Research on Energy Optimization Method of Virtual Power Plant Considering Coordination and Interaction of Source-Load-Storage

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Abstract: Developing renewable energy generation such as wind power and photovoltaics is an effective way to cope with energy shortage and environmental problems. The virtual power plant (VPP) realizes the grid-connected operation of intermittent distributed renewable energy by aggregating multiple types of distributed energy resources. In order to achieve the energy optimization problem of the VPP, an optimization method of VPP considering coordination and interaction of source-load-storage is proposed in this paper. First, models of components in the VPP are established. Next, an energy optimization model of the VPP considering coordination and interaction of source-load-storage is constructed. Finally, a case is studied to verify the correctness and effectiveness of the method. The results show that the coordinated consideration of distributed generation, energy storage and demand response loads contributes to reducing the operating costs and carbon emissions of the VPP.

1. Introduction

With the increasing proportion of renewable energy in terminal energy consumption, Distributed Energy Resources (DERs) have been widely used. DERs specifically includes Distributed Generation (DG), energy storage system (ESS), flexible load (FL), electric vehicles, etc., which can make full use of renewable energy [1]. The output of distributed generation, such as photovoltaics (PV) and wind turbine (WT), depends largely on the weather and has a strong fluctuation. At present, the “fit and forget” method [2-3] is usually adopted for the grid connection of distributed generation. This increases the technical complexity of the system operation and brings many problems, thus making it difficult for DERs to play the expected role in the power system.

To meet the above challenges, a "virtual power plant" concept is introduced to accelerate the development of DERs. The VPP provides technical support for the integration of DERs in the current power system by aggregating a variety of different entities, including DG, micro turbine, demand response (DR), and ESS, etc [4].

Although the VPP can provide an effective way for consuming renewable energy, the power coordinated management inside VPP still faces some difficulties.[5] Demand response technology and
energy storage enable the coordinated interaction of source-load-storage, thereby achieving a bi-directional flow of energy.

The main contributions of this paper are as follows: Firstly, models of components in the VPP are constructed, and the demand response mechanism is analyzed. Secondly, considering the environmental benefits of the VPP, a dispatching optimization model of the VPP based on the coordinated interaction of source-load-storage is established. Finally, the case study based on the actual data of a certain place in Guangzhou is presented.

2. Optimization Model

2.1. component models in the VPP

2.1.1. Model of controllable distributed generation units

The output of Gas Turbine (GT) is completely controllable, and its starting and climbing speed is fast. It plays the role of tracking net load and reserve in VPP.

The cost of controllable distributed generation units can be express as a quadratic function:

$$C^{GT} = a^{GT}P^{GT}^2 + b^{GT}P^{GT} + c^{GT}$$

Where $C^{GT}$ is the cost of controllable DG units; $P^{GT}$ is the output power; $a^{GT}$, $b^{GT}$ and $c^{GT}$ are generation cost function coefficients.

2.1.2. Model of random distributed generation units

when constructing the model of random DG units inside the VPP, this paper only considers distributed wind power generation and PV [6].

1) model of wind power generation

$$P^w = \begin{cases} 
0, & v \leq v_c, v > v_m \\
av^3 + b, & v_c \leq v \leq v_m \\
p^{rw'}, & v_m < v \leq v_{co}
\end{cases}$$

Where $v_c$, $v_m$, $v_{co}$ are cut-in, rated and cut-out wind speed respectively; $a$ and $b$ Fitting parameters determined by the power curve; $P^{rw'}$ is the rated power.

2) model of photovoltaics

$$f(P^{PV}) = \frac{1}{P^{PV,n}} \frac{\Gamma(\alpha + \beta)P^{PV}}{\Gamma(\alpha)\Gamma(\beta)}(\frac{P^{PV}}{P^{PV,n}})^{\alpha - 1}(1 - \frac{P^{PV}}{P^{PV,n}})^{\beta - 1}$$

Where $\alpha$ and $\beta$ are two parameters for BETA distribution; $P^{PV,n}$ is the rated power of PV unit; $\Gamma(\cdot)$ is the Gamma function.

2.1.3. Model of energy storage units

When the ES unit is charged as a load, it absorbs energy; when the ES unit discharges as a power source, it releases energy. The relationship between its state of charge (SOC) and the charge and discharge power can be expressed as follows:

$$S_t^{es} = S_t^{es,0}(1 - \sigma) + \eta^{es}P_{t}^{es} - \frac{P_{t}^{es}}{\eta^{esd}}$$

Where $S_t^{es}$ is the storage capacity of ES units during T period; $\sigma$ is the energy loss rate of ES units; $\eta^{es}$ and $\eta^{esd}$ are the charge and discharge efficiency of ES units respectively; $P_{t}^{es}$ and $P_{t}^{esd}$ are the charge and discharge power of ES units during T period.

2.1.4. Model of demand response load

Demand response can be divided into price-based DR and incentive-based DR according to the action mechanism. The benefits of DR load are described as follows:

1) benefit of price-based DR load
\[ \pi^i_T = \sum_{i=1}^{K} (p_{ij}^u L_{ij}^u - p_{ij} L_{ij}) \]  

Where \( \pi^i_T \) is the profit of user I participating in price-based DR; \( p_{ij}^u \) and \( p_{ij} \) are the electricity prices of user I at time T before and after participating in price-based DR respectively; \( L_{ij}^u \) and \( L_{ij} \) are loads of user I at time T before and after participating in price-based DR respectively.

2) Benefit of incentive-based DR load

\[ \pi^1_i = \sum_{n=t}^{T} [\tau n p^0_{n,i} \Delta L_{n,i}^d + (1 - \tau n) p^0_{n,i} \Delta L_{n,i}^u] \]  

Where \( \pi^1_i \) is the profit of user I participating in incentive-based DR; \( \Delta L_{n,i}^d \) and \( \Delta L_{n,i}^u \) are the up and down rotation reserve capacity provided by user I at time T when participating in incentive-based DR respectively; \( p^0_{n,i} \) and \( p^0_{n,i} \) are the prices of up and down rotation reserve provided by user I at time T when participating in incentive-based DR respectively.

2.2. Energy optimization model of VPP considering the coordination and interaction of source-load-storage

2.2.1. Objective function

The optimization goal of VPP coordination and control center can be expressed as:

\[ \min C = C_{DG} + C_{DR} + C_{carbon} \]

\[ C_{DG} = \sum_{k=1}^{K} \sum_{t=1}^{T} [a_k (P_{k,t})^2 + b_k P_{k,t} + c_k] \]  

\[ C_{DR} = \sum_{n=1}^{N} \sum_{t=1}^{T} [\tau n p^0_{n,i} \Delta L_{n,i}^d + (1 - \tau n) p^0_{n,i} \Delta L_{n,i}^u] \]

\[ C_{carbon} = p V_c. \]

Where \( C_{DG} \), \( C_{DR} \) and \( C_{carbon} \) are the generation costs of DG, DR compensation costs and carbon emission costs respectively; \( T \) is the total periods number of VPP optimization; \( K \) is the number of non-renewable energy generation units in the VPP (such as gas turbines, etc.); \( P_{k,t} \) is the optimal output of unit \( K \) at time \( T \); \( a_k, b_k, c_k \) are generation cost coefficients of unit \( K \); \( N \) is the number of incentive-based DR loads; \( \Delta L_{n,i}^d \) and \( \Delta L_{n,i}^u \) are the up and down rotation reserve capacity provided by DR load \( n \) respectively; \( p^0_{n,i} \) and \( p^0_{n,i} \) are the prices of up and down rotation reserve capacity; \( \tau n \) is the 0-1 variable; \( p \) is the carbon emission cost per unit; \( V_c \) is the total carbon emissions per day.

2.2.2. Constraints

1) Power balance constraints:

\[ \sum_{k=1}^{K} P_{k,t} + P_{ES,t} + u_t P_{PHE} + (1 - u_t) P_{PHE} = L_{i,t} + \Delta L_{i,t} \]

Where \( P_{ES,t} \) is the power of ES at time \( T \), and the positive value means discharge state and the negative value means charge state; \( L_{i,t} \) and \( \Delta L_{i,t} \) are the loads at time \( T \) after participating price-based DR and incentive-based DR respectively.

2) Distributed generation constraints:

\[ 0 \leq P_{WT,t} \leq P_{WT,max} \]  

\[ 0 \leq P_{PV,t} \leq P_{PV,max} \]  

\[ u_{MT,t} P_{MT,min} \leq P_{MT,t} \leq u_{MT,t} P_{MT,max} \]
Where $P_{WT, \text{max}}$ and $P_{PV, \text{max}}$ are the upper limit of the output of WT and PV units respectively; $u_{\text{MT}, j}$ is the start-stop variable of GT at time $T$; $P_{\text{MT, max}}$ and $P_{\text{MT, min}}$ are the upper and lower limits of the output of GT respectively.

For the gas turbine, it also needs to meet the constraints of climbing and minimum start and stop time constraints:

$$u_{\text{MT}, j}R_{\text{MT, min}} \leq P_{\text{MT}, j} - P_{\text{MT}, j-1} \leq u_{\text{MT}, j}R_{\text{MT, max}}$$ (15)

where $R_{\text{MT, max}}$ and $R_{\text{MT, min}}$ are the up and down climbing limit of GT respectively.

3) Demand response load constraints:

Price-based DR constrains:

$$\Delta l_{\text{min}}^{\text{PB}} \leq \Delta l_{\text{u}}^{\text{PB}} \leq \Delta l_{\text{max}}^{\text{PB}}, \quad t \in [t_{\text{min}}, t_{\text{max}}]$$

$$\Delta l_{\text{u}}^{\text{PB}} = 0, \quad t \in [t_{\text{min}}, t_{\text{max}}]$$ (16)

Incentive-based DR constrains:

$$\Delta l_{\text{min}}^{\text{IB}} \leq \Delta l_{\text{u}}^{\text{IB}} \leq \Delta l_{\text{max}}^{\text{IB}}$$ (17)

where $\Delta l_{\text{max}}^{\text{IB}}$ and $\Delta l_{\text{min}}^{\text{IB}}$ are the upper and lower limits of the interruptible loads in the VPP during period $T$ respectively.

4) Energy storage constraints:

$$P_{\text{ES}, j} = u_{\text{ES}, j}P_{\text{ES, max}}^{\text{ch}} + u_{\text{ES}, j}P_{\text{ES, max}}^{\text{dis}}$$ (18)

$$0 \leq P_{\text{ES}, j}^{\text{ch}} \leq u_{\text{ES}, j}P_{\text{ES, max}}^{\text{ch}}, \quad 0 \leq P_{\text{ES}, j}^{\text{dis}} \leq u_{\text{ES}, j}P_{\text{ES, max}}^{\text{dis}}$$ (19)

$$SOC_{\text{min}} \leq SOC_{j} \leq SOC_{\text{max}}$$ (20)

2.3. Model solution

The energy optimization model of VPP proposed in this paper is a mixed integer nonlinear programming problem (MINLP), which can be solved by commercial solvers, such as CPLEX, GUROBI, etc.

3. Case study

The actual data of a certain industrial park in Guangzhou are used for case study. It is assumed that the VPP is equipped with a 3x12MW gas turbine, a 25.38MW PV generator set and a 5MW/10MWh battery energy storage. The predicted PV output and load for a typical day of the VPP are shown in figure 1.

![Figure 1. PV output and load forecast for a typical day of the VPP](image)

In order to analyse the impact of DG, ES and DR loads on the overall optimal scheduling of VPP, the following four scenarios are set for comparison:
Scenario 1: Consider DG, ES, and DR loads to participate in the energy optimization scheduling of VPP, i.e. consider only MT1-MT3, PV, ES, and DR loads to participate in the optimization operation of VPP.

Scenario 2: Regardless of the participation of ES, compared to Scenario 1.

Scenario 3: Regardless of the participation of DR loads, compared to Scenario 1.

Scenario 4: Regardless of the participation of ES and DR loads, compared to Scenario 1.

According to the simulation results, it can be concluded that the coordinated participation of ES and DR loads has a significant effect on reducing the operating cost of VPP.
4. Conclusion

To achieve the internal energy optimization of the VPP, this paper proposes an energy optimization method of VPP considering coordination and interaction of source-load-storage. Based on case study, it can be concluded that the coordinated scheduling of DG, ES and DR loads in VPP can contribute to the reduction of total costs of VPP and carbon emissions.

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