Analysis On Typical Scenarios of Virtual Power Plants

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Abstract. Virtual power plant (VPP) is trading entities in the new generation of power markets that can rapidly aggregate various energy sources, create value by leveraging a large number of flexible resources, and bring volatility to the grid. To address some of the issues in the development of VPPs, this paper starts from the basic theory of virtual power plants, first summarizes the evolution of its definition, and ultimately refers to it as a power operation organization model that aggregates various decentralized resources, and collaborates in the optimization of the power system and power market transactions. Secondly, the existence architecture of VPPs is divided into a three-layer structure of energy, information, and value, explaining the entire process of how to transform energy into information and bring value. Subsequently, the basic and advanced characteristics and functions of VPPs are introduced. In the application scenarios section, the aggregation and types of distributed energy sources are first mentioned, followed by some typical domestic VPP cases and their related data. Finally, multiple operational and transaction models of VPP markets are introduced. In the third part, the problems of resource aggregation and coordinated control encountered by VPPs are summarized. Resource aggregation requires a large amount of data and continuous calculation, while coordinated control has three architectures: centralized control with the advantage of central decision-making, distributed control with a wide control domain, and the currently underdeveloped centralized-distributed control. Each has its own advantages, so this paper also analyzes the preferred solutions in different situations.

Keywords: VPPs, New power system, Distributed energy resources

1 Introduction

With the continuous integration of global renewable energy sources into power generation enterprises and the increasing proportion of new energy in the new power system due to the proposal of the dual carbon goals, the world has ushered in a new generation of energy revolution. However, along with this comes the significant randomness and volatility brought by new energy power generation to the power grid, posing a huge challenge to the traditional power grid that was originally focused on maintaining power and energy balance and stability [1]. VPPs are a platform formed by connecting distributed energy storage or energy storage devices that are opposite to traditional centralized power plants. They are used to regulate and control the

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randomness of power in the new power market. Currently, VPPs are a popular platform supported by power enterprises for resource aggregation and will also become a new power trading method to complement the traditional centralized power generation industry [2].

This article will elaborate in detail on the theoretical basis, application scenarios and challenges of VPPs, as well as optimization strategies. In the explanation of the theoretical basis, the author will first sort out the evolution of the definition of VPPs, presenting the understanding and definitions of their functions in various countries and regions from their proposal to the present. Secondly, the three-layer basic architecture of VPPs will be analyzed and expounded, demonstrating the corresponding functions of each layer, how they operate and ensure the stable operation of each layer. At the same time, the connection between the three layers and the decision-making logic between the upper and lower layers will be summarized. Subsequently, the typical characteristics and functions of VPPs will be introduced to ensure the completeness of the theoretical explanation in this article. The second part of the "three layers" will first review the known types and characteristics of distributed energy sources, introduce the classic cases of VPPs in China, analyze their advantages, and finally introduce the operation and transaction aspects, such as their profit models and transaction processes. The third part of the article will analyze and interpret the two difficulties encountered by VPPs, point out the problems and propose the author's suggestions for solving such problems.

2 Theoretical Foundation Analysis

2.1 Evolution of the Definition of VPP

In 1997, Professor Shimon, an American economist, first proposed the concept of VPP. It is defined as a virtual public facility whose function is to provide power services to consumers [3].

In 2000, Germany introduced in a law aimed at promoting the electricity market that it was a system capable of connecting and controlling distributed power sources, participating in electricity transactions and various services, and capable of establishing an overall operation mode by integrating the parameters of each power source.

In reference [4], a VPP is defined as an information and communication system that can aggregate controllable distributed energy units or active user networks and is connected in a direct centralized control mode; in reference [5], a VPP is defined as an energy internet that relies on a software system to remotely and automatically allocate and optimize generation, demand response, and energy storage resources.

In 2023, the China Electric Power Research Institute proposed in the standard, that it is a main body or system that realizes the aggregation, optimization and control of distributed power generation, energy storage and controllable loads [6].

Based on the above definitions and what I have learned, the author believes that a VPP is a system that is built on the existing power system and communication technology, and integrates control technology. It can aggregate and regulate distributed energy and energy storage, and is a system that participates in the optimization and trading of the new power system.

2.2 Basic Architecture

The three-layer network of the new power system consists of energy, information, and value. These three networks complement each other and promote each other. The VPP is the concentrated manifestation of this system in the user side and the field of distributed energy. Its value is also reflected in the power trading platform function of the VPP. Similar to the three-layer network of the new power system, the VPP also has an energy-information-value three-layer network [7].

The energy layer can calculate the adjustable load volume aggregated in devices such as energy storage equipment, air conditioners, and charging piles. After being aggregated and combined through the energy network, the physical load is transformed into existing data information that can be used in the information layer. Thus, the energy in various places becomes available and adjustable information, achieving the first information interaction.

All kinds of information are transmitted, integrated, encrypted, stored and finally aggregated to a higher-level centralized control platform for response and handling. This is the information layer.

The value layer is the electricity trading market. The information collected on the platform is sent to the market for transactions across a wide area. Once the transactions are completed, the instructions from the centralized control platform will be sent down to the grassroots network platforms, causing the loads to respond accordingly.

During this process, the rational optimization and utilization of resources are of utmost importance. During the optimization process, the grassroots level or the centralized control platform will automatically select distributed energy sources that can respond promptly, are efficient and high-powered, and are beneficial to the stability of the power grid. The reason why they are "optimal" has already been determined when the resources are aggregated.

In addition, the large power grid plays a crucial role in ensuring the rapid transmission of energy and information, and is the most essential infrastructure for a VPP. Basic structure of VPP is shown in Fig.1.

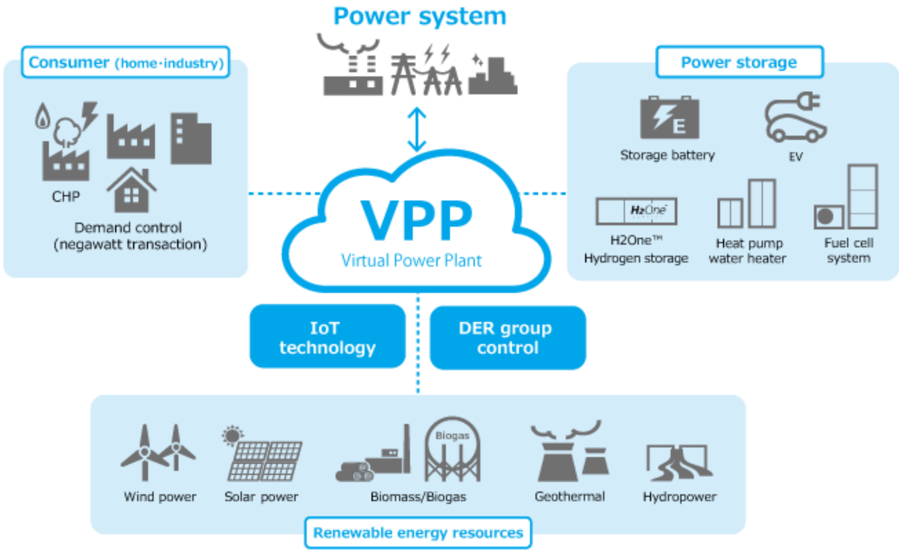

Fig. 1. Basic structure of VPP [7]

2.3 Karyotype Characteristics and Functions:

The functions of the VPP can be divided into two main parts: the basic functions and the advanced functions. The fundamental aspect involves the regulation, aggregation, coordination and optimization of resources. The advanced stage is when it acts as a resource aggregation entity and conducts transactions with the power grid and the electricity market. Within its basic functions, the equipment of the virtual power grid continuously monitors the operating status of all connected resources, generating data.

Resources are aggregated into a controllable entity, enabling various resources such as distributed power sources and distributed energy storage to receive control commands from distributed resources according to the optimized scheduling instructions and execute them promptly.

The optimization scheduling instructions are derived from high-precision short-term and ultra-short-term predictions made by different algorithms. In its advanced functions, its value ultimately lies in its interaction with the power market.

As a whole, the VPP quotes prices in the electricity market and conducts power trading. During peak electricity consumption periods, it reduces grid peak pressure by cutting loads or releasing energy storage, and compensates for the power supply gap.

At the same time, a portion of electricity is reserved. In case of sudden accidents in the grid, it provides emergency support for the grid, alleviates congestion, and avoids overloading of grid equipment. Thus, it significantly enhances the grid's ability to accommodate a high proportion of renewable energy and ensures the safe and stable operation of the grid.

3 Application Scenario Analysis:

3.1 Aggregation of Distributed Energy

The aggregation of distributed energy can leverage advanced information communication technologies, algorithms, and platforms to integrate scattered, diverse, and differently characterized distributed energy resources into a single, coordinated, and controllable entity. This entity can then participate as a whole in the electricity market and grid operation.

As one of the existing power trading market platforms for most distributed energy sources, the VPP has unparalleled potential and capability in resource aggregation. Starting from its own characteristics, the VPP widely aggregates distributed energy resources, whether scattered or integrated. These include photovoltaic power generation, wind power generation, and industrial adjustable energy storage. Photovoltaic power generation is found on the rooftops of customer groups and some industrial rooftops, providing clean and environmentally friendly electricity but dependent on weather factors and being unstable; wind power generation is located on mountain peaks and is also a clean energy source, but is also subject to natural factors. Industrial adjustable energy storage, such as charging stations, central air conditioning systems and public lighting facilities, are highly flexible and fully controllable, making them the key resources of VPPs. This indicates that the aggregated resources of VPPs have the characteristics of being widely distributed with small individual capacities and significant differences in characteristics. However, despite these drawbacks, it can actively support the distribution network, balance the electricity supply among multiple regions, flexibly aggregate resources with different characteristics, and through the integration of the Internet of Things, artificial intelligence and the market economy, organize the originally disordered and fragmented energy resources into a large-scale adjustable capacity, meeting the requirements of resource allocation, releasing huge system value, while improving technical and economic efficiency, reducing costs, and better serving the power grid [8].

3.2 Domestic Typical Cases

Although the VPP technology and architecture in our country started relatively late, they have developed to a considerable extent and now possess significant controllable energy and risk-resistance capabilities.

At the end of 2019, Jibei completed and successfully operated the country's first VPP demonstration project operated in a market-oriented manner. Its overall structure consists of a platform, two networks, and multiple applications. The platform refers to the VPP control platform; the two networks are the multi-energy flow network of the VPP and the IoT network; the multiple applications refer to the internal connections with the marketing department, power grid dispatching, and trading center, and the external encouragement of participation by energy production and supply enterprises, industrial and commercial or residential users, etc., sharing innovative achievements.

The total VPP capacity connected is 358,000 kW, and the maximum adjustable capacity is 204,000 kW [9].

In August 2022, the Shenzhen VPP Management Center was established, which is the first VPP management center in China. In the following year, it could connect more than 30 VPP operators, signed VPP construction cooperation agreements with units such as China Tower, China Telecom, China Mobile, China Unicom, and Huawei Digital Energy, and the access resource scale exceeded 1.5 million kW, with an adjustable capacity of 300,000 kW. It is currently the VPP platform with the highest data collection density, the most complete access load types, the largest direct control resources, and the most comprehensive application scenarios in China. In August 2023, the municipal-level VPP management platform in Jiaxing, Zhejiang Province, was officially launched and put into operation [9].

In December of the same year, it had connected multiple municipal load aggregation platforms and county-level VPP management platforms, with distributed resources of 4.9244 million kW, of which adjustable load resources reached 8.258 million kW, providing strong support for power supply during the cold and hot seasons. In the summer of 2024, in the face of extreme weather challenges, the Shanghai Electric Power Company carried out 32 demand response activities for VPPs, with the maximum response load reaching 704.3 MW [9]. These aggregation measures have led to a rapid increase in the total scale of VPP calls, alleviating the pressure on power supply during cold and hot seasons. They have made significant contributions to providing rapid and flexible regulation capabilities to ensure the security of the energy and power system.

3.3 Operational Transactions

VPPs are one of the entities participating in power transactions, so most of them have the ability to predict the market and operate.

VPPs can integrate results through precise market predictions, efficient trading strategies, and refined VPP data. They can utilize resources flexibly to respond to complex market environments, realizing their commercial value and promoting the healthy development of the power market. The complex market structure, including various trading scenarios such as the spot market and ancillary service market, ultimately achieves a win-win value outcome for all parties. In the spot market, the profit model, for example, VPPs adjust peak and off-peak electricity consumption to obtain regulation income and distribute it among the participating companies to generate profits, while also reducing electricity costs and lowering costs. If combined with charging piles, it can regulate load, save electricity costs, and also reduce costs. The ancillary service market is currently the main source of revenue for VPPs, and it can reserve power capacity, mainly through frequency modulation and responding to changes in the grid frequency and peak load reduction services, and then quickly respond or fill the power gap. Therefore, in summary, the operational transactions of VPPs are essentially high-quality algorithms that transform market uncertainties into predictability, form a large-scale capability, and convert into economic benefits. Ultimately, it builds an intelligent and efficient system.

4 Challenges and Analysis

4.1 Technical Bottlenecks

One major challenge for VPPs is how to aggregate a large number of distributed energy sources and coordinate their control. Even though VPPs have great potential for resource aggregation, they are merely potential [10]. Currently, there is no VPP in the market that can truly aggregate a large amount of information resources quickly, accurately, and efficiently and control and guide them to participate in the power market promptly. After analysis, the key to resource aggregation is to model and integrate the resources, which can only be achieved by analyzing their fundamental physical characteristics and distribution, and feeding this information into statistical and artificial intelligence algorithms to establish physical and mathematical models. The two models must be compatible and coordinated with each other to control the target in the highly variable distributed resources and perform aggregation. There are three types of collaborative control architectures: centralized control, distributed control, and centralized-distributed control. In the centralized control architecture, all decisions of the VPP are made by the central authority, achieving overall optimal operation. However, as the scale of aggregated resources increases and the number of variables increases, the computational difficulty increases, and the current system is difficult to support the high reliability and efficiency operation requirements of the new power system. In the distributed control architecture, the VPP is divided into multiple local control subsystems with control authority, and the VPP only provides inter-system information communication services. The computational burden is greatly reduced, but only local optimization can be achieved, and the operation of each local subsystem may be contradictory, resulting in a decrease in the overall competitiveness of the VPP.

In the centralized-distributed control architecture, the control system of the VPP consists of a centralized control center and local control systems. The centralized control center decomposes the overall task and issues it to the local control systems. The local control systems control the distributed resources under their jurisdiction based on the control task. Centralized-distributed control enables local systems to share resource calculations, which can accelerate the efficiency of internal optimization of the VPP and ensure overall competitiveness. However, due to the exchange of information between the local and central authorities, it is vulnerable to network attacks, communication bottlenecks, etc., causing congestion. It can be seen that the compatibility of centralized-distributed control is limited by the communication conditions.

4.2 Optimization Analysis:

When aggregating resources, in order to meet the different theoretical requirements of the power system, the VPP also needs to aggregate distributed resources from multiple dimensions such as time, space, and resource characteristics, providing the model with real information from multiple aspects and dimensions, accelerating the construction speed of the model, system control goals, and dynamically constructing aggregation models. When selecting the collaborative model architecture, it should be adapted to local conditions and based on one's own situation and external demands, choosing the most suitable control method. If it is a small-scale VPP, the information aggregation speed will be very fast, and there is no need to worry about computing power issues, so the most optimized centralized control is the first choice. If it is an extremely large-scale VPP, distributed control is the best choice, even though information interaction may lead to contradictions, each distribution will not suffer significant losses due to system errors, and local control rights are monopolized by the local authorities. As for centralized-distributed control, the author believes that before solving the compatibility problem of information between the central and all parties and the issue of insufficient computing power, this method is not as good as the other two. However, once it truly develops, through the shared computing power it provides, nearly independent transaction models, the decision-making processing of the central authority will be faster and more accurate, and the overall competitiveness will be stronger.

5 Conclusion

The VPP is a new generation of energy aggregation method, one of the organizations of the new power system, and an unattainable participant in the trading market. It has permeated every aspect of the power grid, making significant efforts for the continuous development and stability of the grid as well as its maintenance. As an operating entity with a three-layer structure model, its aggregation of distributed energy information can provide information resources assistance to the power grid. The information resources already organized by the interacting parties are used to make benefit decisions. It can mobilize distributed energy sources such as photovoltaic, wind power generation and air conditioners.

Up to now, many VPPs can also step forward when facing major grid security issues, bear the peak load, and provide great help for the stable operation of the grid in emergency situations. As one of the power trading entities, it can not only reduce peak electricity prices through its own advantages, form price differences for sale, but also reduce power generation costs and obtain more profits. The aggregation and coordinated control of distributed energy sources are one of the major difficulties of the VPP. The scope of data collection should be expanded, a large number of models should be established for comparative analysis, and the optimal solution should be continuously updated for energy aggregation. At the same time, the coordination control methods should be selected based on the size of the VPP it has mastered, to achieve local adaptation and maximize benefits.

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