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Coordinated Control Strategy within VPP for Operation Flexibility Improvement under Tertiary Frequency Regulation of Internal Power Deviations#

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ABSTRACT

A virtual power plant (VPP) plays a key role in integrating renewable energy and responding grid frequency fluctuations caused by the variable output of renewable sources. However, correcting frequency deviations doesn't represent maintain the power balance. VPPs must maintain stability through tertiary frequency regulation (TFR), often relying on power trading with the grid due to limited internal resources. To reduce this grid dependency, a coordinated control strategy is proposed to optimize the use of internal energy storage. It includes three methods: time-sharing to handle fluctuation timing uncertainty, demand analysis to address fluctuation power uncertainty, and resources selection to identify VPP resources for TFR participation. Simulations show that during the "longest duration of fluctuation", the strategy effectively stabilized the VPP and reduced power trading, decreasing the grid power from 32.5 MW to 3.8 MW through coordinated control of plan adjustments, over-limit power regulation. In the "highest power deviation of fluctuation" coordinated control of plan adjustments and over-limit power regulation reduce power trading from 43 MW to 9.7 MW and energy traded from 215 MWh to 48.5 MWh—a 77.44% reduction.

Keywords: Coordinated control strategy, tertiary frequency regulation, Virtual power plant, operation flexibility improvement

NONMENCLATURE

Abbreviations	
VPP	Virtual Power Plant
PFR	Primary Frequency Regulation
SFR	Secondary Frequency Regulation
TFR	Tertiary Frequency Regulation
BESS	Battery Energy Storage System
ILES	Interruptible Load Energy Storage
EMS	Energy Management System
CFPP	Coal-Fired Power Plant

1. INTRODUCTION

As renewable energy penetration grows, its inherent volatility presents significant challenges to grid stability [1]. Virtual Power Plants (VPPs) play a key role in integrating renewable energy and managing grid fluctuations [2]. Addressing the fluctuations in renewable energy output power has thus become a main focus in VPP research [3]. The process of mitigating output power fluctuations is referred to as frequency regulation [4]. A complete frequency regulation process typically includes three stages: primary, secondary, and tertiary frequency regulation. The goal of primary frequency regulation (PFR) and secondary frequency regulation (SFR) is to correct frequency deviations caused by power imbalances, bringing the frequency back within the dead band [5]. Tertiary frequency regulation (TFR), on the other hand, occurs once the frequency has stabilized, during which grid dispatch reserves and storage resources are used to make up for the energy shortfall caused by the deviation [6].

Current research on VPP frequency regulation focuses on the PFR and SFR. Efforts in these areas aim to optimize control systems and coordinate energy storage. Shu et al. [7] proposed a control strategy where energy storage aids in the PFR. The method addresses the issue of secondary frequency drops caused by using rotor kinetic energy from wind turbines during PFR. Qiu et al. [8] developed an optimized control model for VPPs, which leverages the flexibility of multiple energy storage systems to meet the frequency regulation demands of low-carbon power systems. Ranginkaman et al. [9] enhanced VPPs' frequency regulation capabilities by integrating thermal and thermostat loads and designing droop curves based on load characteristics. Wang et al. [10] introduced an AGC allocation optimization strategy

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based on data-driven key parameter predictions of frequency distribution, effectively narrowing the frequency distribution range and minimizing costs. However, even when PFR and SFR successfully restores system frequency within the dead band, this does not imply the elimination of power deviations.

As power deviations persist, VPPs face increasing power demands that must be addressed through backup energy storage, a process known as TFR. However, VPPs have limited storage resources compared to grid systems and often rely on power trading with the grid. While this method quickly addresses power deviations, it is economically inefficient and adds to the grid's regulatory burden, conflicting with VPP goals of integrating renewable energy, ensuring grid security, and enhancing flexibility. Gautam et al. [11] proposed a cooperative game theory-based reserve optimization method for distributed energy resources in tertiary frequency regulation, ensuring that primary and secondary reserve requirements are met at minimal cost. Salahshour et al. [12] explored the integration of electric vehicles into the power market as backup energy storage for tertiary regulation, which helps reduce the operational costs for market operators. Additionally, Gautam et al. [13] introduced a coalition game theory-based reserve allocation method that enables distributed switches to participate in TFR.

1: Existing literature mainly focuses on the transient process of frequency response, often using frequency curves as the evaluation metric. However, this approach is not fully applicable to the TFR process. To effectively respond to TFR and maintain the stable operation of a VPP, it is necessary to conduct research on the dynamic process.

2: Current research predominantly targets the optimization of VPPs' PFR and SFR control systems and strategies, with limited studies specifically addressing TFR. The TFR process is often simplified to power trading with the grid, which not only increases VPP operating costs but also adds to the grid's regulation burden.

This paper aims to propose a coordinated control strategy for the TFR process in VPPs to address internal power deviations and fill the research gaps identified. The key contributions of this study are as follows:

1. Coordinated Control Strategy in VPPs for TFR: The strategy coordinates various resources within the VPP to participate in the TFR process, reducing the reliance on grid power during the regulation stage. This approach enhances the flexibility and stability of VPP operations. When power demand is low, the strategy allows the VPP to operate normally and meet power deviation needs solely through internal resources.

2. Dynamic Simulation Model: A dynamic simulation model of the VPP system is constructed in APROS software. The study conducts simulations of the TFR process under the proposed control strategy and introduces evaluation metrics suitable for dynamic process analysis. The dynamic analysis can demonstrate the participating power and proportion of different resources in the VPP during the TFR process, providing a basis for the safe and efficient operation of the VPP.

2. MODEL DEVELOPMENT AND CONTROL SYSTEM FOR LARGE SCALE VPP

As shown in Fig.1, the composition of the VPP includes a 350 MW coal-fired power plant (CFPP), a 100 MW photovoltaic unit, and three sets of electric bus energy storage systems (capacity of 96.2 MW·h for every one) connected to the grid at different times. Additionally, it includes a 20 MW interruptible load backup energy storage system, a grid model, and a user-side load model. All generation and load models are based on actual existing units, and the capacity selection of the electric bus energy storage system is calculated based on the VPP's basic control strategy. The VPP model is constructed in APROS (a high-precision dynamic simulation software). All models have undergone both steady-state and dynamic validations, ensuring the modeling accuracy meets the requirements for subsequent simulations. For detailed information on the VPP's basic control strategies, modeling principles, and model validation, please refer to our previous research article [14]. The basic control systems in the VPP include the internal energy management system (EMS) and the PFR system. The control methods and calculation principles applied are well-established and widely used [15].

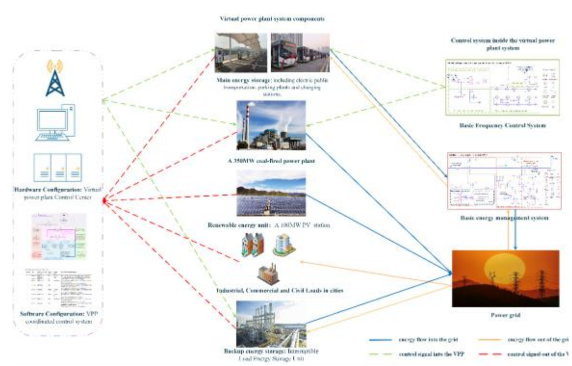

Fig. 1 Schematic diagram of virtual power plant model

3. COORDINATED CONTROL STRATEGY TO RESOURCES WITHIN VPP DURING TERTIARY FREQUENCY MODULATION PROCESS

The target of the coordinated control strategy is to manage the resources within a VPP to satisfy the power demands caused by deviations during the TFR process, aiming to minimize power trading with the grid. Given the randomness of renewable energy power deviations, including unpredictable start times and deviation values, the strategy's effectiveness hinges on its ability to adapt to these uncertainties. To achieve optimal control, the strategy incorporates three methods:

1. Time-Sharing Method: This addresses uncertainty in timing, helping the VPP to adjust based on when deviations occur.

2. Demand Analyze Method: This method focuses on addressing the uncertainty in power deviation values, ensuring that the VPP can respond to varying power demands.

3. Resource Selection Method: This identifies and selects the appropriate resources within the VPP to participate in TFR, ensuring that the right resources are utilized at the right time to maintain system stability.

3.1 Time-sharing method based on internal power deviation start time and VPP operation plan

The time-sharing method in the coordinated control strategy is designed to address the uncertainty in the start time of renewable energy power deviations. This method segments time based on three key factors: critical times related to renewable energy output power, the VPP power curve, and the VPP scheduling strategy.

1. Renewable Energy Output Power Critical Times: These reflect the characteristics of power fluctuations in renewable energy and include three key points: the time when power output begins, the time when power output ends, and the time when power output reaches its maximum.

2. VPP Power Curve Critical Times: These are related to the system's normal operational needs, including two key points: the time when VPP load demand exceeds 90% and the time when peak shaving period begins.

3. VPP Scheduling Strategy Critical Time: This represents the system's normal operation plan and includes one key point: the time when interruptible load energy storage (ILES) starts being scheduled. For specific scheduling strategies, please refer to our previous work in Reference [14].

The selection of these six critical points covers all potential times when power deviations might occur, transforming the randomness of the start time into five specific time periods. After determining these periods, the demand analyze method is proposed to address the uncertainty in power deviation values

3.2 Demand analyze method based on time period and power deviation variation characteristics

Although power deviation values are highly uncertain, they are constrained by the characteristics of the renewable energy output curve. This constraint is evident in two key aspects:

1. Initial transient deviation: The transient deviation value at the start of the power deviation is limited by the maximum output power of the renewable energy source at that time.

2. Dynamic deviation during regulation: Throughout the TFR period, the dynamic deviation value may fluctuate along with changes in renewable energy output. Specifically, at the start of power deviation, the deviation value will not exceed the maximum renewable energy output at that moment. As the power deviation continues, the deviation value is likely to vary with renewable energy output. When output falls below the deviation value, the deviation equals the real-time output power. If the deviation value remains unchanged during the power deviation period, it is possible to estimate the total energy demand for each period. Based on an analysis of the time segments determined by the time-sharing method, the following conclusions can be drawn:

1. Period from renewable energy output start to VPP load exceeding 90%: The maximum renewable energy output is low, resulting in a lower transient deviation value. but the deviation may last the longest and will cover the entire time when renewable energy generates output power. Therefore, the total energy demand has the largest possible range of variation.

2. Period from VPP load exceeding 90% to renewable energy output reaching maximum: During this time, the maximum renewable energy output increases, leading to a higher transient deviation value. The dynamic deviation is less influenced by renewable energy output, although the possible duration of the deviation is shortening. As a result, the total energy demand for TFR is higher in this period.

3. Period after renewable energy output reaches maximum: The transient deviation value peaks during this time; however, as renewable energy output declines throughout the period, the dynamic deviation is significantly constrained. Consequently, the total energy demand for TFR decreases substantially as the start time is delayed.

3.3 Resource selection method considering the power demand and VPP operation status

After addressing the uncertainty of power deviation start times and deviation values, it is essential to determine the dispatchable resources for the VPP to respond to TFR based on potential electricity demand at different times. Dispatchable resources are allocated according to the VPP's state during different periods, specifically whether it is in a peak-shaving period. A peak-shaving period is defined as a time when real-time power demand exceeds 90% of the maximum power demand. During normal operation, the VPP insist on the rule that more than 90% of the electricity in peak-shaving periods must come from energy storage and renewable sources. There are no power limits in non-peak-shaving periods. Thus, during peak-shaving periods, the output power of coal-fired units is limited, and energy storage discharges to meet the demand. However, these limitations can be adjusted under special circumstances, allowing excess power from coal-fired units and adjustments to energy storage discharge plans to be used as resources for responding to three-stage frequency regulation.

The types and characteristics of these resources are as follows:

1. Over-limit power regulation: During peak-shaving periods, the portion of CFPP output power exceeding 90% of the limit. When there is a significant power gap, CFPP can exceed the limit to meet VPP demands. The over-limit power is categorized into above 90% and above 95%, with the grid using these periods to assess VPP operational safety. Different levels of over-limit power have varying requirements from the grid.

2. Plan Adjustments: Modifying plans to change the charge and discharge amounts of energy storage during the specified period. This can be done at any time, but must consider the charge and discharge limitations of the storage. Energy storage can also be controlled to discharge during peak-shaving periods to meet three-stage frequency regulation needs.

3. Grid Power Trading: Includes adjusting the on-grid power by the VPP and conducting power transaction to reduce power deviation. On-grid power is the amount of power from CFPPs minus the power demanded by the VPP, with the remaining power directly on the grid. This power is available in non-peak-shaving periods and can be used when the VPP participates in TFR. Conducting power transaction is a major method to satisfy the VPP TFR power demands, available at any time but costly and increases grid regulation pressure.

Based on the usage requirements and limitations of different methods, the resource participation types for different states and periods can be determined, as shown in Fig 2.

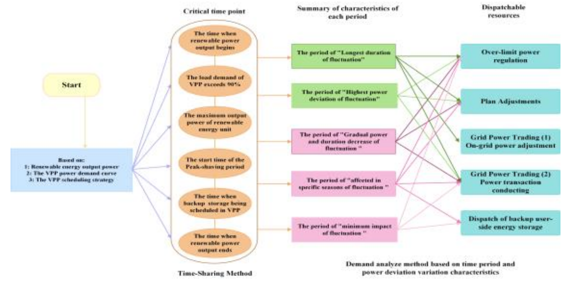

Fig. 2 The control logic diagram of coordinated control strategy

4. RESULTS AND DISCUSSION

This paper introduces a coordinated control strategy for a VPP aimed at addressing the TFR process in response to internal power deviations. The strategy employs three methods to tackle the uncertainties related to the timing and magnitude of power deviations. Additionally, it utilizes the internal resources of the VPP to participate in the frequency regulation process, thereby reducing the system's dependence on external grid power during this period.

4.1 Case description

In this study, the load demand curve is derived from Shaanxi Province's typical daily power demand curve in

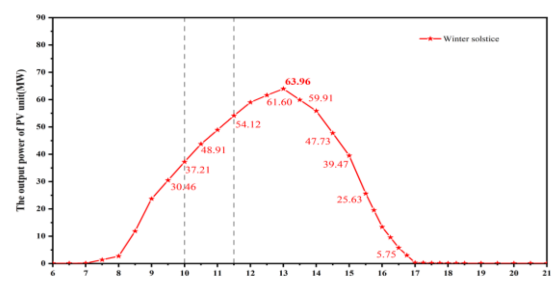

Fig. 3 The diagram of output power curve of the PV unit in the VPP in winter solstice

2020 [16]. The solar intensity is selected on the typical day of the winter solstice [17]. The power demand curve of the VPP system can be obtained. This is the power curve that the load and coal-fired units need to satisfy to maintain the normal operation of the VPP. The output power curve of the PV units is illustrated in Fig.3. The load curve and the power demand curve of the VPP are shown in Figs.4 and 5, respectively.

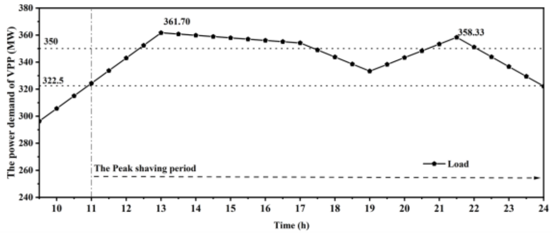

Fig. 4 The diagram of load demand curve in the VPP

Power deviations caused by fluctuations in renewable energy output can occur at any time during sunlight hours. Based on the selected operating conditions, the strategy can be analyzed for several

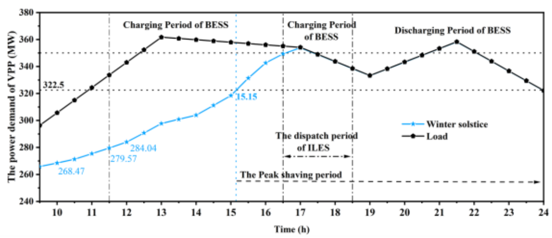

Fig. 5 The comparison diagram of power demand curve of VPP in the winter solstice and load demand curve

specific periods:

1. Longest duration of fluctuation: On the typical winter solstice day, sunlight begins at 7:00 AM, and the load demand exceeds 90% at 11:00 AM. During this period, the maximum output power of the PV units is 48.91 MW. The power deviation is limited by the PV output power constraints, so deviations during this period are less than 48.91 MW. However, the duration of these deviations is the longest among all periods. This scenario is referred to as the "Longest duration of fluctuation".

2. Highest power deviation of fluctuation: On the same day, the maximum sunlight intensity occurs at 1:00 PM, with the PV units' maximum output power reaching 63.96 MW. During this period, the potential power deviation significantly increases compared to the first period, with a substantial increase in the energy gap. This scenario is referred to as the " Highest power deviation of fluctuation".

4.2 Improvement of operational stability through resources response controlled by strategy

During the "Longest Duration of Fluctuation" period, the fluctuation start time is set to 10:00 AM, at which point the PV units' output power is 37.21 MW. The extreme condition is defined as: the fluctuation starts at 10:00 AM with a power drop of 37.21 MW and ends at 5:00 PM, when the PV units' output power reaches zero (on a typical winter solstice day). After the power fluctuation occurs, the start time for the peak shaving period is adjusted from 3:00 PM to 12:00 AM.

During this period, the VPP can engage its internal energy storage resources to participate in the TFR process, which includes plan adjustments and over-limit power regulation. By integrating power trading with these two resources, different dispatch strategies can be developed.

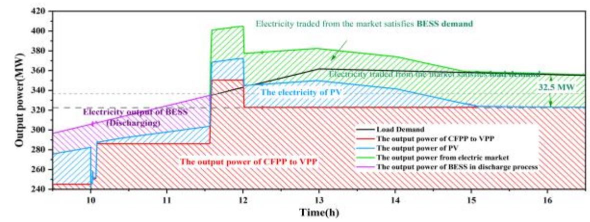

Fig. 6 Output power of units in VPP during TFR under "longest duration of fluctuation" scenario through power trading only

From the Fig.6, it can be observed that at 10:00 AM, the output power of the PV units experiences a step change. The VPP maintains initial system stability through PFR and SFR. However, as the process moves into the TFR process, the PV units' output power significantly decreases. The strategy compensates for this by adjusting the VPP’s on-grid power, thereby increasing support from CFPPs to fill the power deviation within the VPP. By 11:30 AM, the high-price period ends, and during the lower-price period, energy storage systems begin charging. The VPP reduces its on-grid power, and more power from the CFPP is scheduled to supply the VPP. However, at 12:00 PM, the peak shaving period begins, and the CFPP power dispatched to the VPP is capped below the 90% maximum load demand, which equates to 322.5 MW. To ensure sufficient charging power and maintain adequate energy in the BESS for the

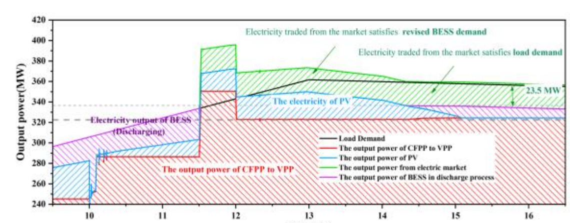

Fig. 7 Output power of units in VPP during TFR under "longest duration of fluctuation" scenario through power trading and plan adjustment

subsequent operations, power trading is initiated at 11:30 AM. The grid supplies the VPP with the energy shortfall caused by the fluctuations in PV output. After calculation, the grid needs to provide 32.5 MW of power until after 4:30 PM, resulting in a total energy demand of 162.5 MWh.

As shown in Fig.7, the electric bus energy storage was not only required to meet basic operational needs but also to maximize profits by electricity price differences, leading to higher energy demand during low-price periods in the original plan. However, through plan adjustment, focusing solely on meeting the basic operational energy requirements allows the VPP to better adapt to power deviations. With the help of plan adjustments, the power from trading of VPP is reduced by 27.7%, with the power demand lowered to just 23.5 MW.

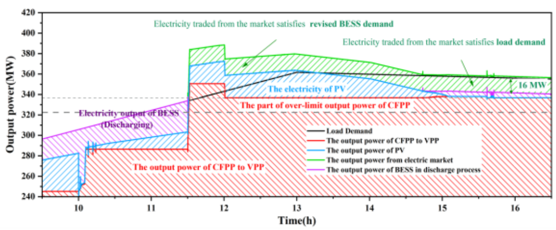

Fig. 8 Output power of units in VPP during TFR under "longest duration of fluctuation" scenario through power trading and Over-limit power regulation 95%

From the Fig.8 and 9, the over-limit power regulation compensates for energy shortages caused by fluctuations in renewable energy by increasing the output power that the VPP can receive from the CFPP. When the limit is increased to 95%, the VPP's power demand from the grid decreases by 50.8%. When raised

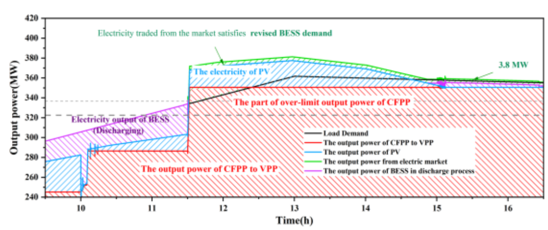

Fig. 9 Output power of units in VPP during TFR under "longest duration of fluctuation" scenario through power trading and Over-limit power regulation 100%

to 100%, the demand decreases by 88.3%. Compared to plan adjustments, over-limit power regulation more effective in reducing the system's reliance on grid power. This is mainly due to the longer duration of the over-limit process, allowing more energy to be supplied during this period.

4.3 Enhancement of operational flexibility through coordinated control of multiple resource

During the "Highest power deviation of fluctuation" period, the fluctuation starts at 11:30 AM with a PV output of 54.12 MW, and ends at 5:00 PM when the PV output is zero. This extreme condition reflects a power drop of 54.12 MW over this period. The timing coincides with the switch between high and low electricity price periods, causing fluctuations as scheduling signals overlap with frequency regulation signals. After completing the PFR and SFR processes, the VPP's power fluctuations stabilize, and the system moves into the TFR phase.

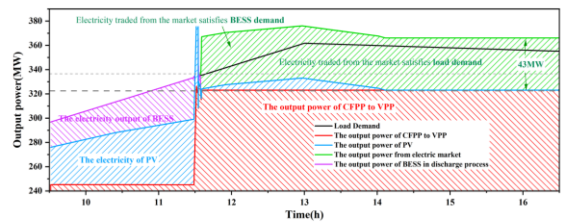

Fig. 10 Output power of units in VPP during TFR under " Highest power deviation of fluctuation" scenario through power trading only

When the power fluctuation occurs at 11:30 AM, after the PFR and SFR, the grid output power reaches its limit. As shown in Fig.10, the power deviation is compensated through power trading, with a trading power of 43 MW over a duration of 5 hours, resulting in a total energy supply of 215 MWh. This supplied energy not only meets the load demand but also supports the charging of the BESS, ensuring it can meet operational requirements while capitalizing on price differentials for profit.

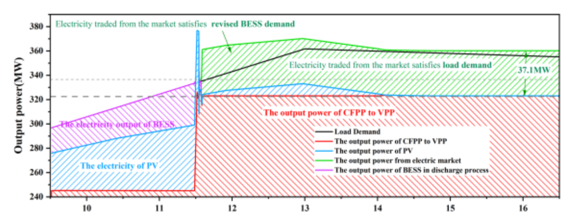

Fig. 11 Output power of units in VPP during TFR under " Highest power deviation of fluctuation" scenario through power trading and plan adjustment

As shown in Fig.11, the power provided by power trading is then reduced to 37.1 MW, with a total energy supply of 185.5 MWh. Plan adjustments reduce the energy demand by 29.5 MWh, leading to a 13.7% decrease in power. When the profit from electricity price differentials is less than the power trading price, plan adjustments effectively lower operational costs.

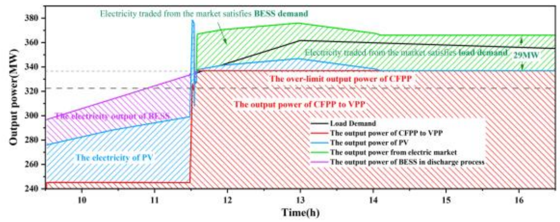

Fig. 12 Output power of units in VPP during TFR under " Highest power deviation of fluctuation" scenario through power trading and plan adjustment

As shown in Fig.12 and 13, at 95% Over-limit Power: The additional coal-fired power partially meets the load demand. The power obtained from power trading is reduced to 29 MW, with a total energy supply of 145 MWh, a 32.6% reduction compared to relying solely on power trading. At 100% Over-limit Power: The additional

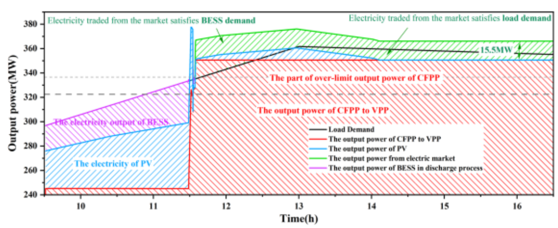

Fig. 13 Output power of units in VPP during TFR under " Highest power deviation of fluctuation" scenario through power trading and plan adjustment

coal-fired power not only meets the load demand but also provides energy for battery storage. The power obtained from power trading is reduced to 15.5 MW, with a total energy supply of 77.5 MWh, representing a 64.0% reduction compared to relying solely on power trading.

As shown in Fig.14 and 15, combining over-limit

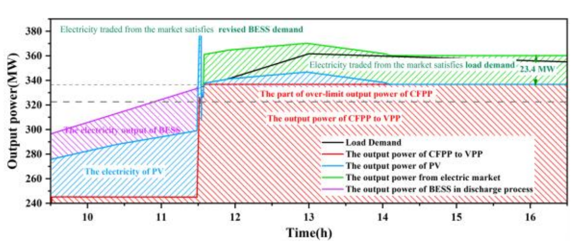

Fig. 14 Output power of units in VPP during TFR under " Highest power deviation of fluctuation" scenario through power trading and plan adjustment

power regulation with plan adjustments further reduces the power demand while increasing energy supply, thereby decreasing the VPP's reliance on power trading. When combine 95% over-limit power with plan adjustments, the power obtained from power trading is reduced to 23.4 MW, with a total energy supply of 117 MWh, a 45.6% reduction compared to relying solely on

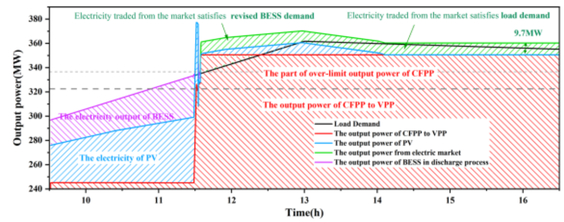

Fig. 15 Output power of units in VPP during TFR under " Highest power deviation of fluctuation" scenario through power trading and plan adjustment

power trading. When combine 100% over-limit power with plan adjustments, the power obtained from power trading is reduced to 9.7 MW, with a total energy supply of 48.5 MWh, a 77.4% reduction compared to relying solely on power trading.

5. CONCLUSIONS

This study proposes a coordinated control strategy to address internal power deviations in the tertiary frequency regulation (TFR) process of VPPs. The strategy reducing VPP's dependence on grid power during TFR and enhancing system flexibility in frequency regulation by efficiently utilizing power resources. The strategy includes three methods: the Time-sharing method and Demand analysis method address the uncertainty of renewable energy output in terms of time and power; Resources selection method allocates appropriate resources based on different periods and power fluctuations, adjusting according to operational needs. Simulation results show that during the longest duration of fluctuation, plan adjustments and over-limit power regulation reduced power trading in TFR from 32.5 MW to 3.8 MW, lowering grid demand by 88.3%. During the highest power deviation of fluctuation, these resources decreased power trading from 43 MW to 9.7 MW, reducing grid demand by 77.4%. This strategy effectively utilizes the resources of VPP to reduce the regulation pressure of power grid and lays a foundation for large-scale renewable energy development.

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REFERENCE

[1] Rasool M, Khan M A, Aurangzeb K, et al. Comprehensive techno-economic analysis of a standalone renewable energy system for simultaneous electrical load management and hydrogen generation for Fuel Cell Electric Vehicles[J]. Energy Reports, 2024, 11: 6255-6274.

[2] Mahmud K, Khan B, Ravishankar J, et al. An internet of energy framework with distributed energy resources, prosumers and small-scale virtual power plants: An overview[J]. Renewable and Sustainable Energy Reviews, 2020, 127: 109840.

[3] Zhao X, Chen H, Liu S, et al. Economic & environmental effects of priority dispatch of renewable energy considering fluctuating power output of coal-fired units[J]. Renewable Energy, 2020, 157: 695-707.

[4] Yan S, Zhang Y, Yin W, et al. Flexibility enhancement of renewable-penetrated power systems coordinating energy storage deployment and deep peak regulation of thermal generators[J]. Electric Power Systems Research, 2024, 231: 110354.

[5] Kim J, Muljadi E, Gevorgian V, et al. Capability - coordinated frequency control scheme of a virtual power plant with renewable energy sources[J]. IET Generation, Transmission & Distribution, 2019, 13(16): 3642-3648.

[6] Eto J H. Use of frequency response metrics to assess the planning and operating requirements for reliable integration of variable renewable generation[J]. 2011.

[7] Shu H, Wang G, Chen J, et al. Coordinated control of wind-storage combined with primary frequency regulation and variable coefficient based on wind speed and SOC[J]. Journal of Energy Storage, 2024, 87: 111356.

[8] Qiu D, Baig A M, Wang Y, et al. Market design for ancillary service provisions of inertia and frequency response via virtual power plants: A non-convex bi-level optimisation approach[J]. Applied Energy, 2024, 361: 122929.

[9] Son S, Lee J I. Feasibility and performance limitations of Supercritical carbon dioxide direct-cycle micro modular reactors in primary frequency control scenarios[J]. Nuclear Engineering and Technology, 2024, 56(4): 1254-1266.

[10] Wang Z, Wang Y, Ding Z, et al. Optimal AGC allocation strategy based on data-driven forecast of frequency distribution key parameters[J]. Electric Power Systems Research, 2024, 226: 109916.

[11] Gautam M, Lakouraj M M, Bhusal N, et al. Allocating reserves in active distribution systems for tertiary frequency regulation[C]//2022 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT). IEEE, 2022: 1-5.

[12] Salahshour R, Mirmoradi E, Ghasemi H. EVs participation in energy and reserve market considering primary and tertiary frequency regulation constraints[C]//2014 Smart Grid Conference (SGC). IEEE, 2014: 1-6.

[13] Gautam M, MansourLakouraj M, Hossain R, et al. Enabling Active Distribution Systems' Participation in Tertiary Frequency Regulation Through Coalitional Game Theory-Based Reserve Allocation[J]. IEEE Access, 2024.

[14] Tian Z, Wang Z, Chong D, et al. Coordinated control strategy assessment of a virtual power plant based on electric public transportation[J]. Journal of Energy Storage, 2023, 59: 106380.

[15] Eisazadeh H, Moghaddam M M, Alizadeh B. Optimal frequency response of VPP-based power systems considering participation coefficient[J]. International Journal of Electrical Power & Energy Systems, 2021, 129: 106881.

[16] Shaanxi Provincial Development and Reform Commission, Notice of Shaanxi Provincial Development and Reform Commission on Adjusting the Sales Price of Electricity in the Catalogue of Shaanxi Power Grid.

[17] OneBuilding meteorological database, a free climate data repository for building performance simulations and from the creators of EPW (EnergyPlus Weather Format). https://climate.onebuilding.org.