Coordination and Optimization of Muti-region Building Virtual Power Plant with Photovoltaic and Wind-power Units

Chen FANG¹, Xiao-long HU²*, Xiu YANG², Ying-jie TIAN¹ and Hao-jing WANG¹

¹East China Electric Power Test & Research Institute Company Limited, Shanghai 200437, China
²Shanghai University of Electric Power, Shanghai 200090, China
*Corresponding author

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Abstract. In order to solve the unstable or economical shortages of power grids and realize the coordinated optimization of distributed energy supply systems in different regions of virtual power plant (VPP), a coordinated optimization scheduling model for multi-region building virtual power plants with wind-power and photovoltaic units is established. The VPP is made up of wind turbine, household photovoltaic, energy storage system (ESS) and electric vehicles (EV). Through inter-regional comprehensive energy interconnection, multi-regional VPP power is complemented. In order to make the electric energy sharing within VPP reasonable, the optimal model with the objective function of reducing the transaction cost between VPP and distribution network, the maintenance cost of wind-power and photovoltaic units and the maintenance cost of EV was established. Finally, the validity of the proposed model is verified by a case study of a typical building VPP with a residential building and a commercial building. The simulation results show that the proposed method can realize the coordinated and optimal power scheduling of different regions and different types of aggregation units, and effectively reduce the net cost of VPP.

Introduction

With the upgrading of industrial structure and the improvement of people's quality of life, fluctuations in power load and peak-to-valley differences continue to increase, which has a great impact on the stability of the power grid. As an international metropolis, Shanghai puts high demands on the stability of power supply. At the same time, due to the greenhouse effect and depletion of non-renewable energy, Shanghai is also transforming its energy structure with the goal of green and low carbon. New challenges presented by energy supply of Shanghai. In response to the energy transformation, clean energy and electric vehicles have developed rapidly in Shanghai, which has caused an impact on the stability of the power grid. The virtual power plant technology realizes the aggregation and coordination optimization of different types of distributed energy resource (DER) such as distributed generation, energy storage system, controllable loads, and EV through advanced technologies such as control, metering, and communication [1]. It’s a solution to the above problem.

Public building is an important part of the energy Internet. The integrated resources such as distributed energy resource, energy storage systems and flexible loads in public buildings are integrated in the form of VPP to participate in the coordination of the source network of the power system to achieving peak cutting and valley filling and reducing the capacity of the system standby unit.

At present, there are many achievements of optimized scheduling of VPP. Reference [2-4] proposed a VPP economic optimization or multi-objective optimization model with thermal power units, photovoltaic, wind power, etc. as power generation units. Reference [5] proposed a coordinated optimization scheduling model for multi-region VPP including wind power, photovoltaic hydropower and carbon capture units. Reference [6] also proposes an optimal scheduling model for multi-region VPP, at the same time, achieving optimal coordination between multiple energy sources.
However, in the existing achievements on VPP, public buildings are rarely studied. Therefore, based on the existing research, this paper uses the distributed energy resource inside the public buildings as the aggregation unit to model, and proposes the economic optimization scheduling model of VPP for photovoltaic, wind power, energy storage system and EV.

**Principles of Building VPP**

Compared with VPP built by a single building, VPP built by multiple buildings could complement each region's energy, coordinate the output of each region's power generation units and effectively reduce the net cost of VPP [5]. Due to the difference in the peak-to-valley period of different types of buildings, the role of the energy complementation is obvious. In order to analyze the energy conversion, storage and distribution in the energy system better, the concept of energy hub is generally adopted in the VPP structure [6]. Wind power, photovoltaic, EV and energy storage system in each public building are taken as an energy hub. The various aggregation units in the VPP are coordinated through the Energy Management System (EMS).

When the VPP is running, the EMS collects the information of each unit in the electricity market (EM) and the energy hub, predicting the EM price and the electrical load accordingly. Then based on the prediction and information of each unit in the energy hub, the EMS formulates a control strategy and sends scheduling instructions to control the operation of each unit. When there is a power shortage in a building, other building supply power to the building through the inter-area interconnection line. The structure of VPP in public buildings is shown in Fig. 2.
Scheduling Model of Building VPP

Objective Function

VPP targets the minimum net cost in a day. The decision-making volume includes the maintenance costs of wind power and photovoltaic, the maintenance costs of EV and transaction costs in the EM. The objective function is:

$$\min \sum_{t=1}^{T} \sum_{i=1}^{S} (C^G_{i,t} + C^EV_{i,t} - C^M_{i,t})$$

where:

$$C^G_{i,t} = \lambda_{PV} \times P^PV_{i,t} + \lambda_w \times P^W_{i,t}$$

$$C^EV_{i,t} = \lambda_u \times P^EV_{i,t}$$

$$C^M_{i,t} = \lambda_{EV} \times P^PP_{i,t}$$

Where: T is the total number of the scheduling period, and S is the number of public buildings. $C^G_{i,t}$ is the maintenance costs of photovoltaic and wind power. $C^EV_{i,t}$ is the charging maintenance costs of EV. $C^M_{i,t}$ is the transaction costs between the VPP and the EM. $\lambda_{PV}$, $\lambda_w$ and $\lambda_{EV}$ are the unit maintenance costs of photovoltaic, wind power and EV. $P^PV_{i,t}$, $P^W_{i,t}$ and $P^EV_{i,t}$ are the output of photovoltaic, wind power and EV.

Constraints

Constraints of Power Balance in Each Region.

$$P^PV_{i,t} + P^W_{i,t} + P^CM_{i,t} + \sum_{j=1}^{S} P^PV_{j,i} + P^CM_{j,i} + \sum_{i=1}^{S} P^WM_{i,t} + P^EV_{i,t}$$

Where: $P^PV_{i,t}$ is the power input from j-region to i-region in t-period, $P^CM_{i,t}$ is the power output from the i-region to the j-region in t-period. $P^CM_{i,t}$ is the load of the i-region in t-period.

Constraints of ESS.

$$0 \leq P^ESC_{i,t} \leq P^{ESC,max}_{i,t} \times \mu^ESC_{i,t}$$

$$0 \leq P^{ESD}_{i,t} \leq P^{ESD,max}_{i,t} \times \mu^{ESD}_{i,t}$$

$$0 \leq \mu^ESC_{i,t} + \mu^{ESD}_{i,t} \leq 1$$

$$S^{ESC,min}_{i,t} \leq S^ESC_{i,t} \leq S^{ESC,max}_{i,t}$$

$$S^ES_{i,0} = S^ES_{i,24}$$

Where: $P^{ESC,max}_{i,t}$ and $P^{ESD,max}_{i,t}$ are the maximum charge and discharge powers of energy storage system (ESS); Boolean variables $\mu^ESC_{i,t}$ indicates whether the ESS is charged, if it is set to 1, otherwise set to 0, and $\mu^{ESD}_{i,t}$ indicates whether the ESS is discharged, if it is set to 1, otherwise set to 0; $S^{ESC,min}_{i,t}$, $S^{ESC,max}_{i,t}$ is the upper and lower limits of the storage capacity of the ESS; $S^ES_{i,0}$ and $S^ES_{i,24}$ are the starting and ending values of the ESS for one day.
**Constraints of EV.** Although the interaction between the EV and the grid is two-way, since the EV user is usually only used for charging, this paper ignore the discharge process of EV and only consider the charging process.

\[ 0 \leq P_{i,t}^{EV} \leq P_{i,t}^{max} \times N_i \]  
(10)

\[ SOC_{i,t}^{in} \leq SOC_{i,t,n} \leq SOC_{i,t,n}^{max} \]  
(11)

\[ SOC_{i,t,n}^{max} \geq SOC_{i,t,n}^{down} \]  
(12)

\[ SOC_{i,t,n} = SOC_{i,t,n}^{down} + \frac{P_{i,t,n}^{out} \times \eta}{E_{max}} \]  
(13)

\[ t_{i,n}^{on} \leq t_{i,n} \leq t_{i,n}^{off} \]  
(14)

Where: \( P_{i,t}^{EV} \) is the charging power of the EV, \( N_i \) is the number of EV parking lots of i-region, \( SOC_{i,t,n} \) is the state of charge of EV, \( SOC_{i,t,n}^{max} \), \( SOC_{i,t,n}^{min} \) is the maximum and minimum value of the state of charge of the battery, \( SOC_{i,t,n}^{down} \) is the state of charge required for the end of charging of the EV, \( E_{max} \) is the maximum capacity of battery of EV. \( t_i \) is schedulable time of EV.

**Constraints of Interconnection Power.**

\[ 0 \leq P_{i,j}^{in} \leq P_{i,j}^{max} \times \mu_{i,j}^{c} \]  
(15)

\[ 0 \leq P_{j,i}^{in} \leq P_{i,j}^{max} \times (1 - \mu_{i,j}^{c}) \]  
(16)

Where: \( P_{i,j}^{max} \) is the upper limit of the energy transfer between the i-region and the j-region, and the Boolean variable \( \mu_{i,j}^{c} \) indicates whether the i-region is transmitted to the j-region in t-period, if it is set to 1, otherwise set to 0, the Boolean variable guarantees that the transmission direction of power is unique for any period of time..

**Case Study**

**Scheme Comparison**

Take a residential building and a commercial building to build a VPP. The residential building contains photovoltaic, ESS and 30 EV. The commercial building contains wind power, ESS and 20 EV. The study mainly proves two points: one is to verify the economic benefits brought by the coordinated optimization of distributed energy resource in public buildings; the other is to verify the economic benefits brought by the combination of multiple public buildings. In order to get better results, three different models will be used for simulation. The whole algorithm of this paper is implemented under the MATLAB 2016b platform, and it is solved reliably by the widely used commercial software package CPLEX12.6.
Table 1. Comparison of schemes.

| Scheme | Whether to participate in the EM | Whether to constitutes VPP | Whether to regional interconnection |
|--------|---------------------------------|---------------------------|-------------------------------------|
| 1      | √                               | ×                         | ×                                   |
| 2      | √                               | √                         | ×                                   |
| 3      | √                               | √                         | √                                   |

The results is shown in Table 2.

Table 2. Comparison of results.

| Scheme | EM revenue [yuan] | Maintenance costs [yuan] | Net costs [yuan] |
|--------|-------------------|--------------------------|-----------------|
| 1      | -7654.2           | 5676.5                   | 13330.7         |
| 2      | -7424.8           | 5729.7                   | 13204.3         |
| 3      | -7262.7           | 5729.7                   | 13027.9         |

From the above table, we can get the following conclusions:

(1) Compared with scheme 1, scheme 2 has an additional maintenance cost of 35.5 yuan, at the same time reduced the electricity purchase cost of 161.9 yuan, resulting in a total cost reduction of 126.4 yuan. This shows that the internal power of VPP is effectively utilized and coordinated with each other, which reduces the exchange of energy with EM and reduces the cost of purchasing electricity.

(2) Compared with scheme 2, scheme 3 further reduces the cost of purchasing electricity from EM. This is because the buildings in scheme 3 realize the interconnection of power, which makes the heavy load area supply power to the light load area, further reducing the exchange of electricity and reducing the total cost of 176.4 yuan. It shows that compared with the individual optimization of each building, multiple buildings VPP model could effectively use energy from different regions to achieve rational allocation of resources, thus achieving better economic benefits.

**Scheduling Optimization Result Analysis**

The optimization results are shown in Fig. 3 to Fig. 5.

![Figure 3. Power trading in residential building and commercial building.](image-url)
From 1:00 am to 9:00 am, commercial building has excess power generation and residential building is under-powered. Therefore, commercial building transmit electricity to residential building which reduces the energy trading between residential building and EM. From 10:00 am to 2:00 pm, commercial building purchase electricity from EM. And residential building transmit electricity to commercial building, because commercial building have large load demand and wind power cannot meet the requirements. From 3:00 pm to 0:00 am, both residential building and commercial building are under-powered, so there is no power transmission between buildings. Residential building and commercial building both purchase electricity from EM.

EV in residential buildings are charged from 22:00 pm to 9:00 am, because the electricity price is lower during this period, charging during this period effectively reduce the net cost of VPP and play an important role in cutting peaks and filling the valley. Commercial buildings have commuting time, so the dispatching time is not 24 hours a day, but 8:00 am to 21:00 pm. Therefore, EVs in commercial buildings charging at the period when the price of electricity is lower.

**Conclusion**

This paper implements a coordinated optimization model for VPP in public buildings, and achieves joint optimization among multiple buildings, effectively reducing net cost. We can draw the conclusion as follow:

1. The construction of VPP in public buildings is more effective in optimizing the distributed energy resource in buildings, which effectively reduce the energy exchange between buildings and EM and effectively utilize the energy in buildings, thus reduce the net cost of public buildings.
Through the regional integration of multiple buildings, the energy exchange between different buildings is realized, so that the light load buildings supply power to the heavy load buildings, and the power consumption of the heavy load buildings to the EM is reduced, thereby reducing the net cost of the VPP. Building a VPP in public buildings and realizing regional interconnection is a future development trend, this model is economical, flexible and reliable, and realize the rational allocation of resources better. It has a better application prospect in a big city like Shanghai.

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