Recent Advances on Distributed Dispatching and Control Algorithms in Virtual Power Plant

Hong Liu\textsuperscript{1a}\textsuperscript{*}, Zhiwei Li\textsuperscript{1b}\textsuperscript{*}, Pengde Liu\textsuperscript{1c}\textsuperscript{*}, Qing Cheng\textsuperscript{2c}\textsuperscript{*}, Yajuan Ji\textsuperscript{2d}\textsuperscript{*}, Jiping Qu\textsuperscript{1d}\textsuperscript{*}

\textsuperscript{1} China Energy Engineering Group Gansu Electric Power Design Institute Co., Ltd. 730050, China;
\textsuperscript{2} Sichuan Energy Internet Research Institute, Tsinghua University 610200, China
\textsuperscript{a}\textsuperscript{*}daoshulife@126.com, \textsuperscript{b}\textsuperscript{*}13519672585@126.com, \textsuperscript{c}\textsuperscript{*}@chengqing@tsinghua-eiri.org

Abstract—In recent years, the concept of Virtual Power Plant (VPP) is becoming more and more popular due to its capability of aggregating Distributed Energy Resources (DERs) and exploring its potential of providing flexibility to the existing power grid. Distributed algorithms have several potential advantages over centralized approaches, such as sharing limited amounts of information, performing parallel computations, and having strong robustness. In this context, this paper surveys the literature of distributed algorithms regarding VPP applications. Firstly, we established the VPP framework and operation control modes. Secondly, the basic distributed algorithms were given. Then, this paper studied distributed algorithms in VPP for economic dispatch, bidding optimization, autonomous control strategy within VPP, coordinated control strategy among multi-VPP, and interactive control strategy with grid side. Finally, the key issues and research potential were analyzed.

1. Introduction

In recent ten years, in response to the challenge of non-renewable fossil energy and the increasing demand for electricity, the Chinese government has published a series of policies to stimulate clean energy access to the power grid. With the increasing output proportion of various large-scale new energy power generation in the power system, the traditional power grid structure is facing a new change. The connection of a large number of distributed energy resources equipment and the intermittent connection of new energy resources have brought great technical challenges to the operation and control of the power grid\textsuperscript{[1-2]}.

In 1997, Dr. Shimon Awerbuch proposed the term "VPP" (virtual power plant) for the first time\textsuperscript{[3]}. In the context of in-depth reforms of the power market, VPP\textsuperscript{[4]} has gradually become an important supporting scheme for DER's (distributed energy resources) access to the power grid and participation in the power market. Through aggregation modeling of DER in different regions, VPP can realize the optimal and coordinated operation of the whole power plant while keeping the original operation mode of each distributed energy resource system (such as wind/solar/gas/heat, etc.)\textsuperscript{[3]}.

In actual operation, the internal members of VPP may include small-scale DER, micro-grid and even part of the distribution network, and the resources in VPP plant can be subordinated to different parties. VPP's participation in the power market and provision of auxiliary services is not only conducive to the safe and economic operation of the power grid side, but also beneficial for its members (such as energy storage equipment with fast response) to maximize market revenue\textsuperscript{[6]}.

Applying distributed algorithms
in VPP bidding optimization can achieve the purpose of protecting private information such as unit cost and operating parameters of different parties through decentralization. Most of VPP research focuses on bidding\(^7\)-\(^9\), aiming at improving the competitiveness of small DER in the power market. Under the framework of distributed control algorithm, the system can simultaneously decrease the construction cost of the communication network and ensure stability; the system has strong robustness, and meets the "plug and play" requirements of DER. In this paper, starting from the basic framework of VPP, the operation control modes of VPP are verified, and the main distributed algorithms are built. On this basis, the modeling optimization of distributed algorithms in VPP dispatching is analyzed, and then the application of distributed algorithms in VPP coordinated control is further discussed from three aspects: intra-plant autonomy, inter-plant collaboration and plant-grid interaction. The existing problems of distributed algorithms in VPP are discovered.

2. Writing Rules of Quantity
At present, even though scholars at home and abroad have respectively launched enormous and abundant researches on the virtual power plant, there has been no unified official definition of the virtual power plant framework\(^1\)\(^0\). This paper puts forward the following structure of VPP framework.

2.1 VPP concept
On the basis of keeping the original grid connection mode of each DER, VPP acts as a carrier that organically combines distributed generator sets, controllable loads and distributed energy storage facilities to realize integrated regulation and control on DER by applying advanced coordination control technology, intelligent measurement technology and communication technology; therefore, it participates in the power market as a special power plant and provides auxiliary service for the power grid, so as to further promote the rational and optimal configuration of resources.

The operation of VPP mainly relies on the software, and its core functions are realized by the energy management system (EMS) of VPP. EMS predicts the output and controllable load demand of each generator set by receiving and analyzing the real-time data from different remote measuring equipment, so as to make the optimal operation plan of DER and transmit regulation signals to manage the operation of each DER.

![Fig. 1 Basic structure for VPP](image)

2.2 VPP function division
Based on the functional characteristics, VPP can be divided into technical VPP and commercial VPP.

Technical VPP (TVPP) is a power plant aggregated by DERs located in the same geographical location; the influence of aggregated resources on power grid is mainly analyzed from the prospective of system. TVPP guarantees the safety of power grid operation by regulating the distribution of DER power flow, and provides auxiliary services for distribution network management and main network. TVPP mainly has the following functions:

Commercial VPP (CVPP) is a power plant that enables DER to participate in the power market and ensures the balance of transactions. It focuses on the economic operation of aggregated resources in
terms of the commercial benefit without dealing with technical problems. CVPP mainly has the following functions:

3. VPP Operation Control Modes
The VPP operation control modes can be divided into three categories: centralized control mode, hierarchical coordinated control mode and fully distributed control mode.

3.1 Centralized control mode
In centralized control mode, EMS of virtual power plant needs to master the complete information of all members (including operation parameters, marginal cost, etc.), so as to carry out the unified optimal computation. With the support of a robust communication network, each member receives and responds to the dispatching results released by EMS of the virtual power plant.

In terms of information interaction, EMS of virtual power plant communicates with each member node in a "one-to-many" manner, and the information of all member nodes is transparent to EMS. In terms of optimal control, only EMS of the virtual power plant performs all optimal computations, and this mode requires EMS of the virtual power plant to have control over all members. Under the centralized control mode, the VPP can achieve a global optimum, but EMS of virtual power plant bears the heavy computational load, thus requiring long computation time; as a result, the system has high requirements for communication network, and has poor robustness.

3.2 Hierarchical coordinated control mode
Under the hierarchical coordinated control mode, VPP is entirely modeled as a two-tier structure. The EMS of the upper virtual power plant needs to exchange partial information with each member node of the lower level, that is, after completing the corresponding optimization calculation in each iteration, the updated coordination variables are transferred to the lower level nodes. The lower-level member nodes perform parallel optimization calculation according to the coordinated variable value and self-information of each iteration, and at the same time, update the relevant information and feed it back to EMS of the virtual power plant.
In terms of information interaction, EMS of the upper virtual power plant carries out information exchange with the lower member nodes, but it only needs to master relevant partial information of each member. In terms of optimization control, the optimal computation is iteratively completed by EMS of the virtual power plant and each member node, and the overall optimization time can be shortened by parallel computing among members, and the specific scheduling plan is controlled by the decision-making of members themselves. This model improves the computation efficiency through the decomposition of optimization problems and parallel computing, but it still has high requirements for the reliability of the communication network.

3.3 Fully distributed control mode
In the fully distributed control mode, VPP can be reckoned as a multi-agent system, and its member nodes are all single autonomous intelligent agents. Through the information interaction between adjacent nodes and the iteration of local optimal computation, the intelligent agent finally reaches the overall consensus of VPP.

![Fig. 4 Fully distributed control mode](image)

In terms of information interaction, each intelligent agent needs to communicate with adjacent nodes in a "point-to-point" manner; therefore, information security is higher, and information leakage caused by an attack on EMS of the virtual power plant can be avoided. In terms of optimization control, intelligent agents make decisions through multiple iterations of local optimization, eliminating the controlling force of EMS in the virtual power plant.

Due to its high sensitivity and low robustness, the centralized control mode is not suitable for the VPP framework to which large-scale distributed resources access. Compared with fully distributed control, the hierarchical coordinated control mode is more widely applied in VPP currently. However, the two-tier interactive control mode may cause communication delay and affect overall operation efficiency.

4. Optimal Computation of VPP Dispatching
As an important approach for DER to participate in the power market, VPP has improved its market competitiveness on the basis of integrating complementary dispatching DER. In light of economic efficiency, in order to improve the overall operating efficiency and realize the optimal configuration of its internal resources, dispatching optimization related issues should be researched as a focus. This section will analyze and have research on the application of distributed algorithms in VPP dispatching optimization.

4.1 Experiments on distributed optimization algorithm
Centralized optimization algorithm has been widely applied in the power system. The central controller collects all the information and executes the corresponding optimization decision uniformly. However, with the expansion of the power system scale, and due to communication restrictions, network topology
time varying and information privacy issues, the advantages of distributed optimization algorithms have become more useful. Under the distributed optimization algorithm, the original problem is decomposed into many sub-problems and submitted to the nodes for collaborative solutions. This algorithm can greatly reduce the communication demands and adapt to the dynamic changes of the system.

Mathematically, distributed optimization algorithms can be concluded into two categories: original decomposition method and dual decomposition method. In the original decomposition method, the decision variables of the problem are divided into local variables and coupling variables. The sub-problem first fixes the coupling variable to optimize its local variable, and then the primal problem optimizes and updates the coupling variable. In the dual decomposition method, local problems are handled in a relaxed manner, and local optimization is coordinated by updating dual variables to achieve global optimum. Among them, the commonly used dual decomposition algorithms are derived from Lagrange Relaxation and its derivatives, or computed from the optimality of Karush-Kuhn-Tucker (KKT) condition.

(1) Dual gradient ascent

When Lagrange function optimizing problems has the following separable structure, dual gradient ascent can be used to decouple.

\[
\begin{align*}
\min_x &\sum_{i=1}^N f_i(x_i) \\
\text{subject to} &\, \sum_{i=1}^N A_i x_i = b \\
L_i(x,y) &= \sum_{i=1}^N L_i(x_i,y) \\
L_i(x_i,y) &= f_i(x_i) + y^T A_i x_i - (1/N)y^T b
\end{align*}
\]  

In order to keep the constraint conditions consistent, decoupling in this structure is realized by copying multiple Lagrange subfunctions to share dual variables. Based on the relationship between the original problem and the dual problem, the gradient ascent method is used to solve the problem iteratively, and the specific mathematical formula is shown in (2).

\[
\begin{align*}
x_i^{k+1} &= \arg\min_{x_i} L_i(x_i,y^k) \\
y^{k+1} &= y^k + \alpha^k \left(\sum_{i=1}^N (A_i x_i^{k+1}) - b\right)
\end{align*}
\]  

In each iteration, \( x_i \) is obtained through an independent solution of each decoupling sub-problem; as a shared dual variable, the updated computation \( y \) is undertaken by the central coordination layer. Even when dealing with convex optimization problems, the dual decomposition method cannot guarantee its convergence in theory, and the specific analysis of convergence depends on the selection of step length \( \alpha \) and the characteristics of optimization problems.

(2) Alternating direction method of multipliers (ADMM)

Similar to dual gradient ascent, the difference of ADMM algorithms lies in its need for the augmented form of Lagrange function. ADMM is a common method for solving separable convex optimization (mostly in the case of decision region partitioning), which is featured by good convergence and strong robustness. Its mathematical model is as follows.

\[
\begin{align*}
\min &\, f(x) + g(z) \\
\text{subject to} &\, A x + B z = c \\
L_\rho(x,z) &= f(x) + g(z) + y^T (A x + B z - c) \\
&\, + \frac{\rho}{2} \| A x + B z - c \|^2 \bigg) \\
x^{k+1} &= \arg\min_x L_\rho(x,z,y^k) \\
z^{k+1} &= \arg\min_z L_\rho(x^{k+1},z,y^k) \\
y^{k+1} &= y^k + \rho (A x^{k+1} + B z^{k+1} - c)
\end{align*}
\]  

When \( f(x), \ g(z) \) are both convex functions, the ADMM algorithm can prove its convergence in theory. When the accuracy requirement is high, the convergence rate of ADMM is usually slow and depends on
the selection of $\rho$ value. At the same time, the ADMM algorithm can also be applied to nonconvex problems, but it cannot guarantee the convergence of results.

Traditional ADMM algorithm needs the central coordination layer to update the dual variable $\hat{y}$, while ADMM with proximal message passing (PMP) is a fully distributed algorithm. In each iteration of this algorithm, information is collected and updated between connected nodes, and the convergence of convex optimization problem is inherited through information transmission between adjacent regions.

(3) Multi-parameter projection decomposition

Multi-parameter projection decomposition is often used to deal with large-scale linear or quadratic programming problems, and it is an original decomposition algorithm. Because the information exchanged between sub-problem and primal problem is more effective, the convergence rate of this algorithm is much higher than that of related algorithms based on Lagrange Relaxation, for example, ADMM. Its optimization problem often has the following mathematical model:

$$
\min_{x_1, x_2, y} \left[ c_1(x_1, \xi_1) + c_2(x_2, \xi_2) \right]
$$

subject to

$$
A_1^i x_1 + A_2^i y + b_i 
$$

$y \in Y$

(4)

The mathematical models of primal problem (5) and sub-problem (6) after decomposition are as follows:

$$
\min_{y \in Y} f^*_i(y; \xi_1, \xi_2) = f_1^i(y; \xi_1) + f_2^i(y; \xi_2)
$$

$$
\begin{align*}
\min_{x} & \quad c_1(x; \xi) \\
\text{subject to} & \quad A_1^i x + A_2^i y + b_i
\end{align*}
$$

(5)

(6)

According to the multi-parameter (linear/quadratic) programming theory, the optimal function of sub-problem $f^*_i(\cdot; \xi)$ is a subsection (linear/quadratic) convex function about $y$, and the optimal subobjective function of each subsection corresponds to the polyhedron partition of zone $y \in \bar{Y}$.

4.2 Optimization of VPP economic dispatching

When VPP performs internal dispatching optimization, information such as DER operation parameters, marginal cost and predicted data is used. When the members in the plant belong to different operating entities, based on the privacy and commerciality of the information, it is difficult for the virtual power plant EMS to master all the information and control of all the members, so the traditional centralized optimization algorithm is no longer suitable for this scenario. The distributed algorithm only needs to share limited information to realize the optimization of economic dispatch, and at the same time, it can provide autonomous decision-making rights for plant members with different dispatch preferences, which is conducive to realize "plug-and-play".

In the hierarchical distributed algorithm, the upper scheduling center needs to coordinate the optimization results of the lower nodes to achieve convergence in the continuous iterative update.

In the fully distributed algorithm, information is only exchanged between adjacent nodes, and the participation of the coordination layer is not required. In Literature [11], the ADMM with near-end messaging was adopted to realize the complete distributed optimization of dynamic economic dispatch; simulation results show that the algorithm has low requirements on computation and communication, with fast convergence rate and strong robustness.

The consistency theory is a renewal and consensus mechanism, which can be divided into discrete time and continuous time. Based on the communication network topology, for information exchange and update among adjacent nodes, the common mathematical model is as follows:

$$
x = L x
$$

$$
x[k + 1] = D[k] x[k]
$$

(7)
For the economic dispatch, in most of the literatures, the micro increasing rate (Lagrange multiplier of optimization problem) of DER cost is adopted as the consistency variable. In Literature \[12\], a distributed Newton algorithm based on consistent algorithm information interaction was adopted to solve the multi-regional economic dispatch problem, which has quadratic convergence and obviously improves convergence rate.

4.3 Bidding optimization in VPP market
One of the main characteristics of VPP is to integrate DER to participate in the power market and provide auxiliary services, so as to realize the optimal allocation of resources in the whole network. The bidding optimization is a problem of external dispatch between VPP and the power grid. In the power market, VPP is a special power plant as a whole, and its internal members and topological structure are unclear on the power grid side. VPP needs to aggregate the cost characteristics of its internal resources and participate in the market bidding.

Adopting the internal economic dispatch algorithm in the last section, the characteristics of DER portfolio cost can be obtained, which can be used as the reference benchmark for VPP market bidding. In Literature \[13\], the bi-level bidding model of the VPP dynamic game was solved in a distributed manner based on the first-order KKT optimal conditions.

5. Coordinated control of VPP operation
In addition to relying on advanced technologies such as intelligent measurement and information communication, for the actual operation of VPP, a major difficulty needs to be solved: how to optimally decompose and execute the market clearing results and auxiliary service market real-time signal VPP. In the short run, VPP needs to coordinate among intermittent new energy, fluctuating load and "plug-and-play" resources to quickly respond to dispatching instructions, so as to realize achieve perfect complementarity among internal resources and the efficiency and economy of the whole power system.

5.1 Autonomous control in the plant
The VPP concept emphasizes overall performance. In order to complete the contract content of power market clearing, it is necessary to coordinate and control the comprehensive energy in the virtual power plant EMS in the actual operation. When the VPP communication network is limited by bandwidth, especially in the case of a large number of internal members, it is difficult to achieve effective control in the plant by the centralized method. Using the distributed control algorithm, the VPP communication fault tolerance rate increases, and the system robustness is enhanced. In addition, under the distributed control algorithm, different from the VPP direct control mode of the centralized algorithm, the internal members of the VPP can master the independent decision-making power.

![Autonomous control structure within VPP](image)

Fig. 5 Autonomous control structure within VPP
Renewable energy in VPP usually needs to operate in coordination with energy storage equipment, dispatchable generator sets, and controllable loads due to the uncertainty of its output.

VPP can also provide auxiliary services for the power grid by implementing the distributed control algorithm of in-plant resources. In the literature \cite{14}, the sub-gradient projection decomposition algorithm is used to control the DER in the plant to provide primary frequency modulation service, and an example shows that this method is suitable for certain communication time delays. In Literature \cite{15}, the distributed frequency modulation strategy of DR was discussed. In Literature \cite{16}, based on the collection of electric vehicle frequency deviations, a consistency-based filtering algorithm was proposed to complete the frequency modulation application of large-scale electric vehicles under limited communication.

5.2 Inter-plant collaboration control
Due to factors such as the intermittency of renewable energy and load volatility, a single VPP is extremely easy to cause unbalanced power in the plant. Multi-virtual power plants (multi-VPP) can implement joint dispatch by establishing bilateral contracts and other trading modes to complement the resource flexibility of both sides. VPP with different subject ownership can establish the inter-plant cooperation model of cooperative game to realize the win-win situation of power market economy. When multiple VPPs are located at different nodes of the power grid, it is necessary to further consider the operation safety of the distribution network.

5.3 Interactive control of plant and network
When VPP aggregates a large number of DERs to connect to the grid, it is necessary to take into account the security constraints and economic operation of the entire grid. For example, the excessive output of distributed generator sets in VPP may cause overvoltage problems in the distribution network. In this case, the power grid and VPP should coordinate to carry out the voltage optimization control. In the paper, the generalized Benders decomposition method is used for optimal cutting, and its convergence rate is better than traditional optimization methods.

6. Conclusions
Under the research topic of deepening the reform of the power market and the incentive policy of clean energy grid connection, the research upsurge of VPP has been set off at home and abroad. Because of the distributed nature of VPP internal resources, distributed algorithms have many advantages when applied to VPP.

Starting from the basic framework of VPP, this paper discovers the application of distributed algorithms in VPP one by one from five aspects, i.e. internal economic dispatch, external bidding
optimization, in-plant autonomous control, inter-plant coordination control, and plant-network interaction control. Based on the previous analysis, the following key issues still exist in the application of distributed control algorithms, which require further research:

1. It is difficult for distributed algorithms to deal with the uncertain models in optimization problems in offline dispatch planning under the same time scale with previous researches.

2. In the control of real-time operation of VPP, based on the requirements of resource response speed, the distributed control algorithm needs to have a faster convergence rate and high stability, so the algorithm still needs more in-depth theoretical research.

3. Due to inaccurate forecast data and other factors, there is a deviation between the market clearing value of VPP and the actual operation value. In order to encourage internal resources to actively participate in the coordination, a corresponding distributed market mechanism should be established in the VPP. At present, there is little research in this field.

4. When choosing a VPP scheduling framework, the communication network architecture should be fully evaluated and a reasonable distributed control strategy should be selected.

Acknowledgments
This work was financially supported by the Applied Research Project of Regional integrated energy system planning and key technology research.

References
[1] SUN Hongbin, GUO Qinglai, PAN Zhaoguang, et al. Energy Internet: Concept, Architecture and Frontier Outlook[J]. Automation of Electric Power Systems,2015, 000(019):1-8.

[2] SUN Hongbin, GUO Qinglai, PAN Zhaoguang, et al. Energy Internet: Driving Force, Review and Outlook[J]. Power System Technology, 2015, 39(011):3005-3013.

[3] S. Awerbuch, A. Preston, The virtual utility: accounting, technology and competitive aspects of the emerging industry, vol. 26. Kluwer Academic Pub, 1997.

[4] Wang X, Liu Z, Zhang H, et al. A Review on Virtual Power Plant Concept, Application and Challenges[C]// 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia). IEEE, 2019.

[5] Molzahn D K, Dorfler F, Sandberg H, et al. A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems[J]. IEEE Transactions on Smart Grid, 2017:1-1.

[6] Jin X, Wang J, Shen X, et al. An Overview of Virtual Power Plant Development from the Perspective of Market Participation[C]// 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2). IEEE, 2018.

[7] E. Mashhour and S. M. Moghaddas-Tafreshi, "Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets—Part I: Problem Formulation," in IEEE Transactions on Power Systems, vol. 26, no. 2, pp. 949-956, May 2011, doi: 10.1109/TPWRS.2010.2070884.

[8] Nguyen H T, Le L B, Wang Z. A Bidding Strategy for Virtual Power Plants. With Intraday Demand Response Exchange Market Using Stochastic Programming[J]. IEEE Transactions on Industry Applications, 2018:1-1.

[9] Xiangyu Kong, Jie Xiao, Chengshan Wang, et al. Bi-level multi-time scale scheduling method based on bidding for multi-operator virtual power plant[J]. Applied Energy, 2019,249, 178-189

[10] WEI Zhinong, YU Shuang, SUN Guoqiang, et al. Concept and development of virtual power plant[J]. Automation of Electric Power Systems, 2013, 37(13):1-9.

[11] LI Peijie, LU Yong, BAI Xiaqing, et al. Decentralized Optimization for Dynamic Economic Dispatch Based on Alternating Direction Method of Multipliers[J]. Proceedings of the CSEE, 2015, 35(10):2428-2435.

[12] Qin J, Wan Y, Yu X, et al. A Newton Method-Based Distributed Algorithm for Multi-Area Economic Dispatch[J]. IEEE Transactions on Power Systems, 2019(99):1-1.
[13] FANG yanqiong, GAN lin, AI qian, et al. Stackelberg Game Based Bi-level Bidding Strategy for Virtual Power Plant [J]. Automation of Electric Power Systems.

[14] LU Qiuyu, YANG Yinguo, WANG Zhongguan, et al. Economic Primary Frequency Control of Virtual Power Plant Applying Distributed Control Method Based on Sub-Gradient Projection[J]. Electric Power Construction, 2020(3):79-85.

[15] A. Molina-García, F. Bouffard and D. S. Kirschen, "Decentralized Demand-Side Contribution to Primary Frequency Control," in IEEE Transactions on Power Systems, vol. 26, no. 1, pp. 411-419, Feb. 2011, doi: 10.1109/TPWRS.2010.2048223.

[16] H. Yang, C. Y. Chung and J. Zhao, "Application of plug-in electric vehicles to frequency regulation based on distributed signal acquisition via limited communication," in IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 1017-1026, May 2013, doi: 10.1109/TPWRS.2012.2209902.