IET Generation, Transmission & Distribution

Review Article

Comprehensive review on structure and operation of virtual power plant in electrical system

ISSN 1751-8687
Received on 13th June 2018
Revised 27th September 2018
Accepted on 8th November 2018
E-First on 18th December 2018
doi: 10.1049/iet-gtd.2018.5880
www.ietdl.org

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Abstract: Constrained by low capacity and volatility, the rapid growth of distributed energy resources are obviously slowdown resulting in consumption difficulty and investment obstacle. As an effective integration and management technology, virtual power plant (VPP) becomes a suitable cornerstone of renewable energy future development. Based on current scientific research, this study intends to provide a detailed review of VPP from an internal perspective (e.g. energy resources' integration and operation) to the external aspect including participation in electricity market. In accordance with market diversity, different bidding strategy optimisation problems of VPP are formulated and their corresponding mathematical solution methods are literately reviewed. To extract characteristics of VPP, a comparison between energy management techniques (e.g. VPP, microgrid, active distribution network, and load aggregator) is conducted, where advantages and defects of VPP are also concluded. Meanwhile, realistic deployments of VPP in European electricity markets are elaborated to verify its feasibility and applicability. To better accommodate future development of renewable energy, a flexible structure and effective management mechanism of VPP should be built leading to its technical innovation and management reform. Possessed with the threefold development orientation, VPP will undoubtedly improve the utilisation and management of renewable energy sources as a coordinated and operational entity.

1 Introduction

Since the first industrial revolution in 19th century, the world stepped into the era of steam engines leading to the increasing consumption of primary energy resources like coal, wood etc. [1]. Along with the tremendous improvements in social productivity, environmental pollution and energy depletion highlight the importance of sustainable development. As a double-edged sword, steam power not only increases social industrialisation, but also results in great London fog and several other well-known environmental pollution incidents. In order to reach the equilibrium between social development and environmental protection, numerous scientists and engineers had been seeking alternative energy resources for decades.

As a result of the breakthrough in electric generation and transmission technology, the second industrial revolution provided us with a reliable and clean energy since 20th century [2, 3]. Unlike coal-based steam power, electric power maintains efficient productivity while enabling wide-area transmission. However, confined by generation technology at that time, most of electric demand was still fulfilled by the consumption of primary fossil fuels like coal, petroleum etc., which produced countless greenhouse gases and accelerated global warming. Although energy dependence on fossil fuels is still strong, electric power pointed out an alternative solution to improve social productivity while decreased the side effect on natural environment. With the increasing desire for clean and reliable energy resources, the emergence of renewable energy generation technology opens a brand-new era of energy revolution.

Unlike fossil fuel resources developed after millions of years, renewable energy sources (RESs) are abundant in nature and reproducible [4–6]. Judged from their features, the mature application of RESs are believed to be the ultimate solution to 21st century's energy crisis. However, the utilisation of RESs into power grid brings about new challenges, which may jeopardise power system safety and reliability if not handled properly [7]:

i. The deployments of large-scale wind turbine (WT), photovoltaic (PV), and hydroelectric power (HP) are usually located far away from load centre, which requires long-range cross-regional electricity transmission. Also, confined by expensive investment of storage devices, the excess quantity of renewable power will be curtailed if not consumed in time [5–8]. For example, in China, the electricity demand centres concentrate in eastern coast area like Shanghai, Beijing etc., while RESs are abundant in western inland like Gansu and Xinjiang province. The transmission distance is around 2000 km, which is obviously uneconomic and unreliable for power transaction. Meanwhile, the local demand in western China is not sufficient enough to utilise the installed capacity, which results in shocking curtailment of RESs in recent years [9].
ii. The intermittent nature of RESs originates from forecast difficulty of natural resources resulting in power imbalance and frequency deviation of power system. To neutralise RESs side effect, ancillary services should be deployed. Concerned by both economic and technical drawbacks, the willingness of power system to absorb RES is significantly decreased [10, 11].
iii. The penetration of distributed energy resources (DERs) in the user-side intensifies the volatility of load demand, which in turn aggravates the instability of power flow in distribution network (DN). To maintain the safe operation of DN, real-time monitor and dispatch by distribution network operator (DNO) is essential. Moreover, the low capacity of DERs makes them invisible during the day-ahead dispatch of DNO, while their tremendous influence upon power balance leaves DNO with tremendous challenge [12–15].

In order to approach the above challenges, numerous scientific researches were conducted and uncountable solutions have been proposed in recent years, among which the proposal of virtual power plant (VPP) is believed to be the most promising and effective method in DER management. Thus, this paper attempts to provide a comprehensive review of VPP from its internal energy resources dispatch to external bidding strategy in electricity market. Although there is no academic agreement in definition and structure of VPP, yet there still exist similar characteristics beneath different VPP models. Aimed at elaborating the current progress in

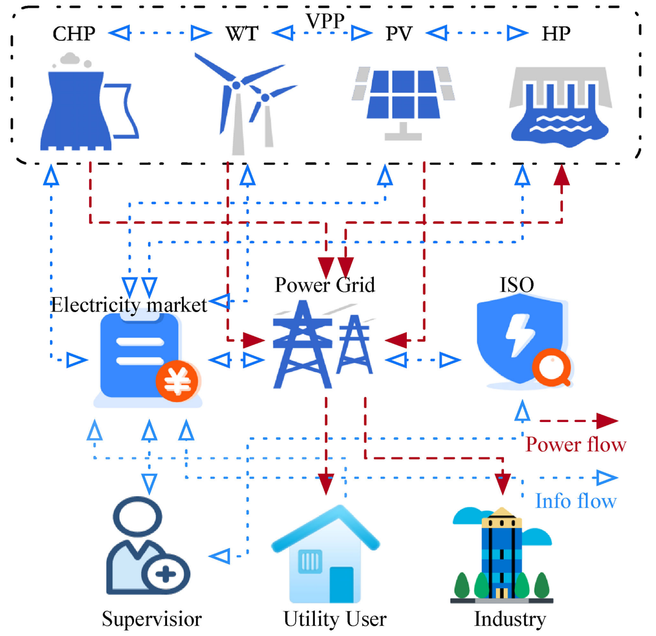

Fig. 1 *Topology of power system with VPP involved*

VPP and illuminating the future research orientation, this paper is constructed as follows: Section 2 summarises the internal energy resources integration and control method of VPP. The focus of Section 3 is concentrated on VPP participation in electricity market, which is not only confined in day-ahead market (DAM) but also extended to joint electricity market like real-time balancing market (RBM) and ancillary service market (ASM). In Section 4, a detailed comparison is conducted to illustrate the correlation and difference between different DER management techniques. In Section 5, several realistic applications of VPP in European electricity markets are illustrated and the performances of RES utilisation are evaluated individually. The future development and scientific research orientation of VPP are discussed in Section 6, where the conclusion of this paper is additionally presented.

2 Integration and control method of VPP

According to Section 1, the importance of RESs management, especially proper utilisation of DERs in the user side, formulates the foundation of power system safety and reliability. Thus, this section investigates the concept and framework of VPP, where the internal energy resources integration and control method are provided. In addition, the advantages and defects of different control methods of VPP are compared.

2.1 Concept of VPP

The concept of VPP originated from the framework of virtual utility proposed by Awerbuch and Preston [16] in 1997. Defined as a flexible cooperation between public utilities, its establishment enables individual participator to provide highly efficient power service to customers through virtually sharing of their private properties, which not only improves individual utilisation efficiency but also avoids redundant construction. To expand the original definition of virtual utility, VPP concept focuses on virtual aggregation of DERs, which mainly depends on mathematical combination of different cost curves of energy resources. As depicted in Fig. 1, VPP alters the traditional topology of power system by establishing information connection between variable energy resources and coordinating their generation profiles.

Although decades of years have passed since the first proposal of VPP, still there is no settlement in the commonly recognised definition of VPP. For example, VPP is defined as an energy Internet hub in [17], which relies on remote control technology and central optimisation. In contrast, the concept of VPP is confined to a loose coalition between same type of energy resources, like microgrids (MGs) in [18], combined heat and power plants (CHPs) in [19] or active distribution networks (ADNs) in [20], and hybrid energy system in [21]. Indeed, the above assumptions towards VPP are separately verified effective and reasonable, but the definition of VPP deserves further expansion. Therefore, the key characteristics of VPP could be concluded threefold [17–25]:

i. *Information gathering and processing*: In almost every VPP simulation model, information sharing and gathering constitute the foundation of VPP operation and optimisation. Although the control model of VPP could be either centralised or distributed, an information centre is established without exception. Thus, VPP could collect real-time information of its internal energy resources and process them efficiently in order to extract useful clues for its overall optimisation. To obtain and analyse enormous real-time information in time, sufficient communication bandwidth and high-speed processing algorithm are essential.
ii. *Geographical influence ignorance*: As the most distinctive characteristic of VPP, the geographical distribution defect of DERs is falling out of scope in VPP control and optimisation, which enables VPP to integrate DERs beyond the constraints of power grid topology. However, the power flow limitations are still valid and the generation profile of VPP should not violate safety regulations of independent system operator (ISO).
iii. *Dynamic operation and optimisation*: The integration of DERs by VPP is a dynamic profile instead of a static math combination, which means that the optimisation strategy proposed by VPP not only is the best economic operation schedule but also accounts for real-time operation status of power system. To reach the equilibrium between profit and safety, the dynamic decision-making procedure of VPP largely depends on real-time information gathering and processing.

Besides similarities in definitions and characteristics, energy resources integrated by VPP could also be categorised into two main types and seven subclasses as follows:

- RES:

    i. *WT*: Large-scale wind power stations with hundreds MW capacity are usually connected directly to the main power grid, which is beyond the control ability of VPP. However, low-capacity WTs deployed in the user side are suitable for VPP integration and operation.
    ii. *PV*: Centralised PV station is usually dispatched by ISO directly, thus low-capacity PV panels installed on the building roofs are perfect components of VPP.
    iii. *HP*: Large hydropower stations, like Three Gorges and Gezhou Dam in China, are connected to power grid directly to satisfy the base demand of load centre. However, the low-capacity pumped hydropower station around demand centre could be integrated by VPP as a competitive participator in ASM load shifting and peak shaving services.

- Conventional energy resources:

    i. *CHP*: With the popularisation of domestic heating system in North China, CHPs constitute the major part of domestic utility consumption in winter. To figure out the equilibrium between heat demand and utility consumption, the optimised control of CHP deserves further investigation under the framework of VPP.
    ii. *Energy storage system (ESS)*: The integration of ESS into VPP could undoubtedly enhance the reliability and quality of VPP's power supply, which could neutralise the power imbalance of intermittent RESs.
    iii. *Plug-in hybrid electric vehicle (PHEV)*: The popularisation of PHEV in public transportation magnifies the importance of power charging and discharging scheduling among PHEVs. Otherwise, the disorderly power charging and discharging actions could result in unpredictable load

fluctuation. Thus, through proper management of VPP, PHEVs' charging actions could be reasonably distributed and the adequate charging demand could also fill up the valley demand in the night period.

iv. *Demand response (DR)*: Known as demand-side management (DSM), DR focuses on the optimisation control of flexible load demand in reaction to utility price incentive. By the control of VPP, utility demand decrease could be equivalent to the power adjustment of distributed generator (DG), which could be combined with RESs as an effective reserve service to neutralise its volatility.

Above all, in order to effectively combine different sorts of DERs, the basic framework of VPP need to be established, which is provided in the next subsection.

2.2 Framework of VPP

As aforementioned, VPP aims at integrating different sorts of DERs into a coordinated operational entity, which could competitively participate in electricity market. In order to achieve this target, the basic framework of VPP should be built. Based on the characteristics of integrated energy resources and the key operation features described above, the framework of VPP could be divided vertically into two main parts, i.e. commercial VPP (CVPP) and technical VPP (TVPP) [22, 23]. Judged from their different purpose, VPP are categorised based on its internal and external features as demonstrated in Fig. 2. By dividing VPP's framework into two main parts, the target and detailed structure of each section could be summarised separately.

2.2.1 CVPP framework and operation: As indicated in Fig. 2, CVPP focuses on economic profit obtained from electricity market. As a merchant seeking for profit maximisation, the framework of CVPP could be expressed as a flexible profile of DERs' investment, which not only requires a precise marginal cost assessment of internal energy resources, but also depends on a rational evaluation of external market status [24]. According to Section 2.1, the marginal cost of RESs could be neglected compared with non-RESs, which guarantees the prior scheduling of RESs in VPP's power dispatch [25]. However, the potential risk beneath the volatility of RESs may compromise the expected economic profit, which highlights the importance of a reliable output forecast for the integrated RESs during dispatch cycle. Moreover, a rational estimation of load demand and other participators' bidding strategies could serve as foundation for CVPP's optimised bidding strategy in electricity market. So far, numerous researches have focused on forecast accuracy of RESs output and load demand [26–29]. Since this paper concentrates on VPP's structure and operation, RES forecast techniques and corresponding improving methods are falling out of scope of this paper. As a conclusion of the work in [30–33], the operation procedure of CVPP could be summarised as follows.

i. Based on a proper estimation of integrated RESs and non-RESs economic parameters (e.g. cost curve, forecast output), CVPP determines the priority order of its internal energy resources.
ii. CVPP collects and processes electricity market intelligence, which includes not only load demand but also the historical information of other participators' bidding strategy.
iii. Based on the information gathered above, CVPP formulates an optimised generation profile with an economic scheduling for each integrated energy resources. After that VPP submits bidding strategy to ISO as a unique entity.
iv. ISO collects bidding information and conducts market clearing/central dispatch. Depending on the market clearing results [e.g. accepted bids and market clearing price (MCP)], CVPP optimises the internal scheduling profile.
v. CVPP submits the final generation profile for power system safety check. If any technical violation discovered by ISO, CVPP should reschedule the generation profile and go through steps (iii)–(v) again until all safety regulations are satisfied.

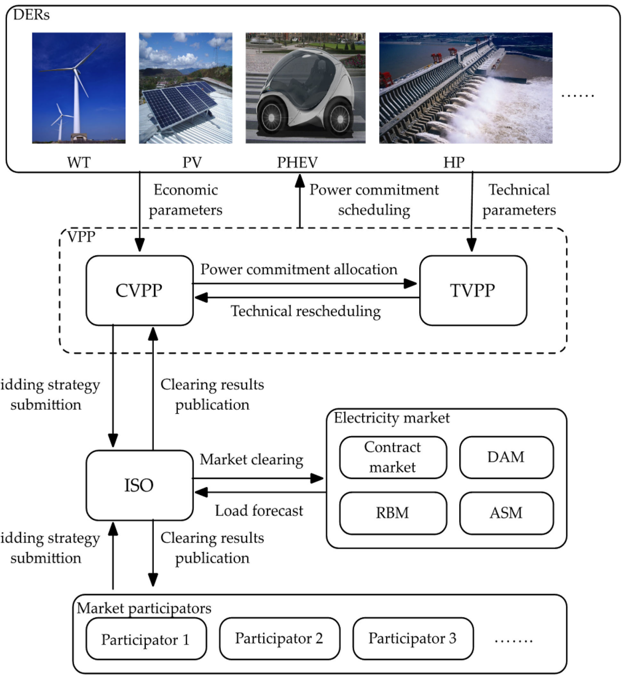

Fig. 2 *Basic framework of VPP*

vi. By the end of dispatch cycle, CVPP settles accounts with ISO and conducts internal profit redistribution based on each resources' operating performance and deviation punishment calculated by TVPP.

By following the above procedures, CVPP manages to integrate different sorts of DERs into a coordinated entity to participate in all forms of electricity market, which not only relieves the difficulty of DER management but also improves the utilisation of RESs in user-side.

2.2.2 TVPP framework and operation: As the other essential section of VPP, TVPP aims at ensuring the safety operation of VPP and providing real-time data of DERs' operation status. Unlike CVPP's profit seeking, TVPP shares the same responsibility of ISO, which mainly focuses on execution of power scheduling and performance of power balance [22, 23, 34]. The operation procedure of TVPP could be expressed as follows.

i. TVPP collects technical parameters of integrated DERs, which contain static technical information (e.g. DER's ramp limit, capacity limit etc.) and dynamic operation data (e.g. malfunction, operation status, output power, electricity storage situation etc.).
ii. TVPP submits overall technical parameters to ISO and receives related system safety regulation from ISO (e.g. power system topology, power flow limitations).
iii. Based on economic profile determined by CVPP and the system safety regulations provided by ISO, TVPP conducts VPP's security check and communicates with CVPP about necessary modifications.
iv. Once a security violation is detected by ISO, TVPP reacts in time to ensure the safety requirement and reschedules power commitment until all safety regulations are satisfied.
v. During execution of VPP's power commitment, TVPP supervises the real-time operation status of all DERs to maintain internal power balance, which could be achieved by altering controllable DERs' output in accordance with RESs' deviated output.
vi. By the end of dispatch cycle, TVPP calculates the exact output of each DER and delivers the settled output to CVPP for profit calculation and redistribution.

As a conclusion, the fulfilment of TVPP's responsibilities largely depends on the cooperation of communication technology

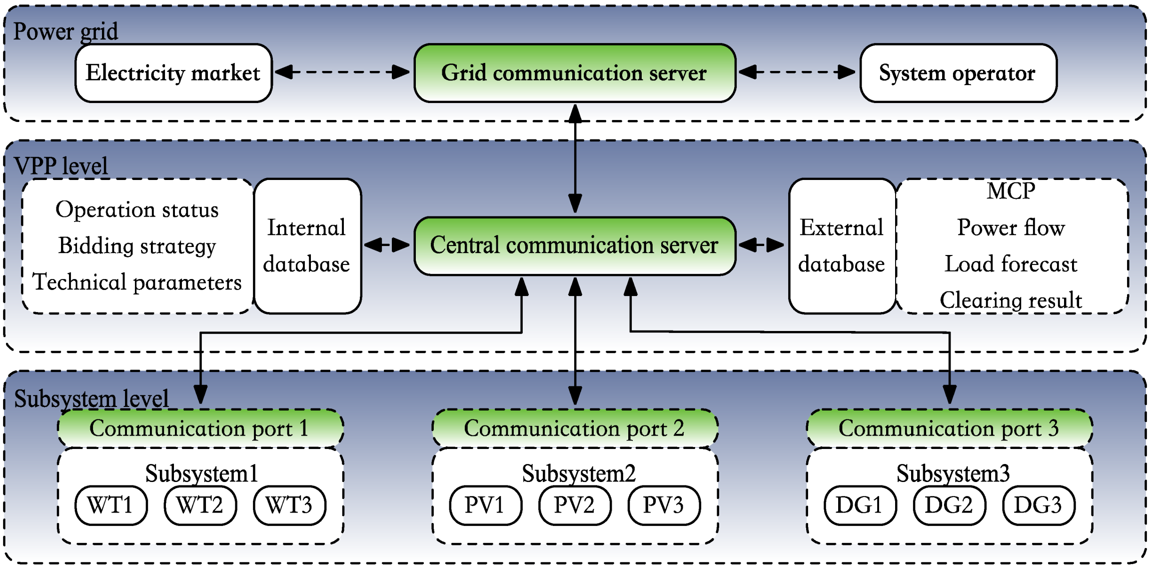

Fig. 3 *Structure of VPP distributed control method*

and situation awareness technology. Also, the topology of the power grid plays an important role in security check of TVPP, which directly limits the power flow in each transmission line. To satisfy the power flow limit, an internal rescheduling of power commitment will be conducted through the cooperation between CVPP and TVPP. Only the two distinctive aspects of VPP cooperating closely with each other could VPP operate efficiently and smoothly as a whole.

2.3 Internal control of VPP

Based on VPP's framework, a proper internal energy control method formulates the foundation of VPP's economic operation. To be a representative participator in electricity market, the integration of DERs and the corresponding control methods attract numerous scientific researches. From the perspective of VPP's control models, the internal control methods could be divided threefold, i.e. centralised control, distributed control, and comprehensive control. The characteristics of each control method are separately presented as follows.

2.3.1 Centralised control method: Compared with the other methods, the centralised control method enables VPP with ultimate control power. In [22, 23], a control coordination centre is established by VPP, which guarantees itself the absolute authority to dispatch all integrated DERs. As indicated in Fig. 2, the control topology of the centralised control method largely depends on communication network, which combines both internal and external information for VPP decision-making. Also, through the efficient communication channel, VPP power scheduling could be transmitted to generation terminal in time. Thus, the centralised control method enhances the integration of DERs and converts the original uncoordinated low-capacity DERs into a large-scale generation alliance. As discussed in [19, 25], by centrally coordinating large-scale generation capacity, VPP is regarded as a price-maker in electricity market due to its enormous influence upon market clearing procedure. Nevertheless, in [35, 36], VPP is defined as a price-taker due to its low capacity and limited influence. Although the market role of VPP may vary with its integrated resources, the growing influence of VPP upon the operation of power system and electricity market is gradually recognised.

Apart from the market competitiveness brought by VPP's growing capacity, the calculation burden of the centralised control method continues to multiply. Since all of DERs’ operation profiles are determined by VPP in centralised control method, numerous variables need to be considered during optimisation procedure, which aggravates the calculation difficulty of VPP control centre. As illustrated in [30], the internal centralised control method of VPP is usually a mixed integer non-linear programming (MINLP) model, which could be mathematically transformed into a mixed integer linear programming (MILP) through the Karush−Kuhn−Tucker (KKT) optimality conditions or dualistic transformation. After that, the bi-level optimisation problem between VPP and ISO could be transformed into a single-level problem and CPLEX or Python software package could be deployed to solve the problem. As for risk analysis, stochastic programming is introduced in [33] with a distribution of uncertainty probabilities predefined. Meanwhile, in [35, 37], the centralised control problem of VPP is also formulated into a MILP, where robust optimisation technique is deployed. Compared with stochastic programming, robust optimisation takes the worst scenario into consideration, which improves the reliability of optimisation results. Besides mathematical solutions mentioned above, the non-linear optimisation problem is considered when non-linear constraint exists. In [22, 23], the centralised control problem of VPP is defined as a unit commitment (UC) problem, where inter-temporal constraints prohibit the application of the mathematical method, thus heuristic algorithm like genetic algorithm (GA) or particle swarm optimisation (PSO) is applied to solve it. By introducing grid topology constraints, the UC problem is evolved into security constrained unit commitment (SCUC) problem as illustrated in [38, 39], where modifications are applied to original heuristic algorithms aiming at accelerating computation efficiency.

As a conclusion, in centralised control method, VPP is responsible for internal energy resources’ optimised scheduling, where sufficient communication bandwidth formulates the foundation of information gathering and decision-making. Confined by computation efficiency, centralised control VPP is limited at reasonable scale.

2.3.2 Distributed control method: Different from centralised control method, the structure of distributed control method is achieved by dividing VPP into two independent levels. As indicated in Fig. 3, the first level is the central communication level operated by VPP and the other is independent subsystem level operated by generator stakeholders. As presented in [40, 41], the independent subsystem schedules regional energy resources aiming at individual profit maximisation, while VPP provides information communication service between multi-subsystems. Since all energy resources are beyond control of VPP, the application of distributed control method helps avoid market monopoly problem brought by centralised large-scale VPP. Moreover, allocating decision variables into subsystems could also relieve massive calculation burden.

Despite the above advantages of distributed control, potential drawbacks are also pointed out by recent researches. Owing to the lack of centralised optimisation, the operation profile of each

Table 1 Comparison of functionalities, advantages, and defects of VPP internal control methods

Type of control method	VPP authority	Market position	Computation burden	Function of VPP control centre	DER compatibility	Market participation
centralised control [19, 22, 23, 26, 30, 37–39]	completely control	price-maker	large and concentrated	central communication and computation	complex and required algorithm updating	very competitive
comprehensive control [45–49]	partly control	mainly price-maker	normal and partly distributed	central communication and partial computation	ordinary with some modification required	competitive
distributed control [40–42, 44, 50]	self-control	mainly price-taker	completely distributed	only communication	flexible and open-access	less competitive

subsystem may contradict with each other, which decreases the overall competitiveness and aggravates market competition. As discussed in [40, 42], the coordination of selfish operation strategies requires heavy computation. However, the application of game theory could accelerate the convergence of uncoordinated strategies. However, in order to use game theory, original constraints must be converted into standard mathematical constraints and equivalent assumptions are applied to replace unconvertible constraints, which greatly limit the applicability of game theory in realistic situations.

Apart from game theory, distributed calculation algorithms are also applied to solve the distributed control problem. In [20], the subsystem is defined as an agent, whose main target aims at individual profit maximisation. Through the updating and sharing of each individual participator's bidding strategy, the multi-agent system could be effectively combined and reach an equilibrium, which formulates a loose corporation relationship among all engaged agents. The similar proposal could be found in [40] where a distributed primal-dual subgradient algorithm is proposed. By limited communication, individual decision-making of DERs is coordinated by VPP and reaches overall profit maximisation. In [41], a communication matrix is introduced to simulate the information exchange between independent DERs. By satisfying connectivity constraint, the local communication network is believed to accommodate distributed gradient algorithm and formulates the optimised equilibrium. In [43], a newly conceived control strategy called symmetrical components control algorithm is proposed in distributed energy system operation. While in [44], a non-ideal communication network is taken into consideration, which contains time delays, channel noises, and channel faults. By applying distributed primal-dual subgradient algorithm, the communication effectiveness and computation efficiency in the distributed scenario are both improved.

Above all, in the distributed control method, VPP acts as a communication server providing information exchange service. By deploying distributed algorithms, VPP helps formulate a loose alliance among independent DERs, which improves the overall benefit as long as the connectivity of communication network is satisfied.

2.3.3 Comprehensive control method: The comprehensive control method is also defined as central-distributed control in [45, 46]. Judged from definition, this method combines the characteristics of centralised control and distributed control. As indicated in Fig. 4, the comprehensive control method could be divided into two subcontrol levels while all sublevels are closely connected by VPP control centre.

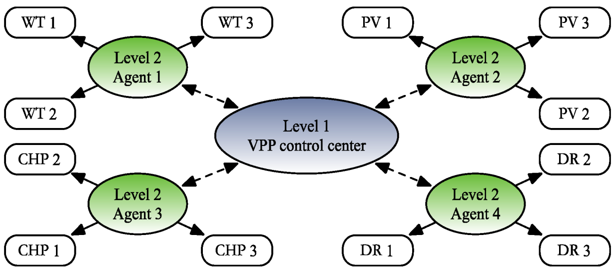

Fig. 4 *Structure of VPP comprehensive control method*

- *Level I*: VPP centralised control: In level I, VPP centrally coordinates the bidding strategy of each agent and formulates a final bidding strategy for market participation. Unlike the massive computation burden in centralised control method, the computation burden of VPP is allocated to agents in level II through the introduction of agent representative mode.
- *Level II*: Distributed agent control: In level II, distributed agents take the responsibility of regional optimisation and submit regional operation profile to VPP for overall optimisation. After receiving the final coordinated operation profile issued by VPP, all agents conduct regional rescheduling and proceed to execute.

As indicated in [47], by adopting agent representative mode, partial computation burden is allocated from level I to level II accelerating the convergence of VPP internal integration. Moreover, the existence of VPP central coordination avoids disordered competition and ensures the Nash equilibrium of agents' bidding strategies. By formulating linearised agent optimisation model, the computation speed of VPP central optimisation is tremendously improved.

Besides the above advantages, the drawbacks of comprehensive control method reside in communication and compatibility. Owing to the information exchange between two levels, the comprehensive control method is vulnerable for cyber-attack and the insufficient communication channel is likely congested [48]. To improve communication reliability, more physical investment and software modification are required. Thus, the compatibility of the comprehensive control method will be confined by the communication bandwidth.

To sum up, a comparison is conducted regarding the mentioned three control methods of VPP as presented in Table 1, where both advantages and defects are provided.

3 Market bidding strategy of VPP

In Section 2, the components and internal framework of VPP have been illustrated. To further investigate its external performance, this section focuses on VPP participation in electricity market.

3.1 Structure of electricity market

Originated from the second industrial revolution, monopolised electric corporations were established to maintain the reliable operation of large-scale power industry [51]. However, the operation efficiency of electric industry was compromised due to monopoly management. Aimed at transparency and equity, market reform was put forward around the world. In America, under the supervision of Federal Energy Regulatory Commission (FERC), several regional electricity markets, e.g. PJM Interconnection and California ISO etc., were established [52]. Since these regional transmission operators (RTOs) focused on the management of regional electricity market, the transmission and distribution responsibilities were taken by local DNOs. Based on this social division, electricity market operators were vulnerable against serious market crashes like the crises of California electricity market in 2001 and the New York grand blackout in 2003 [53]. Although potential risk lay beyond the imperfect market structure, the high efficiency and the reasonable electric pricing mechanism demonstrated the successful transformation in America electricity market [54].

Apart from America, an electricity pool framework was first built in England, which was upgraded into double auction market through the application of New Electricity Trading Arrangement (NETA) in 2003 and later applied to the whole Great Britain electricity market by the announcement of British Electricity Trading Transmission Arrangements (BETTA) in 2005. Recently, the British government put forward a new Electricity Market Reform (EMR) project in 2015 aiming at improving the pricing scheme and market efficiency [55].

Based on the commodity attribute of electricity, electricity markets could be categorised into three major submarkets, i.e. DAM, RBM, and ASM [35, 56]. Although the definitions and regulations of each submarket may vary from each other in different nations, still there exist common characteristics, respectively. In DAM, the majority of electricity commitment is scheduled to determine the benchmark prices for RBM and ASM [35]. However, with the penetration of DERs in the user side, more concerns focused on RBM, where proper DSM and power adjustments of DGs are conducted to neutralise power deviations. Despite power transactions in DAM and RBM, ancillary services like peak shaving and load shifting are equally essential for the safe operation of electric industry. By concentrating all forms of ancillary services into ASM, the classification of electricity submarkets becomes clear and reasonable. Thus, this section focuses on VPP involvement in these three submarkets, where a comprehensive bidding strategy of VPP in joint market is also presented at last.

3.2 Day-ahead market

Aimed at generation scheduling, the clearing procedure of DAM is essential for power system operation. For now, DAM clearing procedure could be categorised threefold based on different trading mechanisms. The participation of VPP in different procedures of DAM is separately illustrated as follows.

3.2.1 ISO central dispatch: Regarding this scenario, all market participators including VPP are required to submit bidding information to ISO within stipulated time. For every participator, the bidding information should simultaneously contain the willing generation offer and the corresponding cost curve. By the end of information collecting, power scheduling is conducted by ISO aiming at social benefit maximisation. Based on the proposed bidding information, ISO power scheduling could be formulated as a price-based unit commitment (PBUC) problem, where technical constraints of generators are introduced. Moreover, the above PUBC problem could transform into an SCUC problem if network power flow constraints are taken into consideration [57].

Unlike the other DAM mechanisms, price regulation is the most distinctive characteristic of ISO central dispatch. Currently, the electric pricing scheme of ISO central dispatch could be divided into peak-valley price, flat price, time of use price (TOU) etc. In [22, 23], the peak-valley electric pricing scheme is employed, where VPP demonstrates its ability in peak shaving and load shifting. However, in [46], flat pricing scheme is applied demonstrating the importance of VPP in stabilising electricity prices, especially in peak periods where the deployment of VPP spare capacity help relieve the tension of insufficient power capacity.

Despite pre-determined fixed price tariffs in central dispatch model, lots of researches focus on price uncertainty in TOU. As indicated in [58–60], TOU is acquired through forecast techniques. By taking historical price and load demand into consideration, the accuracy of price forecast is evidently improved. Despite linear prediction, DAM price is assumed to follow a specific distribution in [49], where point estimation method is adopted to handle the uncertainty in order to neutralise the bidding risk of VPP. Similar in [45], the DAM price distribution function is simulated based on historical data and Monte Carlo simulation method (MCSM) is applied to generate DAM price scenarios, which could be used to evaluate the applicability and potential risk of VPP's bidding strategy.

Since DAM tariff is unilaterally pre-determined by ISO, VPP acts as price-taker in ISO central dispatch. By adapting its proposed bidding strategy in accordance with variable DAM electricity price, VPP maintains its overall market revenue. As illustrated in [30, 61, 62], the optimisation problem between VPP and ISO is formulated as bi-level optimisation problem with power scheduling constraints coupling both levels. In the upper level, VPP aims at maximising market revenue while internal energy dispatch constraints are considered during its optimisation. Meanwhile, the object of ISO social cost minimisation and other technical constraints constitute the lower level. As an independent entity, VPP represents the integrated RESs in lower-level ISO dispatch, which makes RESs invisible to ISO power scheduling. Owing to power coupling and temporal coupling between the two levels, VPP overall output becomes the key factor in problem-solving. Despite heuristic algorithm, KKT conditions and duality theory are gradually becoming mainstream. By mathematically transforming the lower-level's optimisation problem into upper-level's constraints, the solving procedure of bi-level problem becomes linear and single level, which accelerates the computation efficiency.

Through bi-level optimisation technique, VPP is able to dynamically adapt its generation profile in accordance with ISO's dispatch plan. By searching the equilibrium point of the bi-level problem, the objectives of both levels could be reached simultaneously.

3.2.2 Competitive bidding: In contrast with ISO central dispatch, competitive bidding is completely market-oriented, where all participators submit individual bidding information to ISO containing willing capacity and anticipated price. After that, ISO conducts market clearing by calculating marginal price and determining marginal unit. As long as MCP is confirmed, the power commitment of each participator is confirmed as well. Regarding the different payment patterns, the competitive bidding could be split into MCP and pay as bid (PAB) scenarios.

In MCP scenario, power transactions set accounts by MCP during the entire exchange hours. Thus, the monetary income of each participator could be calculated by the product of realistic output and MCP. As illustrated in [47], the application of MCP increases competition of electricity market by encouraging the integration of DERs with price-incentive. However, without price regulation, MCP is partly dominated by potential market power, which reveals the uneven generation capacity between participators [30]. Owing to profit-seeking nature, the large-scale capacity participator could recklessly increase its proposed bidding price, which forces ISO to accept its bidding price for the sake of power balance requirement [19]. As a result, the dominant participator could achieve arbitrary profit, while utility consumers have to pay for the extra electricity bills due to the unfair competition in electricity market.

To avoid being manipulated by market power, PAB scheme is deployed in [50] as an effective method to improve the fairness of market competition. In PAB scenario, the market revenue of participator is equal to the submitted cost of their accepted power commitment. Thus, the intentional price raise proposed by market power could not manipulate MCP for its less competitiveness [63]. In addition, the surplus value obtained by ISO in this scenario could be allocated to cover up the necessary cost of ASM to maintain the safe operation of power grid.

Whatever payment patterns are deployed in electricity market, VPP could flexibly participate and adjust its bidding strategy in accordance with market regulation. In MCP scenario, the integration of low-cost RESs enables VPP to bid competitively with cost advantage. Since all energy transactions are set accounts by MCP, VPP market revenue is mainly determined by its accepted bids. Thus, the cost advantage of VPP guarantees itself the full integration of its possessed energy resources. However, in PAB scenario, market revenue is relevant to the bidding strategy, which requires VPP to rationally evaluate the potential monetary value of its possessed RESs and accordingly optimise its bidding strategy. Owing to the incomplete information environment, VPP has to simulate opponents' bidding strategy based on their historical data [50]. By establishing opponents' bidding strategy probability functions, chance-constrained programming could be deployed by VPP to optimise its bidding strategy at a certain confidence level

[62]. Also, cooperative game theory is adequate in solving multi-players market bidding [47].

As a conclusion to this subsection, the role of VPP in competitive bidding aims at price-maker, which could substantially influence the clearing procedure of electricity market [35]. However, if VPP integrates excessive DERs and DGs, market power could be possessed by VPP to jeopardise the fairness of market competition, which should be avoided through establishing proper electricity market regulations including price limit and capacity limit etc.

3.2.3 Bilateral negotiation: Along with market reform process, novel power trading categories are included in DAM bidding. Bilateral negotiation enables major market participators to reach trading contract voluntarily. For major power producers and consumers, bilateral negotiation helps avoid price uncertainty and maintains economic arbitrage for both sides.

As indicated in [24], RESs and DERs are not allowed to participate in ordinary bilateral negotiation due to their low capacity and high volatility. However, by the integration of VPP, RESs and DERs are united into a coordinated entity providing reliable and economic energy supply. Compared with thermal power dominated consumption, the introduction of RES into bilateral negotiation not only improves economic efficiency of both sides but also contributes to the utilisation of RES in power system. However, the uncertainty involved within RES volatility is incorporated into VPP internal dispatch through conditional value at risk (CVAR) analysis.

With more trading categories being applied in DAM, the flexible structure and diversified operation profile of VPP guarantees itself competitive advantage. Compared with traditional market participators, VPP bidding strategy combines the advantage of RES and controllable units, which also complements the insufficiency of each other.

3.3 Real-time balancing market

The establishment of RBM aims at providing real-time power adjustment to compensate power deviation. With the penetration of RES in power system, coal-based thermal generators have been gradually replaced by WT stations and PV panels. In China, RES constitutes 24% of power consumption with growth potential [6]. With the advancement of WT and PV technology, low-capacity RESs are widely deployed among utility users, which are usually lack of management and low efficiency. By the integration of VPP, user-side RESs could be properly managed and utilised by power system as a whole. However, the increasing penetration of RESs in the user side aggravates the difficulty of maintaining real-time power balance.

Owing to RESs' volatility, RBM becomes essential in power system operation. In RBM, the production and deployment of spinning reserve service constitutes its main trading category. According to the type of services, spinning reserve could be divided into positive and negative resources separately. Whatever the type of spinning reserve is, it is scheduled by ISO based on willing bidding information without exception. As for the compensation of spinning reserve, they could be traded at a fixed pre-determined tariff or incentive-motivated by ISO [22, 23]. Unlike the output-based revenue in DAM, the compensation for spinning reserve is provided as long as it is scheduled. Once the spinning reserve is called up to produce, an extra compensation will be paid to the service provider [36]. Thus, proper participation in RBM could improve the utilisation of generators' spare capacity, which would contribute to the safe operation of power system simultaneously. As presented in [64], the applicability of game-theoretic based multi-area spinning reserve trading mechanism is investigated, where VPP concept is deployed to virtually integrate distributed spinning reserve capacities. Furthermore, the participation of VPP in the integration of DGs' spinning reserve relieves the computation burden of ISO by decreasing computation dimensionality [65]. Meanwhile, the dominated reserve capacity of VPP may lead to the increase in spinning reserve trading cost, which contradicts with the establishment of RBM [66]. Thus, the spinning reserve capacity of VPP deserves up-limit restrictions for the sake of avoiding market power.

Despite supplying spinning reserve, VPP could also become a consumer of spinning reserve in extreme situations. Once the reserved generation capacity inside VPP is not sufficient enough to cover up RES volatility, VPP will have to purchase spinning reserve from RBM market in the case of power imbalance punishment [64]. To avoid the above situation, VPP must rationally optimise its power allocation in DAM and RBM in the case of emergence. Also, the bidding strategy of VPP in DAM should be rationally optimised to reach the equilibrium between economy and risk.

3.4 Ancillary service market

ASM targets at reliability and security of power system including power balance, frequency stability, reactive power compensation, power quality etc. [65]. Since power balance is mainly considered in DAM and RBM, thus ASM focuses on the other ancillary services instead. Take frequency stability as an example, it constitutes of two main methods, i.e. generators' primary frequency modulation and automatic generation control. The latter one requires the installation of special device leading to an additional monetary investment. Meanwhile, the deployment of primary frequency modulation only receives compensation for its operation cost, which is negligible compared with generation opportunity loss [66]. To further investigate the compensation scheme of opportunity cost, current research concentrates on cost apportionment instead of mechanism optimisation resulting in the fixed tariff of ancillary services [67]. Despite frequency stability, the compensation mechanisms of other ancillary services are also obsolete and hidebound. Thus, the willingness of market participators to provide ancillary service is jeopardised by the lack of market-oriented mechanism.

To improve the vitality and liquidity of ASM, the participation of VPP is the essential catalyst. In [68], the participation of VPP in ASM is simulated, where ESS and reactive power compensations are deployed to neutralise power quality problem caused by RES deviation. Since VPP focuses on the optimum bidding strategy in the energy market, the participation of VPP in ASM serves as a supplement to its spare capacity, which improves the power quality of RES and efficiency of DG at the same time [69]. With the perfection of ASM mechanisms, the participation willingness of VPP as well as other market participants will undoubtedly increase.

3.5 Joint market

Since no submarket could be independent from each other, the inherent correlation between each submarkets demonstrates the importance of overall strategy optimisation in a joint electricity market. In [22, 23], the bidding problem of VPP in a joint market of energy and spinning reserve is formulated, where a deterministic PBUC dispatch model of VPP and an SCUC market clearing procedure are considered. Solved by GA, the simulation results indicate that profit uplift could be achieved through a simultaneous joint optimisation of bidding strategy, which requires a repeated iterative calculation between the two problems. Also, the overall bidding strategy optimisation of VPP in DAM and RBM contributes to its transformation from price-taker into price-maker [70]. As illustrated in [68], the arbitrage value in spinning reserve service is sometimes more than the bidding income in DAM, especially when spinning reserve is in desperate need. The simulation results in [69] also verify the monetary payback and efficiency improvement of VPP in the joint market of DAM and ASM. To sum up, the participation of VPP in DAM constitutes its major market revenue while the supplement of RBM and ASM improves the operation efficiency of VPP by providing additional power demand.

Despite economic analysis, risk evaluation of VPP volatility is also a major concern in joint electricity market. In [30], the influence of uncertain parameters is analysed through the introduction of CVAR. While in [45], the risk-averse level of VPP is evaluated by value at risk (VAR) and taken into consideration during bidding strategy optimisation, where the case results verify the correlation between VPP's net profit and preferred risk level. Regarding the difficulty of measurement in VPP's uncertainty risk, a stochastic approach is proposed in [71] where the performance of VPP's bidding strategy is evaluated in MCSM scenarios, which have been refined through the application of backward reduction method. To incorporate potential risk in VPP decision-making, a chance-constrained programming method is deployed, where VPP risk-averse level is ensured through confidence level constraint [71]. As a supplement to mathematical calculation, stochastic optimisation is frequently adopted [61]. Nevertheless, robust optimisation is also applicable in VPP risk evaluation, which simulates the worst scenario of VPP volatility [37].

As a conclusion, proper integration of internal energy resources and allocation of available capacity in different submarkets constitute the participation problem of VPP in joint electricity market. To solve the above problem, numerous calculation methods have been deployed. Owing to the existence of mixed-integer parameters in VPP decision-making model, the majority models are assumed to be MINLP, which could be transformed into MILP and solved by mathematical methods [30, 37]. On the other hand, MINLP could be directly solved by heuristic algorithms like GA and PSO, but the solution optimality and computation speed are obviously decreased.

4 DER management techniques

So far, besides the concept of VPP, several other energy integration techniques have been proposed to improve the utilisation and management of DERs. In [72–79], the framework of MG is established, while in [80–87], the idea of ADN is believed to be more effective in DER management. Also, the wide application of DSM contributes to the emergence of load aggregator (LA) [88–95]. According to the current research, all DER management techniques have been verified effective with distinctive advantages. Although definitions and structures of the above techniques may be different from each other, still they share common characteristics, which will be summarised and compared in the following fourfold subsections.

4.1 Operation target

According to different models proposed in recent articles, the emergence of each technique initially aims at certain management objectives, which results in the diversity of structures and components. As a conclusion to the current research, the operation target lies within each technique could be summarised as follows.

4.1.1 Virtual power plant: The proposal of VPP essentially aims at encouraging DERs to participate electricity market [68]. As an effective method to integrate DERs into a coordinated entity, VPP technique helps upgrade DERs from price-taker into price-maker. Since the willingness of DER to be integrated by VPP correlates with the monetary revenue, which is expected to exceed the original profit gained by DERs if operated solely. Thus, under profit-incentive, VPP has to improve attractiveness by achieving more monetary profit from electricity market, which in turn enhances the competitiveness of VPP by escalating its available capacity [71].

4.1.2 Microgrid: Unlike the profit-seeking nature of VPP in electricity market, MG focuses on operating regional power grid [72], which contains a bidirectional power exchange instead of one-way selling. Confined by gird topology, power balance constraint and flow limit are essential in MG operation, which is even more challenging in MG island mode [73]. As a consequence of its diversified operation modes, MG mainly participates in RBM and ASM to maintain internal power balance instead of monetary profit in DAM. Thus, the function of MG is similar to DNO rather than a profit-seeking merchant like VPP.

4.1.3 Active distribution network: The concept of ADN originates from traditional DN, which is under control by DNO to accomplish the obligation of power distribution [80]. However, by introducing the concept of ADN to integrate user-side DERs, the power exchange between traditional DN and power grid becomes bidirectional [81]. Similar to MG, ADN mainly focuses on reliable operation of DN while improving the utilisation of DERs in the user side. To satisfy DN power balance demand, a solid corporation between ADN and ISO has to be built in the case of emergency. As a result of its destined nature, the control range of ADN is limited within DN topology with inferior compatibility.

4.1.4 Load aggregator: With the increasing desire for DSM, LA is proposed as an effective method to manage the orderly curtailment of load demand as well as the corresponding compensation [88]. Confined by its integrated resources, LA mainly participates in RBM and ASM. Unlike the above management techniques, LA operates solely to provide a reliable and coordinated load demand management. By optimising the curtailment schedule, LA technique enables flexible load to participate actively in peak shaving and load shifting. Also, the integration of low-capacity flexible load escalates the overall competitiveness of LA and increases the monetary compensation. Meanwhile, the proper allocation scheme of arbitrage could encourage the willingness of flexible demand to join LA management [89].

4.2 Component and structure

To correspond with different operation targets, the structure and component of each technique are distinctive as well. By formulating in diverse physical foundations, the above management techniques are able to fulfil desired responsibilities. Thus, the correlated relationship between components and targets could be summarised as follows.

4.2.1 Virtual power plant: Based on Section 2, the unique ability of VPP to integrate DERs regardless of geographical distribution enables itself to participate in electricity market at a grid-scale. As a foundation of its unique ability, accurate forecast and real-time data access are required, which mainly depends on communication technology and optimisation algorithm. As indicated in Sections 2.2 and 2.3, the structure of VPP is diverse in accordance with its control mode leading to its flexibility and compatibility.

4.2.2 Microgrid: Compared with VPP, the components required to formulate an MG are much more complex and rigid. To maintain MG operation in island mode, devices including ESS and controllable DG are essential. Also, confined by grid topology, MG operates in a specific region instead of whole grid resulting in its limited influence. To take the responsibility of ISO in island mode, a control centre is established to conduct internal power scheduling and ensure the safe operation of entire MG [74]. Meanwhile, in grid-connected mode, this control centre handles power exchange with ISO aiming at reducing power purchase cost of MG.

4.2.3 Active distribution network: As an extension of traditional DN, ADN maintains the components and grid topology of DN. Whereas, the integration of DERs into ADN and the establishment of DNO encourage ADN to participate in electricity market. To further accomplish the function of DN active management, ADN incorporates a lot of auxiliary systems including optimisation technique, communication equipment, power monitoring system etc. [82, 83]. However, confined by its limited capacity, ADN is not allowed to operate off-grid, which evidently differs from MG.

4.2.4 Load aggregator: Concluded from [90, 91], LA aggregates both conventional load demand and flexible load demand. To accomplish the task of load curtailment and compensation, communication instruments and control devices are equipped in the user side. Also, a central controller should be built in LA to conduct optimisation of load curtailment and re-allocation of corresponding monetary compensation. Since the function of LA solely focuses on the management of user-side resources, the generation side is falling out of scope by LA, which limits the adjustment ability of LA in extreme situations.

4.3 Operation mode

The operation modes of the four management techniques are different from each other due to the variable energy resources and topology structure. However, besides the above influential factors, the relationship between ISO and management technique also plays a critical role in defining the sublevel's operation mode. To identify the advantages and disadvantages of each management technique, the operation modes could be summarised as follows.

4.3.1 Virtual power plant: As illustrated above, VPP operates on behalf of DERs' overall profit, which mainly originates from bidding in electricity market. Although, in [22, 23], part of local conventional load is supplied by VPP. Yet, a major part of VPP available capacity is allocated to participate competitively in market bidding. Determined by its function, grid connection serves as foundation of VPP operation.

4.3.2 Microgrid: In most cases, MG gets access to the main grid through certain connection lines, which gives novel diversity to the operation mode of MG. Once the connection between the main grid and MG is cut off, MG transfers into island operation mode, where the internal power balance becomes its top priority. Otherwise, the power exchange between the two sides could benefit the power balance of both sides [75].

4.3.3 Active distribution network: Confined by its affiliation to the main grid, the operation mode of ADN is absolutely grid connected where the off-grid situation is not allowed due to its unaffordable generation capacity to keep the power balance within ADN [84, 85]. Besides the similarities in grid topology constraints, the major difference between ADN and MG evidently lies in the ability to operate off-grid.

4.3.4 Load aggregator: There is no doubt that the integrated load demand within LA is not able to keep balance if operating off-grid. To make full use of load aggregation, grid connection must be kept by LA. Otherwise, flexible load is useless if separated from the main power grid [90]. Thus, the operation mode of LA is confined to grid connected solely.

4.4 Market participation

To participate in electricity market, different management techniques aim at variable bidding objectives, which are related with inherent structure and components. However, the above four management techniques could participate in all aspects of electricity market. Still, the market performance of each technique could be diverse from each other.

4.4.1 Virtual power plant: Based on Section 3, the competitive nature of VPP enables itself to participate in all submarkets of power system. Since VPP is mainly consisted of low-cost RESs and DGs, the operation profile and the bidding strategy of VPP are more flexible than other management techniques, which in turn increases the competitiveness of VPP in DAM. However, confined by its limited capacity and uncertainty of RES, market performance of VPP is below expectation. Owing to low-accuracy forecast, profit obtained from DAM is evidently decreasing, especially when the power deviation of RES becomes severe [45]. Meanwhile, VPP market power gets strength along with the increase in available capacity, which converts VPP from a price-taker into a vital price-maker.

4.4.2 Microgrid: Similar with VPP, MG is also feasible to participate in all submarkets proposed above. However, confined by its network topology, the competitiveness of MG is crippled compared with VPP [76, 77]. By concentrating on power balance within MG, power exchange between MG and the main power grid is more complex, which includes two-way transmission and island operation. Compromised by its limited power output, MG is less competitive in DAM bidding. However, in RBM and ASM, the variable operation modes enable MG to operate and bid in advantage [78, 79].

4.4.3 Active distribution network: Like MG, ADN participates in DAM aiming at internal power balance, which restricts ADN as a price-taker instead of a price-maker like VPP. However, the integration of regional DERs and load demand by ADN increases its ability of power adjustment in RBM, which could be deployed as an abundant reserve capacity resource through proper DSM technology. Possessing quick response ability of load adjustment in emergency, ADN is verified to be suitable and competitive in RBM and ASM [86, 87].

4.4.4 Load aggregator: The participation of LA in electricity market focuses on power exchange in DAM, which intends to achieve a higher utility tariff through the combination of flexible load demand [92, 93]. Owing to its lack of generation ability, the influence of LA upon electricity market could only be achieved by load curtailment and shifting, which compromises its competitiveness in DAM [94, 95]. As a compensation for DAM performance, the flexibility of DSM enables LA to participate in RBM at an advantage position, which increases the monetary profit of LA and the stability of power system at the same time. As for the participation of LA in ASM, since the components within LA are confined as load demand, which has limited power in providing ancillary service, thus the progress of LA in ASM is not evident.

4.5 Comparison conclusion

Despite existing differences, lots of common characteristics could still be found among the above four management techniques. Firstly, their participations in electricity market improve the utilisation level of DERs, which are usually curtailed in the current electricity system due to their unstable output and variable nature. Secondly, the proposed four management techniques could be concluded as agent-based technology, which could relieve the computation burden and avoid dimension overflow if all DERs are under the direct control of ISO. To present in details, functionalities and characteristics of the four management methods are summarised in Table 2.

5 VPP application

Apart from theoretical research, numerous realistic applications of VPP have been deployed in electricity market to verify its feasibility and reliability. Since electricity market revolution originates from America and Europe, the regulations and structures of electricity markets in both nations have been constantly improved, which provides vital experience for VPP future research. Thus, in this section, typical applications of VPP in developed countries are introduced in details, where advantages of each project are summarised as well as potential drawbacks and insufficiencies.

5.1 Power matcher VPP

Aimed at improving power balance, the Energy Center of Netherlands (ECN) proposed an agent-based VPP model in 2007, which combines the technology of power matcher with the integration ability of VPP [96]. In power matcher VPP (PMVPP), a central agent is established to coordinate the operation of DERs and optimise overall bidding strategy in electricity market [97]. Since PMVPP constitutes numerous independent agents, the central agent of PMVPP is responsible to schedule the commitment of each subagent without the concern for their internal dispatch, which accelerates the computation efficiency of PMVPP.

In fact, PMVPP was deployed to the Netherlands power system to verify its applicability. Ten micro-CHPs were assumed under control of PMVPP through bi-directional communication channels. As a price-sensitive participator, the operation of PMVPP

Table 2 Comparison and summarisation of characteristics and functionalities of different management methods

Management method	VPP [22–71]	MG [72–79]	ADN [80–87]	LA [88–95]
operation target	increase competitiveness and improve profit as a utility	maintain stable operation and improve the integration of RES	stabilise power balance of DN and provide ancillary services	improve efficiency and profit of flexible demand curtailment
structure and topology	regardless of topology constraints and a control centre should be built	confined by network topology and power flow limit	limited by DN topology and a DNO control centre is necessary	regardless of grid topology and a control centre is essential
control strategy	centralised, comprehensive or distributed control	mainly centralised control	mainly centralised control	centralised or distributed control
market position	mainly price-maker, sometimes price-taker	mainly price-taker	mainly price-taker	mainly price-taker
market involvement	all forms of electricity market	limited participation in DAM, focused on RBM and ASM	limited participation in DAM, focused on RBM and ASM	mainly focused on RBM and ASM
competitiveness	very competitive in DAM and profit-seeking nature	limited competitiveness and focused on reliable operation	limited competitiveness and focused on reliable operation	very competitive in RBM and profit-seeking

concentrates on demand peak hours as a supplement for insufficient power. According to [98, 99], the utilisation of PMVPP in certain hours successfully neutralised the appearance of peak demand, which contributes to the smooth operation and stabilisation of power system.

5.2 Flexible electricity network to integrate the expected energy solution

In 2005, a cooperation research programme was proposed by eight European countries intending to verify the applicability of aggregating large-scale DERs into a virtual utility to provide clean energy for future Europe. Based on this target, project FENIX (flexible electricity network to integrate the expected energy solution) is carried out in British electricity market [100]. The construction of project FENIX could be divided into three subsections, i.e. FENIX Box, CVPP, and TVPP, where FENIX Box is responsible for the surveillance and control of integrated DERs. The market participation and economic analysis are handled by CVPP, while the safety regulation and operating status are ensured by TVPP as discussed in Section 2.2.

By applying the above three subsections into reality, a VPP with a capacity of 3 MW is established in Britain [101]. The operation results of this project demonstrate the feasibility of VPP in electricity market bidding and operation, where the coordinated operation within VPP promoted overall competitiveness in bidding procedure due to flexible and economic operation profile. In addition, novel communication standard and control algorithm is adopted in FENIX serving as a foundation for future development of VPP, which have been proven validated through the application in realistic environment [102].

5.3 Electrical vehicles in a distributed and integrated market using sustainable energy and open networks

Along with the growing utility demand of PHEV, the unpredictable nature of PHEV compromises the stable operation of power system, which facilitates the emergence of project EDISON (electrical vehicles in a distributed and integrated market using sustainable energy and open networks). In project EDISON, all PHEVs are assumed under control of EDISON VPP, which collects battery status and demand information of each EV and formulates a coordinated operation strategy of EDISON VPP to join into electricity market. To neutralise the side effect of PHEV consumption pattern, a centralised control strategy and consumption preference of EDISON VPP are provided based on historical operation information [103]. Also, the real-time power balance of EDISON VPP is achieved through the participation of RBM and internal energy scheduling control.

The realistic deployment of EDISON VPP was in Denmark by the year 2009. This application verified the applicability of VPP in management of PHEVs, which successfully optimised charging and discharging behaviour of PHEV through installation of realtime communication platform and centralised control centre. By optimising bidding strategy as a whole, EDISON VPP is able to decrease the utility cost of PHEVs' consumption and provide a reliable reserve resource to power system at the same time, which contribute to the stability of the main grid [104].

6 Conclusion and outlook

6.1 Conclusion

So far, the rapid development of RES technology accelerates the integration of DERs into power grid, which could be a double-edged sword to power system operation and management. On the one hand, RES provides clean and economic energy resource, which effectively solves energy crisis and environmental pollution problem. However, on the other hand, the inherent low-capacity as well as volatility of RES brings about uncertain influence upon stable operation of power system. By comparing different DER management techniques, flexible framework and diversified operation profiles contribute to outstanding applicability and unique distinction of VPP in grid-scale management of DERs, which also enable VPP to competitively participate in electricity market.

To sum up, this paper provides a detailed review of VPP regarding its structure and operation in electric system as well as its participation in electricity market. Given the penetration of DERs in power system, the application of VPP could successfully neutralise the challenges brought by RESs unstable outputs as well as management difficulties. As illustrated above, the concept of VPP could be divided into internal and external aspects. For internal aspect, the flexibility of VPP internal constitution contributes to variable integration methods, which also results in different control models of VPP. Based on the diversity of VPP internal control, the external feature of VPP is formulated as a competitive participator in electricity market aiming at profit maximisation. Furthermore, regarding different market structure, VPP could choose the most suitable bidding strategy optimisation technique to improve overall competitiveness in electricity market. The realistic applications of VPP in European countries also verify its applicability and effectiveness. Undoubtedly, the concept of VPP will play an important role in future power system, which could be the major breakthrough in optimisation and management of DERs.

6.2 Outlook

Despite its current progress, the future outlook of VPP research could be concluded threefold.

i. *Innovative structure*: Served as an agent between power resources and load demand, the core function of VPP lies within information gathering and processing. Currently, the structure of VPP is normally categorised into CVPP and TVPP depending on different operation targets. With the explosive growth of information in all aspects of electric industry, information service constitutes the basic foundation of VPP decision-making. Thus, a brand new sublevel IVPP (information VPP) could be added to VPP structure, where IVPP combines the other two sublevels by providing information exchange. Driven by big data, the establishment of IVPP will undoubtedly improve the perception of market information and opponents analysis, which will finally contribute to the increase in VPP overall competitiveness. Besides IVPP, more innovations could be applied in VPP structure to improve its compatibility and universality.

ii. *Diversified optimisation technique*: At present, VPP optimisation focuses on internal energy dispatch and external market participation. The optimisation techniques also concentrate on multi-objectives and risk evaluation. However, the market competition between multi-players deserves further investigation. To avoid cut-throat competition, cooperative game theory could be deployed, which depends on complete information and strategy coordination. Meanwhile, in incomplete information environment, Bayesian Nash equilibrium could be deployed by formulating the probability function of opponents' bidding strategy. Based on IVPP, the characteristics of opponents' bidding strategy could be analysed through data digging and support the decision-making of VPP.

iii. *Novel calculation algorithm*: So far, the convergence and computation speed of heuristic algorithms are obviously not suitable for realistic deployment of VPP. To mathematically solve VPP optimisation problems, KKT conditions, duality theory, and benders decomposition are widely applied, which transform the original MINLP into an MILP. By linearising the objectives and constraints of the problem, mathematical solutions including CPLEX, GAMS, and MATLAB could be deployed. Under the tendency of linearisation and mathematical solutions, novel calculation algorithms could be designed to improve the realistic applicability of VPP.

7 Acknowledgments

This work was supported in part by the National Natural Science Foundation of China (NSFC no. 51577116) and China Postdoctoral Science Foundation (no. 2017M611562).

8 References

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