid. In order to solve the dilemma, the power grid usually uses energy storage devices to store the renewable energy on the spot. In this paper, according to the characteristics of all-vanadium redox flow batteries and regional environmental factors, such as irradiance and ambient temperature, a photovoltaics power generation system model with an energy storage device is established. The problem of capacity allocation in the photovoltaic system is studied. At the same time, the operating cost of the system is evaluated from an economic point of view, and finally the configuration of energy storage and PV capacity with the lowest system operating cost is derived.

Keywords: all-vanadium redox flow battery, photovoltaic power generation system, capacity configuration, operating cost.

1. Introduction

The cumulative installed capacity of PV power generation in China has increased from 0.86 GW in 2010 to about 30.5 GW in 2021. In 2024, China's new PV installed capacity reached 277.17 GW. Up to now, China has become the country with the largest installed capacity of photovoltaic power generation [1].

Since solar power is highly influenced by the natural environment, the power generation is volatile and intermittent. As renewable energy sources replace fossil energy sources on a large scale, the balance and stable operation of large-scale power grids is affected. In bad cases, possible power imbalance in the system and overloading of circuits posing a serious threat to the stable power supply of the grid. At the same time, renewable energy geneation facilities and load are unevenly distributed geographically. In the course of a large-scale roll-out of the phenomenon of "abandoning solar and abandoning wind power" often occurs, resulting in a serious waste of resources. This is not conducive to the long-term development of the renewable energy power generation industry [2][3].

In order to suppress the fluctuation of output, the current mainstream method is to configure a certain amount of energy storage devices in the system to smooth out the inherent volatility and unpredictable intermittency of photovoltaic power generation, constituting an optical storage microgrid system. The introduction of energy storage devices, while improving the stability of photovoltaic output and increasing economy through peak and valley electricity prices, also increases the operating cost of photovoltaic systems. Therefore, the optimal allocation of energy storage and the economy of energy storage in optical storage microgrids have become the focus of current research [4].

2. literature review

This part will analyses the capacity calculation methods of energy storage devices in different renewable energy power generation systems, analyze their characteristics, and the advantages and disadvantages of their methods.

In chaina, minimum storage configuration policies have been published. This is a mandatory requirement for storage capacity configuration. In 2022, the Inner Mongolia Energy Bureau issued the "Implementation Rules for the Integration Project of Source Network Load and Storage in Inner Mongolia Autonomous Region." stipulating that the energy storage configuration ratio should, in principle, be no less than 15% of the installed capacity of renewable energy generation, with a storage duration of 4 hours [5]. The Hebei Development and Reform Commission issued the "Hebei Province 2021 Wind Power and Photovoltaic Power Market Grid-Connected Project Plan Notice." In the Hebei Northern Power Grid area, energy storage is cogured atnfigured at 20% for 4 hours, while in other regions, energy storage devices are configured at 15% for 4 hours. In the Hebei Southern Grid area, energy storage devices are confi 10% for 4 hours [6].

The capacity and location of energy storage device have a great impact on the distribution network. If the capacity is too large, the cost is too high, and the economy is low. It cannot achieve the role of energy storage and distributed power supply to control the distribution network. Therefore, how to locate and size the energy storage system to achieve the optimal goal is also one of the key issues of energy storage configuration.

An improved particle swarm optimization algorithm based on an elite set was proposed in literature [7]. The optimization method of energy storage location and capacity aims for minimum network loss and voltage fluctuation. Its advantage is that it can improve the search efficiency and find the global optimal solution faster. The disadvantage is that computing costs increase, and different parameter settings can have a significant effect on the algorithm.

Literature [8] proposes the configuration of the energy storage capacity based on the improved Q-learning joint frequency modulation strategy. Its advantages are flexibility and scalability. The disadvantage is that the algorithm complexity is high, involving multiple energy sources and multiple agents, making the commissioning and maintenance process relatively complex.

Literature [9] designed a charge and discharge control strategy for an energy storage system to participate in auxiliary peak regulation. Considering the combined load of the grid affected by wind power fluctuations, under the constraint conditions of thermal power and energy storage, the energy storage system capacity allocation schemes of optimal economy, optimal wind power output absorption, and a balance of both are obtained respectively. The disadvantage is that as the capacity and power for the energy storage system increase, the amount of abandoned wind in small wind farms is reduced, but the overall profit is not high.

Literature [10] discusses the orderly charging strategy for the integrated community of solar storage and charging. The advantages include reducing user charging costs, improving user economic benefits, lowering energy costs, and improving system operation efficiency. The disadvantage is the technical complexity, which requires comprehensive consideration and coordination of multiple links such as energy storage and charging piles, making the technical implementation more complex.

3. Case analysis

Through the literature review, this paper finds the highlights and limitations of different algorithms. In the case analysis part, this paper will model the PV power generation system, all-vanadium flow battery energy storage device, and system capacity configuration. With these three models as constraints, the economic model of system operation is set up, and its target value is the lowest total system cost.

The PV power generation system structure, including the energy storage device, is as follows:

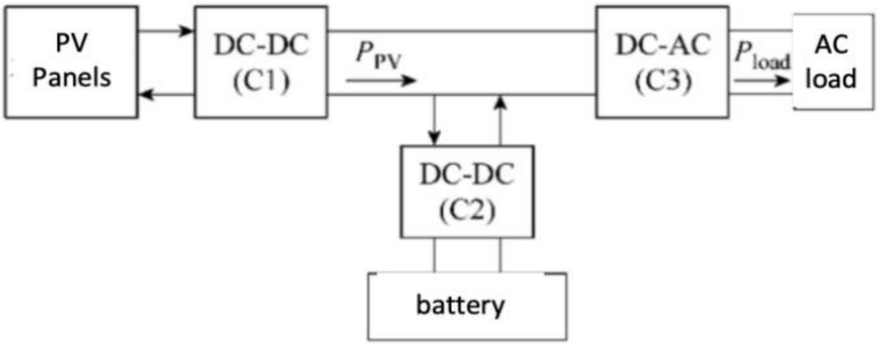

Figure 1. Photovoltaic power generation system with battery

The entire photovoltaic power generation system consists of PV panels, an energy storage device, and load. Energy conversion and flow are managed through corresponding converters and three functional units.The output voltage is primarily boosted by the C1 converter. A bidirectional C2 rectifier is employed to maintain constant DC bus voltage while controlling the discharge process of the energy storage unit. Power inversion from DC to AC is achieved through the C3 converter.

(1) Photovoltaic power generation model

In this paper, we first model the photovoltaic, that is the photovoltaic array in Figure 1. Photovoltaic power output is affected by irradiance, light area and ambient temperature. The output has randomness, and the formula of output power $p_{pv}(t)$is:

$$p_{pv}(t) = In\, s(t)A\eta_r\eta_{pc}\left[1-\beta\left(T_c-T_{cref}\right)\right] \tag{1}$$

Where η_r is the photoelectric conversion efficiency of the component, T_c is the ambient temperature, β is the temperature coefficient, T_{cref} is the ambient reference temperature, η_{pc} is the direct current conversion efficiency, and $Ins(t)$ is the irradiance.

(2) Energy storage device model

The energy storage unit in Figure 1 was modeled, and the energy storage type was an all-vanadium flow battery.

An VRB is an energy storage battery that uses vanadium ion redox reactions to achieve energy storage and release. It is characterized by a long service life, high safety, large-scale application, and other advantages.

The capacity and power of all-vanadium flow batteries are independent of each other. The energy is determined by the active chemicals and the volume of the solution tank, while the output powerP_{VRB} is determined by the electrode plate area and battery size. The formula is as follows:

$$P_{VRB} = p_{vrbout} - p_{para} = V_{cell}I_{cell} - p_{fixed} - k'\left(\frac{I_{stack}}{SOC}\right) \tag{2}$$

WhereV_{cell} is the output voltage of a single battery, and I_{cell} is the output current of a single battery. SOC is the state of charge, I_{stack} is the electrode current, k' is the loss coefficient. Vanadium flow battery loss $p_{para}$is mainly composed of two parts: fixed loss p_{fixed} and solution pump loss.

(3) System capacity configuration model

The equilibrium of s provision and exact of system energy under certain load conditions is intended to be met by the goal of capacity configuration for a PV power generation system and energy storage device.

There are system is divided into two cases. The first case is when the load P_{load} is greater than the generation power$P_{gen}(t)$. The released energy by the energy storage device through C2 meets the energy difference of the system. Consequently, the unit of energy storage in a certain period of time is:

$$E_{store}(t) = E_{store}(t-1) - \frac{\frac{P_{load}}{\eta_{DC/AC}} - P_{gen}(t)}{\eta_{DC/DC}}\Delta(t) \tag{3}$$

The second case is that when the load is less than the PV power generation,PV power generation will supply excess energy to the battery, and then charge the battery through C2,the formula of energy storage unit in a certain time is:

$$E_{store}(t) = E_{store}(t-1) - \frac{P_{gen}(t) - \frac{P_{load}}{\eta_{DC/AC}}}{\eta_{DC/DC}} \Delta(t) \tag{4}$$

Where$\eta_{DC/AC}$ is the converter C3 efficiency;$\eta_{DC/DC}$ is the converter C2 efficiency; $E_{store}$is the energy storage capacity in the energy storage system.

Since the power generation of the system needs to meet the load of users, the input and output energy of energy storage must meet the following constraints:

$$\mathrm{DOD} \cdot \mathrm{E_{store}(t)} \le \mathrm{E_{store}(t)} \le \mathrm{SOC_{max} E_{store}(t)} \tag{5}$$

The DOD depth of discharge in the formula represents the percentage of the total capacity of the battery released from the full charge state to the current state.

(4) Economic model

This system optimization algorithm is based on constraints (1), (2), and (5). It maximizes the economy of a photovoltaic power generation system with a liquid flow battery energy storage device. Therefore, with economy as the goal, the formula of total system cost $C_{sys}$is as follows, and the minimum objective function is optimized:

$$C_{sys} = C_w C_{sm}^2 + C_p \gamma C_{sm} + C_{PV} \delta_{PV} + C_{loss}$$

Where C_p is the unit power operating cost of the energy storage unit, C_w is the unit capacity operating cost of the energy storage unit, and $C_{sm}$is the capacity of the energy storage unit,C_{loss} is the total system loss, $C_{PV}$is the capacity of the photovoltaic power generation unit,γ is the flow battery power level,$\delta_{PV}$is the unit cost of the photovoltaic power generation unit, the minimum cost of a flow battery can be calculated.

Under a certain LPSP (probability of electric failure) condition, the cost of the energy storage unit and the cost of the PV module are monotonic. Therefore, as the capacity of the photovoltaic module increases or decreases, the capacity of its energy storage unit decreases or increases, so as to target the total cost of the system. The unipolar value point solving problem should satisfy:C'_{sys} =0. The optimal capacity configuration can be obtained, that is, when the total system loss is certain, the system satisfies the formula: $\frac{\partial C_{PV}}{\partial C_{sm}} = -\frac{\delta_{pv}}{\gamma C_p + 2C_w}$ the minimum cost of system operation can be obtained [11].

4. Conclusion

This paper establishes the model of photovoltaic power generation system, energy storage device, and system capacity. With these three models as constraints, the economic system modelling is in place. The PV system with flow battery energy storage includes a photovoltaic power generation model based on output power.The influencing factors include component area, light intensity, and other conditions. The VRFB model is characterized by high safety and large storage space. The load model of the system includes two situations where the load is greater than or less than the generating capacity. Through the above constraints, the system is optimally configured. This paper also obtains the optimal capacity configuration and the minimum cost of system operation based on photovoltaic modules and energy storage units. In the future, can mainly study the efficient integrated modeling of all-vanadium flow batteries and photovoltaic power generation, optimize capacity allocation and energy management to improve system economy, and promote large-scale application of clean energy.

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