Review and Prospect of Flexible Loads for Participating in Frequency Regulation

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***Abstract*—The rapidly increasing renewable energy sources (RESs) in the power system bring a large number of disturbances due to the intermittent and random characteristics of power generation. At the same time, most of the RES units are composed of power electronic devices, which can reduce the system inertia and impact the stable operation of the power system. Therefore, more operating reserve resources are required to participate in the rapid regulation in the power system with a high proportion of RES. The rapid development of information and communication technologies make it easier and lower cost to control flexible loads. Based on the new network resources, for example, 5G, flexible loads can be regulated rapidly to participate in power system frequency control. In this paper, the models, categories, and functions of typical flexible loads are analyzed. Then, the research status of various flexible loads for participating in frequency regulation (FR) is combed in detail. On this basis, the advantages and disadvantages of various load control methods and their application scenarios are discussed. Finally, the development prospects of flexible loads for FR are proposed, so as to provide references for practical application.**

Keywords—flexible loads, frequency regulation (FR), renewable energy sources (RESs), review and prospect

I. INTRODUCTION

Frequency is an important index to reveal the balance between supply and demand of the active power in the power system. With the increasingly serious environmental problems and the depletion of fossil energy, many countries are actively promoting the transformation of electric energy, gradually using renewable energy sources (RESs) instead of fossil fuels for power generation. For example, the cumulative installed capacity of wind power and photovoltaic in China have increased to 184GW and 174GW by 2018, respectively [1]. However, the intermittent and random RESs can bring a lot of challenges to the power system. The output of RESs is not stable enough since they are greatly affected by the weather. Besides, the inertia of the power system is reduced because of the increase in the penetration rate of RESs. These factors will cause fluctuations of the power system frequency, thus affecting power quality and power system stability.

At present, the FR of the power system mainly depends on adjusting the active power output of the conventional thermal power plants through the automatic generation control system. However, conventional FR methods are difficult to meet the system requirement, with the decreasing proportion of thermal power plants and the increasing electricity consumption. In addition, these conventional methods also lead to the increase of operation cost and environmental pollution, because these plants cannot be maintained at the most economical operating point.

With the progress of communication technologies, smart controllers and the measuring devices, power system frequency can be regulated by adjusting operating power of demand-side flexible load sources, such as electric vehicles (EVs), constant temperature control loads (TCLs), energy storage systems (ESSs). According to the statistics, during the peak period of summer loads in China, as the most common TCL, air-conditionings (ACs) have accounted for around 30~40% of peak loads, even 50% in Shanghai and Beijing [2]. Therefore, flexible loads, can become an potential alternative to traditional rotating reserve to participate in FR.

II. FLEXIBLE LOADS PARTICIPATE IN FR

A. Overview of flexible loads

The operating power of flexible loads can be adjusted to interact with the power system by participating in regulating. There are three common ways to classify flexible loads: according to energy interaction, management mode, or load characteristics [3], [4], as shown in TABLE I.

TABLE I. FLEXIBLE LOADS CLASSIFICATION

Classification	Category	Typical loads
Energy interaction with the power system	Two-way interaction	ESS, EV, etc.
	One-way interaction	TCL, lights, etc.
Management mode	Shiftable Loads	Loads that can be transferred from one time to another
	Interruptible loads	Loads that can reduce demand during peak period
Load characteristics	Industrial loads	Electric furnace in steelmaking plants
	Business loads	Central Air-Conditionings
	Household loads	TCL etc.

Flexible loads have the characteristics of wide distribution, large number, independence and dispersion, which exist in each node of the power system. Although the single flexible load is not large, they can be integrated as large-capacity backup power sources, considering the large number of users. In addition, flexible loads have small inertia constant and fast response, which means they have obvious advantages as rotating reserve in FR. On the contrary, it is difficult for conventional generators to change their output power and cannot serve as a good reserve[5]. Flexible loads can greatly reduce energy consumption and pollution by replacing the generator in FR. Therefore, the cost of standby generator units for FR can be reduced and the economic benefits of system operation can be improved. At the same time, fast FR by flexible loads can improve the stability of the system and ensure the safe operation of the system.

B. *Overview of Research on Flexible Loads*

The concept of FR by flexible loads was first used by Schweppe in 1980 based on the biological term "dynamic balance". In their research, a dynamic balance application control was proposed, aiming to keep the system frequency in a stable state through "load tracking supply", which is named frequency adaptive power energy reschedualer (FAPER) [6].

The Grid Friendly Appliance™ controllers, developed by the Pacific Northwest National Laboratory (PNNL), can turn household loads off for seconds or even minutes when the system frequency fluctuates to stabilize the grid, by installed computer chips. Another distributed load controller for autonomous renewable energy system is proposed in [7], [8]. It uses frequency and frequency change rate as the input of fuzzy logic load control system. It is tested in an island power system with a small amount of water and heat loads. Patent [9] designed a more complex FAPER, whose control behavior is adjusted by the size of the detected frequency deviation and has been tested in Italy and the UK.

1) EVs

Because of policy incentives and technology maturity, the number of EVs will grow explosively in the future. It is estimated that the annual production of EVs will exceed 100 million by 2050 [10]. Reference [11] proposes the integrated load control scheme of the power system by combining EVs with distributed generation. The model of real-time charging scheduling problem for EV loads is established in [12]. Using the concept of global scheduling algorithm and the earliest deadline priority strategy, a real-time scheduling algorithm is proposed, which can alleviate the power system pressure and meet the charging requirements of users.

2) ESSs

ESS is the key component of smart grid in the future. Reference [13]–[16] carry out several simulations to evaluate its performance from many aspects, such as the speed and effect of ESS participating in FR, and to verify its feasibility and the necessity for practical application. Based on the virtual inertial control and the droop control, an adaptive comprehensive FR control strategy is proposed in [17] by analyzing the dynamic characteristics of ESS participating in primary frequency regulation, which can follow the change of state of charge and the dynamic adjustment of maximum frequency deviation.

3) TCLs

TCL has great application potential because of accounting for the largest proportion of residents' controllable load. It mainly includes heating, ventilation, air-conditioning loads, electric water heater loads and refrigerator loads. Reference [18] proposed a quantitative operating reserve capacity （ORC） evaluation method for large-scale aggregated heterogeneous TCLs without sufficient measurement data. A TCL model based on consumer behavior is proposed and probability density estimation methods are used to evaluate OCR. A novel control strategy for the aggregation model of ACs is proposed in [19], and a series of indexes are proposed to evaluate the operating reserve performance provided by ACs. In[20], a partial differential equation physics-based model is developed to capture the detailed temperature profiles at different tank locations, which is compared with the one-mass and two-mass models, and shows better performance in capturing water thermal dynamics for benchmark testing purposes. A decentralized controller is proposed in [21], which adjusts the temperature setting value of the refrigerator and controls its power consumption according to the change of frequency deviation. Reference [22] develops a dynamic decentralized controller to change the total power consumption of the refrigerator to make it linear with the frequency change, and its effectiveness is proved by simulations.

III. Control Mode of FR of Flexible Loads

According to the different control modes of flexible loads on the demand side for frequency regulation, load control methods can be divided into three categories, including centralized control, distributed control and decentralized control.

A. *Centralized control*

The centralized control system [23]–[25] generally includes one control center, the load control communication channel and many load control terminals. When the frequency of the power system deviates from the normal value, the control center determines loads to be controlled according to the deviation value, and then sends control signals to the load control terminals through the control communication channel to changing operating power of these loads, as shown in Fig. 1.

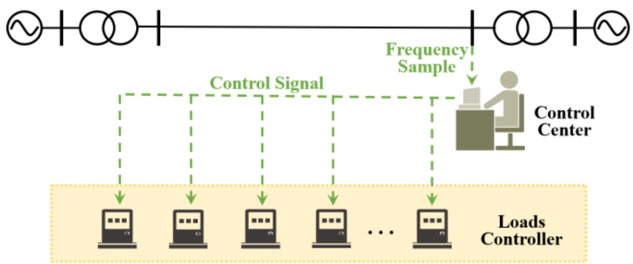

Fig. 1. Centralized control system.

In this mode, all selected flexible loads can be directly regulated by the control center to reduce the response uncertainty of the controllable units. Better load coordination and higher frequency regulation accuracy can be realized. However, it is obvious that the difficulty of the optimization solution for the control center and the communication pressure between the control center and loads will also increase greatly, with a large number of aggregated loads. Therefore, centralized control mode cannot be well applied in large-scale flexible load control.

B. *Distributed control*

Distributed control mode [26]–[29], also known as hierarchical control mode, has one control center with many load aggregators. All flexible loads are divided into several control areas, and each area has its own load management organization i.e. load aggregators. There is a communication channel between the control center and each load aggregator.

Another communication channel exists between load aggregators and response loads, as shown in Fig. 2.

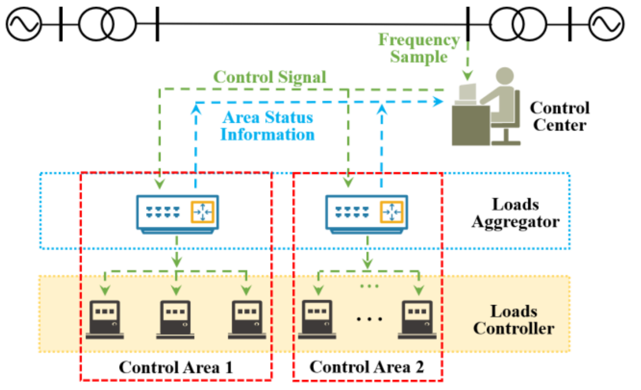

Fig. 2. Distributed control system.

There are obvious primary and secondary modules in the distributed control mode, and the control center has the right to directly control the load aggregator level in the dispatching, while the load aggregators can control very load individual. On the one hand, the load aggregators need to count and upload the state information of the loads to the control center for decision-making. On the other hand, it can selectively control loads according to their state after receiving the dispatching instruction. Distributed control mode can simultaneously optimize power generation resources and load resources as the centralized control mode. Meanwhile, this mode can overcome the disadvantage that too many loads have to takes up too much computing resources.

C. Decentralized control

Distributed control mode [30]–[33] only has load controllers without control center and communication channel. The controller is installed between the socket and the response load, which can measure the system frequency, as shown in Fig. 3. When the system frequency measured by the controller exceeds the set value, operating power or open/close state of loads can be changed automatically according to the control strategy in the controller. In the process, there is no communication with other devices, and the dispatching center of the power system cannot know the state of these loads.

This mode can speed up the response speed and save the construction cost of communication channel, because of no communication channel. However, all response loads only consider their own state without coordinating with each other, due to the absence of communication. At the same time, this mode may lead to overshoot and oscillation of FR, which can be solved by optimizing control strategies and parameters.

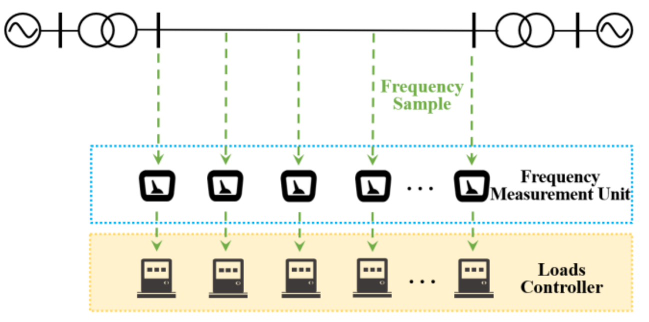

Fig. 3. Decentralized control system.

IV. Development Prospect

From the above discussion and analysis, it can be seen that flexible loads participating in the FR has a relatively complete implementation method at the technical level. Nevertheless, there is still room for improvement in the technical and policy fields.

- In 2019, the State Grid Corporation made a strategic plan to comprehensively promote the construction of "Three Types and Two Networks" and speed up the construction of world-class energy internet enterprises with global competitiveness, among which the construction of Ubiquitous Power Internet of Things (UPIoT) is a key point. The development of UPIoT will bring more electric meters and controllers into the scope of monitoring and management. That means more flexible loads can be controlled and participate in the FR of the power system, which can increase the reserve capacity of FR.
- Since the Central Government issued document [2015] No. 9 in 2015, China's power market reform has been deepening. The power market mechanism has been continuously improved, and the demand response (DR) has also developed. Price-based DR allows consumers to directly face time-based (or space-based) price signals and independently make arrangements and adjustments in the time and mode of electricity consumption. Incentive-based DR is to directly use rewards to motivate and guide users to participate in load reduction projects [34]. The incentive funds and the reduction of electricity payments encourage users to actively participate in DR. Therefore, the further deepening of power market reform will promote the increase of flexible loads in the power system.
- Since 5G network started the commercial road in China in 2019, the Ministry of Industry and Information Technology has put forward a series of plans to promote 5G in the industrial sector. The application of 5G or higher communication technology in the field of flexible loads management and control can effectively shorten the communication time between the loads and the load aggregators or control center. Besides, high reliability, robust security, low power consumption, and massive number of connections can doubtless provide better infrastructure for flexible loads control [35]. For example, 5G-based fog computing and cloud computing are proposed to connect massive numbers of EVs to provide ancillary services for the power system within milliseconds in [36].

V. Summary

This paper summarizes the FR of the power system considering flexible loads. First, the existing research on the FR by EV loads, ESS loads and TCLs is summarized and analyzed. Besides, the advantages and disadvantages of three load control modes are introduced and studied respectively. At the technical level, a lot of research has proved that flexible loads participating in FR can quickly balance the power shortage, by their fast and strong FR capability, when there is power fluctuation in the power system. Therefore, it can improve the stability of the power system. At same time, flexible loads can reduce the number of rotating reserves in the power system, achieving the purpose of green environmental protection and saving operating costs. However, the commercial mechanism of the FR by flexible loads are incomplete. It is an unavoidable problem to attract flexible loads to participate in the FR by reasonable benefit distribution method.

With the construction of the ubiquitous Internet of things and the improvement of the electricity market, more and more flexible loads can participate in operating and controlling of the power system. They can play a great role in the safe and stable operation of power system due to their advantages of speed and accuracy.

References

[1] K. Xie, H. Hui, and Y. Ding, "Review of modeling and control strategy of thermostatically controlled loads for virtual energy storage system," *Prot. Control Mod. Power Syst.*, vol. 4, no. 1, p. 23, Dec. 2019.

[2] W. Cui *et al.*, "Evaluation and Sequential Dispatch of Operating Reserve Provided by Air Conditioners Considering Lead–Lag Rebound Effect," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6935–6950, Nov. 2018.

[3] S. Yang, J. Liu, J. Yao, H. Ding, K. Wang, and Y. Li, "Model and Strategy for Multi-time Scale Coordinated Flexible Load Interactive Scheduling," *Proc. CSEE*, vol. 34, no. 22, pp. 3664–3673, 2014.

[4] D. Zeng, J. Yao, S. Yang, K. Wang, and Y. Li, "System Dynamics Simulation Model of Flexible Load in Interactive Power Grid," *Proc. CSEE*, vol. 34, no. 25, pp. 4227–4233, 2014.

[5] W. B. Xiang and M. Xu, "Frequency Regulation of Power System Considering PEVs," *Appl. Mech. Mater.*, vol. 651–653, pp. 1078–1083, Sep. 2014.

[6] F. C. Schweppe, R. D. Tabors, J. L. Kirtley, H. R. Outhred, F. H. Pickel, and A. J. Cox, "Homeostatic Utility Control," *IEEE Trans. Power Appar. Syst.*, vol. PAS-99, no. 3, pp. 1151–1163, May 1980.

[7] P. C. Taylor, "Distributed intelligent load control of autonomous renewable energy systems," Ph.D., University of Manchester, 2001.

[8] K. Pandiaraj, P. Taylor, N. Jenkins, and C. Robb, "Distributed load control of autonomous renewable energy systems," *IEEE Trans. Energy Convers.*, vol. 16, no. 1, pp. 14–19, Mar. 2001.

[9] D. R. Hirst, "Grid stabilising system," US7830037B2, 09-Nov-2010.

[10] E. L. Karfopoulos and N. D. Hatziargyriou, "A Multi-Agent System for Controlled Charging of a Large Population of Electric Vehicles," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1196–1204, May 2013.

[11] M. Georgiev, R. Stanev, and A. Krusteva, "Flexible load control in electric power systems with distributed energy resources and electric vehicle charging," in *2016 IEEE International Power Electronics and Motion Control Conference (PEMC)*, 2016, pp. 1034–1040.

[12] J. Kang, S. J. Duncan, and D. N. Mavris, "Real-time Scheduling Techniques for Electric Vehicle Charging in Support of Frequency Regulation," *Procedia Comput. Sci.*, vol. 16, pp. 767–775, Jan. 2013.

[13] S.-J. Lee *et al.*, "Coordinated Control Algorithm for Distributed Battery Energy Storage Systems for Mitigating Voltage and Frequency Deviations," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1713–1722, May 2016.

[14] S. S. Sami, Meng Cheng, and Jianzhong Wu, "Modelling and control of multi-type grid-scale energy storage for power system frequency response," in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, 2016, pp. 269–273.

[15] M. Cheng, S. S. Sami, and J. Wu, "Benefits of using virtual energy storage system for power system frequency response," *Appl. Energy*, vol. 194, pp. 376–385, May 2017.

[16] Z. A. Obaid, L. Cipcigan, and M. T. Muhsin, "Analysis of the Great Britain's power system with Electric Vehicles and Storage Systems," in *2015 18th International Conference on Intelligent System Application to Power Systems (ISAP)*, 2015, pp. 1–6.

[17] Q. Wu *et al.*, "Study on Self-adaptation comprehensive Strategy of Battery Energy Storage in Primary Frequency Regulation of Power Grid," *Power Syst. Technol.*, pp. 1–10, 2019.

[18] D. Xie, H. Hui, Y. Ding, and Z. Lin, "Operating reserve capacity evaluation of aggregated heterogeneous TCLs with price signals," *Appl. Energy*, vol. 216, pp. 338–347, Apr. 2018.

[19] H. Hui, Y. Ding, W. Liu, Y. Lin, and Y. Song, "Operating reserve evaluation of aggregated air conditioners," *Appl. Energy*, vol. 196, pp. 218–228, Jun. 2017.

[20] Z. Xu, R. Diao, S. Lu, J. Lian, and Y. Zhang, "Modeling of Electric Water Heaters for Demand Response: A Baseline PDE Model," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2203–2210, Sep. 2014.

[21] J. A. Short, D. G. Infield, and L. L. Freris, "Stabilization of Grid Frequency Through Dynamic Demand Control," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1284–1293, Aug. 2007.

[22] M. Cheng, J. Wu, J. Ekanayake, T. Coleman, W. Hung, and N. Jenkins, "Primary frequency response in the great Britain power system from dynamically controlled refrigerators," in *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, 2013, pp. 1–4.

[23] S. A. Pourmousavi and M. H. Nehrir, "Real-Time Central Demand Response for Primary Frequency Regulation in Microgrids," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1988–1996, Dec. 2012.

[24] S. A. Pourmousavi and M. H. Nehrir, "Demand response for smart microgrid: Initial results," in *ISGT 2011*, 2011, pp. 1–6.

[25] H. Cui, F. Li, X. Fang, and R. Long, "Distribution network reconfiguration with aggregated electric vehicle charging strategy," in *2015 IEEE Power Energy Society General Meeting*, 2015, pp. 1–5.

[26] Y.-Q. Bao, Y. Li, Y.-Y. Hong, and B. Wang, "Design of a hybrid hierarchical demand response control scheme for the frequency control," *Transm. Distrib. IET Gener.*, vol. 9, no. 15, pp. 2303–2310, 2015.

[27] J. Hu, J. Cao, J. M. Guerrero, T. Yong, and J. Yu, "Improving Frequency Stability Based on Distributed Control of Multiple Load Aggregators," *IEEE Trans. Smart Grid*, vol. 8, no. 4, pp. 1553–1567, Jul. 2017.

[28] Y. Wang, Y. Tang, Y. Xu, and Y. Xu, "A Distributed Control Scheme of Thermostatically Controlled Loads for the Building-Microgrid Community," *IEEE Trans. Sustain. Energy*, vol. 11, no. 1, pp. 350–360, Jan. 2020.

[29] A. De Paola, V. Trovato, D. Angeli, and G. Strbac, "A Mean Field Game Approach for Distributed Control of Thermostatic Loads Acting in Simultaneous Energy-Frequency Response Markets," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 5987–5999, Nov. 2019.

[30] Z. Xu, J. Ostergaard, and M. Togeby, "Demand as Frequency Controlled Reserve," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1062–1071, Aug. 2011.

[31] A. Molina-García, F. Bouffard, and D. S. Kirschen, "Decentralized Demand-Side Contribution to Primary Frequency Control," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 411–419, Feb. 2011.

[32] M. R. Vedady Moghadam, R. T. B. Ma, and R. Zhang, "Distributed Frequency Control in Smart Grids via Randomized Demand Response," *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2798–2809, Nov. 2014.

[33] K. Dehghanpour and S. Afsharnia, "Designing a novel demand side regulation algorithm to participate in frequency control using iterated mappings," *Transm. Distrib. IET Gener.*, vol. 8, no. 10, pp. 1687–1699, Oct. 2014.

[34] P. T. Baboli, M. Eghbal, M. P. Moghaddam, and H. Aalami, "Customer behavior based demand response model," in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–7.

[35] H. Hui, Y. Ding, Q. Shi, F. Li, Y. Song, and J. Yan, "5G network-based Internet of Things for demand response in smart grid: A survey on application potential," *Appl. Energy*, vol. 257, p. 113972, Jan. 2020.

[36] M. Tao, K. Ota, and M. Dong, "Foud: Integrating Fog and Cloud for 5G-Enabled V2G Networks," *IEEE Netw.*, vol. 31, no. 2, pp. 8–13, Mar. 2017.