Optimal Configuration of Energy Storage Systems in Virtual Power Plants Including Large-scale Distributed Wind Power

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Abstract: With energy shortages and environmental pollution becoming increasingly prominent, the power industry is inevitably facing enormous challenges. Distributed power supplies are reliable, flexible, economical and environmentally friendly, while they are widely distributed in number and have great volatility and randomness. The virtual power plant (VPP) helps to integrate a large amount of distributed energy in the smart grid, providing a proven solution to the above from a new perspective. Based on the virtual power plant with large-scale distributed wind power, this paper studies the optimal configuration model of energy storage system (ESS). According to economy, load shifting and safety norms in the energy storage system, the optimal objective function of the energy storage system is established. The model is solved by particle swarm optimization algorithm, and the feasibility of the proposed model is verified by an example. It is concluded that optimization result is affected by weight factors and to the three roles of energy storage system.

1. Introduction
With the development of renewable energy technologies, high-ratio renewable energy power generation has become a future power system scenario that is widely concerned around the world. A virtual power plant is a type of integrated power plant consisting of an energy management system. It participates in the operation and dispatch of the power grid, which coordinates the contradiction between the
smart grid and the distributed power source that fully exploits the value and benefits brought by the distributed energy to the power grid and users. Wind power and photovoltaic power generations are typical high-ratio renewable power resources. The volatility and uncertainty of high-permeability renewable power generation resources have brought great challenges to the operation and scheduling of the power grid [1].

With its rapid power regulation capability, the energy storage system can not only improve the characteristics of renewable energy generation, but also solve many problems caused by renewable energy generation from a system perspective [2]. With the goal of ESS minimum capacity, the determination of ESS rated capacity is to use ESS to stabilize the power fluctuation of renewable energy [3]. With the goal of maximizing comprehensive benefits, the optimal configuration of ESS capacity to improve wind power acceptance is to use ESS to cut peaks and fill the valley [4]. Considering the uncertainty of wind turbines, the VPP system model with wind storage is based on the overestimation of wind power overestimation [5]. In the grid-connected photovoltaic system, based on the time-of-use electricity price, the minimum ESS capacity is solved for all the electricity purchase costs and energy storage loss costs [6]. The above literature uses ESS to suppress the fluctuation of renewable energy and the role of peak load shifting. Or the minimum capacity is the target. The ESS function and the objective function are relatively simple.

Based on the above researches, in order to reflect the multiple roles of ESS in the VPP and make the role of each configuration fully exerted. Based on the analysis of the roles of ESS in the VPP, this paper introduces the norms of economy, load shifting and safety and then builds the optimal objective function of ESS. The particle swarm optimization algorithm is used to solve the optimal configuration model of ESS. Finally, the feasibility of the proposed model is verified in the VPP composed of IEEE33 node system. It is concluded that the changes of weight coefficients will affect the configuration result and the optimal configuration is the coordination effect of the three aspects.

2. The analysis of ESS configuration in the VPP

2.1. The analysis of VPP operation process

This paper builds a VPP operation model of centralized control structure, which includes large-scale distributed wind power, interruptible load and energy storage system as shown in Figure 1.

![Figure 1. Operation model of the VPP](image)

2.2. Energy storage device model

In this paper, a lead-acid battery with wide application, moderate energy and high rate discharge performance is selected as the energy storage device. The stored power is related to the previous time period. The corresponding model is:
In the formula:

\[ E_b(t+1) = (1-\epsilon)E_b(t) + (P_{b,ch}(t)\cdot \eta_{b,ch} \cdot r_{b,ch}(t) - \frac{P_{b,dc}(t)\cdot r_{b,dc}(t)}{\eta_{b,dc}}) \Delta t \]  

(1)

In the formula: \( E_b(t) \) is capacity at battery \( t \). \( P_{b,ch} \) and \( P_{b,dc} \) are the charging power and the discharging power of the battery, respectively. \( \eta_{b,ch} \) and \( \eta_{b,dc} \) are the charging and discharging efficiency of the battery respectively. \( \epsilon \) is self-discharge rate of the battery. \( r_{b,ch} \) and \( r_{b,dc} \) are the state of charge and discharge of the battery is 0-1 variable.

3. Energy storage system optimization norm

3.1. Economic norm

The economic norms include the VPP scheduling revenue, the financial subsidy and the annual cost of the ESS.

The scheduling revenue of VPP in this paper refers to the obtained economic benefits when VPP purchases electric energy through the market or allocates its own distributed power supply to the end users. During the VPP operation, the VPP does not send power to the distribution network, but only purchases electricity from the distribution network if it cannot meet the load demand. Wind power generation has a subsidy policy. At the same time, this paper also considers the cost of energy storage system.

\[ E = \sum_{h=1}^{1080}\sum_{j=1}^{24}\left(\sum_{i=1}^{m}P_{L}(t,j) - \sum_{i=1}^{n}S_{L}(t,i)C_{L}(t,i)\lambda_{2} - P_{LS}(t)\lambda_{3}(t) + P_{SS}(t)\lambda_{3}(t) + \sum_{i=1}^{n}S_{L}(t,i)(\lambda_{3}(t) - \lambda_{2})C_{L}(t,i) + (P_{w}(t) + P_{ESS}(t))\lambda_{3}\right) - E_{SS} \]  

(2)

In the formula: \( E \) is the VPP annual total scheduling revenue. \( P_{L}(t,j) \) is the active demand of the \( j^{th} \) load at time \( t \). \( m \) is the total number of loads in VPP. \( N \) is the number of simulation days in the year. \( P_{w}(t) \) and \( P_{ESS}(t) \) are the power supply of wind power and ESS to load at time \( t \). \( \lambda_{3} \) is the subsidy standard. The unit price of the subsidy is 0.58 yuan. \( E_{SS} \) is the ESS cost fee annual value.

\[ \max f_{1} = E \]  

(3)

In the formula: \( f_{1} \) is the economic norm.

3.2. Load shifting norm

The peak phenomenon of wind power and load makes the difference curve of the two have huge peak-to-valley difference. The load shifting effect of ESS on the difference can be reflected by the peak-to-valley difference of the power supply in the VPP scheduling. When the ESS is properly configured and the load shifting effect of the ESS is maximum, the value of peak-valley difference is the smallest. Combined with the characteristics of the ESS model, 8760 hours can be divided into 365 days when scheduling the ESS. In this paper, the minimum peak-valley difference in daily scheduling is the target and the established load shifting norm is:

\[ \min f_{2} = P_{LS,max} - P_{LS,min} \]  

(4)

In the formula: \( f_{2} \) is the load shifting norm. \( P_{LS,max} \) and \( P_{LS,min} \) are the maximum and minimum power supply for load shifting in one day.

3.3. Safety norm

An important norm in the safety of the system is the stable voltage. ESS has the function of ameliorating the voltage environment and improving the voltage quality. The global index \( H \) measures the sta-
bility of the entire system voltage. In this paper, $H$ is selected as a norm to evaluate the stability of the VPP voltage. The formula is:

$$H = \max(H_j) = \left| 1 - \frac{\sum_{j \in a_H} F_j V_i}{V_j} \right|, \quad j \in a_H$$  (5)

In the formula: $a_G$ is the node set for all generators. $a_H$ is the total load node set. $L_j$ is the partial index of the $j$th load node. $V_i$ is the complex voltage of the $i$th generator node. $V_j$ is the complex voltage of the $j$th load node. $F_j$ is the load participation factor.

The value of $H$ is 0~1. The closer the value of $H$ is to 1, the more easily the system voltage collapses. When the ESS is properly configured, the VPP voltage quality is the best and the value of $H$ is the smallest. Therefore, the safety norm $f_3$ is:

$$\min f_3 = H$$  (6)

4. Energy storage system capacity optimization

4.1. Optimization objective

The ESS optimization objective function is a comprehensive evaluation function after a certain configured ESS is connected to the VPP, which provides a basis for selecting the optimal configuration from different ESS configurations. The ESS optimization objective function in this paper contains economic, load shifting and safety norms, as shown in Equation 7.

$$\max f_i = f(f_1, f_2, f_3)$$  (7)

4.2. Restrictions

1) System power balance constraints. For a VPP, wind power output, ESS charge and discharge, interruptible load switching, user load and grid-connected power should achieve electric energy balance.

$$P_{ch}(t) + P_{dis}(t) + \sum_{i=1}^{n} S_{IL}(t, i)C_{IL}(t, i) = P_{ch}(t) + \sum_{j=1}^{m} P_{L}(t, j)$$  (8)

2) ESS minimum capacity power constraint. In this paper, the VPP does not supply power to the grid. The remaining power of wind power in the net load must be absorbed by the ESS. Therefore, the minimum capacity and minimum power of the ESS need to be set according to the net load size.

$$\begin{cases} P \leq P_{min} \\ C \leq C_{min} \end{cases}$$  (9)

In the formula: $C_{min}$ and $P_{min}$ are the ESS minimum capacity and minimum power respectively, which are obtained from the net load curve.

3) VPP voltage constraint. When VPP is in normal operation, the voltage of each node should be within the allowable range.

$$V_{min} < V_i < V_{max}$$  (10)

In the formula: $V_{min}$ and $V_{max}$ are minimum and maximum allowable voltage values. $V_i$ is the voltage value of $i$th node in the VPP.

4.3. Model Solving

Considering the relationship between the ESS rated capacity and the rated power and the multiple of the rated power, this paper introduces the variable $K$ to guide the model to solve the capacity and power relationship in the ESS configuration. $K$ is the ratio of the ESS rated capacity to the rated power. The physical meaning is the time that the ESS can be used to discharge (or charge) at the rated power.
in the full state (or zero state). The value of $K$ is an integer and the range is $[1, n]$ (the value of $n$ can be selected according to the actual situation). The PSO solves the ESS optimization configuration under each value of $K$. By comparing the optimal configuration results under $n$ values of $K$, the ESS configuration with the largest value of $F_1$ is selected as the ESS optimal configuration of the VPP. The specific solution process is shown in Figure 2.

Figure 2. Flow chart of solving model

5. Case study

5.1. The introduction of the study
This paper selects the IEEE33 node system as the VPP simulation system and its topology is shown in Figure 3. Assume that wind power is connected at the $1^{st}$, $3^{rd}$, $5^{th}$, $7^{th}$ and $9^{th}$ nodes, accessing wind power capacity is 320, 380, 440, 520, 580 kW, wind power capacity penetration rate is 17%. The $11^{th}$, $13^{th}$ and $15^{th}$ nodes are interruptible. The interruptible load capacities are 60, 120, 60 kW respectively. The ESS access to the $1^{st}$ node is located at the power inlet of the VPP. The actual wind speed and load data of a certain area are used for the whole year, and the simulation duration is 8760h, and the interval is 1h.

Figure 3. IEEE 33-node system
5.2. The optimization configuration model of ESS

When using POS to solve the ESS optimization configuration, the ESS optimization objective function is treated as a single objective function. Find the maximum value of each norm function as shown in Figure 4.

\[
F_2 = w_1 \frac{f_1}{200000} + w_2 \frac{f_{2,\text{max}} - f_2}{925} + w_3 \frac{f_{3,\text{max}} - f_3}{0.0014}
\]  \quad (11)

In the formula: \(w_1\) is the coefficient of economic norm, \(w_2\) is the coefficient of load shifting norm, \(w_3\) is the coefficient of safety norm.

Then the weight coefficient relationship of the three norms can be expressed as:

\[
\begin{align*}
    w_1 & > w_2 = w_3 \\
    w_1 + w_2 + w_3 & = 1
\end{align*}
\]  \quad (12)

In order to explore the ESS configuration under different weight coefficients, this paper selects the three weight coefficient combinations that meet the above conditions and finds one ESS configuration as shown in Figure 5:
As shown in Figure 5, when the economic norm weight coefficient $w_1$ is changed from 0.5 to 0.8, the ESS configuration is changed from 1576kW/7538 kW*h to 1305kW/7325 kW*h. The increase of the economic norm weight coefficient makes the ESS rated capacity and rated power decrease, reflecting the higher the VPP benefit, the smaller the ESS configuration. At the same time, the weight coefficients will affect the configuration results. In the actual situation, the weighting coefficients should be selected according to the actual needs. Similarly, through case analysis of multiple sets of control variables, it can be concluded that the optimal configuration of ESS is the result of the combined action of three norms: economy, load shifting and safety.

6. Conclusion
In this paper, the optimal configuration of ESS is solved in VPP with large-scale distributed wind power. The VVP composed of IEEE33 node system uses PSO to solve the ESS model. The feasibility of the model is verified by using the ESS optimization configuration model to find the ESS configuration results. By simulating the ESS configuration under different weight coefficients of the VPP, the conclusion is made that the economic norm weight coefficient is increased and the rated capacity and rated power in the ESS optimal configuration are reduced. The model can reflect the roles of ESS economy, load shifting and safety. The larger the ESS configuration, the worse its economy and the better the effect of load shifting and safety. Compared with the three, economy has a greater impact on ESS configuration.

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