Optimal Allocation of Distributed Energy Storage Capacity in Power Grid With High Proportion of New Energy

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Abstract. In order to reduce the waste of power resources caused by unreasonable capacity allocation, an optimal allocation method of distributed energy storage capacity in power grid with high proportion of new energy is proposed. Taking wind and solar power generation as the research object, the wind power generation model is established by using Weibull algorithm, the photovoltaic power generation model is established by using beta algorithm, and the energy storage system model is constructed based on the state of energy storage device. The economic benefits of power grid are taken as the objective function to constrain the grid side, DG and energy storage. On this basis, the model parameters are optimized by using particle swarm optimization algorithm, Finally, the optimal configuration of distributed energy storage capacity is realized. The experimental results show that the proposed method can quickly calculate the optimal energy storage configuration under the condition of constant power shortage rate, and the reduced economic loss increases significantly with the increase of power shortage rate. It has a certain research value.

1. Introduction
With the depletion of traditional fossil energy, renewable energy has been widely used. As a new and competitive power generation method, renewable energy power generation must play an increasingly important role in the development of modern power system.[1-2]. Among these renewable energy sources, the development and utilization of wind energy and solar energy have been paid universal attention all over the world. They are the renewable energy sources with the highest level of development and utilization, the most extensive application, the most mature technology development and the most commercial development conditions. However, renewable energy has the characteristics of volatility and uncertainty[3-4]. The impact of large-scale renewable energy on power grid cannot be ignored. Deploying energy storage system in the middle of power grid can provide voltage support, smooth the fluctuation of renewable energy output, balance the power flow in the network, and match the demand of power side and load side[5].

At present, the research on capacity allocation of distributed energy storage system in power grid has made some achievements. In order to solve the problems of capacity waste and excessive discharge depth in the commonly used calculation methods of energy storage capacity, a two-layer nested model for the coupling calculation of capacity configuration layer and operation control layer of energy storage system is established by considering the interaction between optimal configuration and operation control process[6]. According to the utilization of distributed renewable energy by
power users, Li et al.[7] proposed a distributed energy storage system composed of compressed air energy storage, lithium battery and super capacitor, and established three mathematical models of energy storage. The results of power and capacity allocation of distributed energy storage system are obtained, and its operation characteristics are analyzed. The coupling of various energy storage technologies can not only give full play to the advantages of each kind of energy storage, but also make up for their respective disadvantages through mutual cooperation, which plays an important role and significance in the full utilization of renewable energy and meeting the severe demand of power load, and has a good engineering application prospect in the field of distributed energy utilization [8]. However, the above two studies did not fully consider the impact of wind solar complementary characteristics, long-term operation of the time value of funds and system operation reliability index on the allocation of energy storage capacity.

Based on this, this paper proposes the optimal allocation method of distributed energy storage capacity in power grid with high proportion of new energy, and tests the effectiveness of the proposed method through experiments. Through this study, we hope to provide valuable reference for the energy management of power system.

2. Distributed grid modeling
In the active power grid system with DG (Distributed Generation), there are two configuration modes of energy storage devices: centralized and distributed[9].

Wind power generation model. The amount of wind power generation is closely related to the wind speed of the wind turbine[10]. In this paper, the widely used Weibull distribution is used to simulate the random fluctuation of wind. The probability density function is as follows:

$$f(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$

Where $k$ and $c$ are the shape and scale parameters of Weibull distribution. According to the random wind speed generated by the distribution, the output $PW$ of the wind turbine in the actual working process can be obtained according to equation (2):

$$f(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$

Where, $k_1 = \frac{P_r}{v_i \cdot v_r}$, $k_2 = k_1 \cdot v_i$, $Pr$ is the rated power of the fan, $v_i$, $v_r$ and $vc$ are the cut in wind speed, rated wind speed and cut out wind speed of the fan respectively. Photovoltaic power generation model.

The amount of photovoltaic power generation is closely related to the light intensity. According to relevant statistics, the change of light intensity basically conforms to Beta distribution. The probability density function can be expressed as:

$$f(r) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot \left(\frac{r}{r_{\max}}\right)^{\alpha-1} \cdot \left(\frac{r}{r_{\max}}\right)^{\beta-1}$$

Where: $r$ Represents the gamma function; $r$ is the current light intensity and $r_{\max}$ is the maximum light intensity; $\alpha$ and $\beta$ is the shape parameter of Beta distribution.

According to the light intensity, the output $Ps$ of photovoltaic in actual work can be obtained, as shown in equation (4):
Where: $\eta_s$ is the photoelectric conversion efficiency, $s$ is the total light receiving area of photovoltaic module, $r_c$ is the threshold constant, $r_0$ is the rated light intensity, $P_z$ is the rated photovoltaic power.

3. Distributed energy storage capacity optimization model

3.1. Objective function

At present, the environmental benefits and power grid reliability benefits brought by the installation of energy storage system can not be directly and accurately quantified as economic benefits. The objective function is shown in equation (5). All the above expenses are converted into one-year period for calculation.

$$\max F = C_B + C_{loss} + C_{w,s} - C_{ESS} \quad (5)$$

In the formula: $C_B$ is the cost saved by reducing the capacity expansion of power grid; $C_{loss}$ is the net loss cost reduced after installing energy storage; $C_{w,s}$ is the income brought by the additional wind power or optoelectronics; $C_{ESS}$ is the total investment cost of energy storage.

$$C_B = I_B \beta \eta \frac{P_m}{\lambda} \quad (6)$$

Where: $I_B$ is the annual depreciation cost of power grid; $\beta$ is the annual depreciation rate of distribution equipment; $\eta$ is the efficiency of energy storage in charge discharge process. $P_m$ is the maximum charge discharge power capacity of the energy storage device.

$$C_{loss} = 86760 (P_0 - P_1) C_l \quad (7)$$

Where: $P_0$ is the active network loss when the grid is not connected to the energy storage system; $P_1$ is the active network loss after the energy storage is connected; $C_l$ is the power loss price.

$$C_{ESS} = \lambda_1 (I_f + k_p P_m) + \lambda_2 k_w E + I_m P_m \quad (8)$$

In the formula: $\lambda_1$ is the annual depreciation rate of grid connected equipment; $I_f$ is the construction cost of energy storage station address; $E$ is the rated energy capacity of the energy storage device. $k_p$ is the cost of power conversion equipment; $\lambda_2$ is the annual depreciation rate of the energy storage device; $k_w$ is the cost of energy storage device; $I_m$ is the annual operating cost of energy storage unit power capacity.

3.2. Constraints

3.2.1. Grid side constraints

(1) Node power balance constraints

For n-node power grid system, $U, \theta$ is the power flow equation can be expressed as

$$P_j(U, \theta) = U_j \sum_{j=1}^{N} U_j(G_{ij} \cos \theta_j + B_{ij} \sin \theta_j) \quad (9)$$

Where $G$ and $B$ are the real and imaginary parts of the admittance matrix respectively.
(2) Node voltage constraint

The integration of DG and energy storage changes the power flow in the power grid system, which will inevitably lead to voltage deviation. As an important index to measure power quality, it needs to be considered as a constraint condition.

\[ U_N (1 - \varepsilon_1) \leq U_i \leq U_N (1 - \varepsilon_2) \]  

(10)

Where \( U_N \) is the nominal voltage of the system; \( \varepsilon_1, \varepsilon_2 \) is the allowable deviation rate.

3.2.2. DG constraints

Constrained by the natural environment and equipment operation constraints, the maximum output of DG is certain. The constraint of DG output can be expressed as follows:

\[ 0 \leq P_{DG} \leq P_{DGmax} \]  

(11)

Where: \( P_{DGmax} \) is the maximum output of DG connected to the power grid; In order to facilitate the subsequent analysis of the main problems, it is assumed that there is no reactive power exchange between DG and power grid.

4. Optimal allocation of energy storage capacity based on particle swarm optimization

4.1. LPSP calculation process

The operation index of wind power generation system is loss of power supply probability (LPSP), which is the ratio of load power shortage \( E_{lps} \) to total load demand \( E_l \). Namely

\[ LPSP = \frac{\sum_{t=1}^{T} E_{lps}(t)}{\sum_{t=1}^{T} E_l(t)} \]  

(12)

When the wind power meets the load requirements, the power shortage of the load is 0, and the energy storage device charges. When the wind power does not meet the load requirements, the energy storage device discharges to supplement the power shortage of the power supply, which can be expressed as

\[ E_{lps}(t) = \{ P_s(t) - P_w(t) \eta \} \cdot t \]  

(13)

4.2. Optimization of energy storage capacity allocation

On the basis of the above, the particle swarm optimization algorithm is used to optimize the energy storage capacity allocation of power grid. The process can be summarized as follows:

1) Initialization of particles in the population;
2) The fitness function of each particle is evaluated, and the current position and fitness value of each particle are stored;
3) Update the velocity and position of particles, \( k = k + 1 \);
4) The current fitness function value of each particle is recalculated to determine whether to update;
5) The position and fitness values of all the particles are compared to judge whether they meet the criteria of stop searching;
6) If the stop condition (usually the default precision or iteration), the search stops, outputs the approximate optimal solution, or returns to the second step of the search.
5. Experience and analysis

5.1. Introduction of calculation test

In this paper, for the optimal allocation of distributed energy storage system capacity, a wind solar hybrid power grid system in a region is selected as an example to solve the problem. Renewable energy in power grid system includes 50MW photovoltaic generation unit and 100MW wind power generation unit. There are 288 groups of wind speed data with 5 min sampling interval on May 10 in this area to obtain the fan output. The parameters of distributed energy storage are shown in Table 1. The service life of the project is set as 20 years, and the system power supply reliability index \( \text{LPSP}_{\text{max}} \) is 0.05 and \( \text{LPPP}_{\text{max}} \) is 0.3.

| Tab.1 Parameters of energy storage system |
|------------------------------------------|
| **Battery** | **Supercapacitor** |
| Rated capacity / Ah | 100 | Capacitance / F | 3500 |
| Rated voltage / V | 12 | Rated voltage / V | 2.7 |
| Discharge depth | 0.4 | Minimum working voltage / V | 0.8 |
| Charging efficiency | 0.7 | Maximum working current / A | 1500 |
| Discharge efficiency | 0.8 | Charging efficiency | 0.98 |
| Cycle life / time | 1500 | Discharge efficiency | 0.98 |
| Maintenance factor | 0.02 | Maintenance factor | 0 |
| Treatment factor | 0.08 | Treatment factor | 0.04 |
| Unit price / yuan | 400 | Unit price / yuan | 350 |

5.2. Optimization results and comparative analysis

(1) Wind solar hybrid system without optimal allocation of energy storage capacity

For the independent wind solar hybrid power generation system without optimal allocation of energy storage capacity, the reliability indexes LPSP and LPPP are taken as the optimization objectives, and the results are shown in Table 2.

| Tab.2 Index values of LPSP and LPPP of the system without optimal configuration of energy storage capacity |
|------------------------------------------|
| **Index** | **Value** |
| LPSP | 0.3418 |
| LPPP | 0.2213 |

It can be seen from table 2 that if the wind solar complementary power grid does not carry out the optimal allocation of energy storage capacity, the values of load power shortage rate index LPSP and energy loss rate index LPPP of the system are at a high level. Among them, \( \text{LPPP} = 0.3418 \), which indicates that there is a large part of energy loss in the operation phase of the system, and the scenery is not effectively utilized; \( \text{LPSP} = 0.2133 \), which indicates that a large number of loads are in the state of power shortage during the operation of the system, resulting in poor power supply reliability of the system.

(2) Wind solar hybrid system for optimal allocation of energy storage capacity

According to the optimization model established in this paper, the methods of this paper, reference [7] and reference [8] are used to analyze and calculate, and the optimal configuration results of distributed energy storage system are obtained. The iterative process of solving is shown in figure 3. The final optimization results are shown in figure 1.
According to the data of the optimization iteration results, figure 1, the method proposed in this paper can reduce randomness and improve the swimming effect, and has better information sharing and transmission mechanism, which makes the global optimization ability greatly strengthened. Compared with the standard literature [7] and literature [8], the optimization accuracy is higher. In addition, an adaptive step size based on cosine is introduced to replace the fixed step size in the original algorithm, which can further enhance the optimization performance of the algorithm.

5.3. Impact analysis of reliability constraints on configuration scheme

LPSP is an important index to measure the power supply reliability of power grid system. Therefore, the experiment compares the optimal configuration results under different LPSP constraints, and the configuration results are shown in figure 2.

Comparing the above results with figure 4, it can be seen that when the maximum index $LPSP_{\text{max}}$ of power shortage rate is set to 0.06, the life cycle cost is about 40 million; When $LPSP_{\text{max}}$ is set to 0.05,
the life cycle cost is about 80 million. Therefore, with the decrease of power shortage rate LPSP, the power supply reliability of the system increases, but the higher reliability of the system is at the cost of increasing investment.

6. Concluding

With the continuous development of economy and society, the contradiction between the increasing demand for electricity and the increasing demand for power supply security, the rapid consumption of resources, and the worsening environment is becoming more and more serious. Further technological innovation of power grid is needed to make contributions to the environment and economy. Therefore, there are three aspects of work focus. First, the proportion of renewable energy generation should be steadily increased, and the proportion of coal power should be gradually reduced, so as to reduce the dependence on traditional non renewable resources; second, safe and reliable high-quality power supply is becoming more and more important. The use of microgrid to form an effective supplement to centralized power generation can improve the ability to deal with risks; Thirdly, the energy storage system used in power grid plays a very important role. Improving its utilization efficiency and optimizing its capacity allocation can improve the operation economy of microgrid.

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