PAPER • OPEN ACCESS

A Decentralized Strategy for Frequency-based Load as Regulation

To cite this article: Yaping Li *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **486** 012136

A Decentralized Strategy for Frequency-based Load as Regulation

Yaping Li[1,*], Mingyu Huang[2], Wenbo Mao[1] and Liang Yin[2]

[1] China Electric Power Research Institute, Nanjing, 210003, China.
[2] State Grid Ningxia Electric Power Co.Ltd., Yinchuan, 750001, China.

[*]Email: liyapingxiaoya@126.com

Abstract. In order to keep frequency stable after UHV DC block fault, demand side resources are needed. Among these, frequency-based load can automatically monitor the frequency change without affecting the user's power consumption experience and can quickly adjust the operating parameters to reduce its own power consumption. Thus, frequency-based load can play a role similar to the primary frequency regulation. In this paper, several physical models of typical frequency-based loads were established and the frequency regulation characteristics are analyzed. Based on this, a decentralized strategy of frequency-based load was proposed. The simulation results show that the grouping decentralized strategy can effectively avoid the “over-control” or “under-control” phenomenon, which helps to quickly maintain the power balance and frequency stability of the grid.

1. Introduction

As the largest regional power grid in China, East China Power Grid has gradually formed an ultra-high voltage and high-end power grid pattern in recent years. During the "12th Five-Year Plan" period, Fufeng, Jinsu and Binjin were put into operation and the total capacity exceeded 20GW. During the "13th Five-Year Plan" period, East China Power Grid will also add 4 new UHV DC transmission lines, with a total capacity of 38GW. UHV DC transmission system plays an irreplaceable role in optimizing energy resource allocation and promoting green development in East China. However, as the proportion of DC capacity continues to increase, the synchronous moment of inertia of the receiving power grid gradually decreases. Once the DC power is lost, the receiving power grid will face a large amount of power loss in an instant, which will lead to a rapid decline of the grid frequency, even when there is a large area of power outage risk [1-3].

Since the conventional power supply on the power generation side is limited by the large-scale replacement of renewable energy, DC, etc., the controllable mode on the power generation side is almost exhausted. At the same time, with the comprehensive construction of the smart grid, the load is diversified and the controllability is greatly enhanced, which becomes an important resource for the safe, reliable and economical operation of the power grid. Among them, the frequency-based load (such as air conditioner, electric water heater, refrigerator, etc.) automatically monitor the frequency change, and quickly adjust the operating parameters to change the power consumption without affecting the user's power consumption experience. When the frequency is low, it can quickly reduce the power consumption or exit the power supply. When the frequency returns to normal, it will be put in order. So, they are a kind of available resources involved in frequency modulation [4]. In the absence of large power shortages such as UHV DC block, these loads can be used to supplement the

IOP Conf. Series: Materials Science and Engineering **486** (2019) 012136 doi:10.1088/1757-899X/486/1/012136

system power regulation capability, quickly increase the system frequency level, and improve the safety and economy of the grid operation.

Nowadays, load participation in regulation mainly includes interruptible load (IL), direct load control (DLC) and Grid Friendly Appliances (GFAs) control. Among them, IL is generally applicable to large industrial and commercial users, and the interrupt capacity and time are agreed by contract [5-6]. DLC is mostly implemented among loads with energy storage capacity such as thermostatically controlled loads (TCLs) or electric vehicles (EVs) [7-8]. Both IL and DLC are centralized control methods. When the number of loads is large, it is difficult to promote the application in a wide range when it is subject to control cost constraints. GFAs can be seen a kind of frequency-based load. They participate in the regulation in the decentralized control mode. The current research mainly focuses on the influence and parameters setting such as threshold, time-delay, and amplitude etc. [9-11]. In the case of dealing with active balance contingencies, such as UHV DC blocking, the active decentralized response of GFAs can play an important role [12]. However, the decentralized control strategy is not easy to determine the overall response capacity, which is prone to "over-control" or "under-control" phenomenon.

In order to solve this problem, this paper divides the frequency-based load into two categories: continuous regulation and discrete adjustment. The regulation characteristics of these two types of frequency-based load are analyzed. Based on these, a grouping decentralized strategy is proposed and verified by simulation.

The rest of this paper is organized as follows. Models and frequency characteristics of typical frequency-based load are analyzed in Section II. Decentralized strategy and flow chart is proposed in Section III. Case studies of different strategies for frequency-based load as regulation are shown in Section IV and conclusions are drawn in Section V.

2. Physical model

Taking the typical frequency-based load of air conditioner, water heater and electric vehicle as an example, the physical model are listed as followings.

2.1. Air conditioning

Assuming that the air conditioner is in the cooling mode, its actual power consumption is related to the working state of the air conditioner. It can be divided into three cases:

1) when the room temperature is higher than the highest value, the air conditioner is "ON";

2) when the room temperature is lower than the lowest value, the air conditioner is "OFF", and its power consumption is almost 0;

3) when the room temperature is within the air conditioning temperature setting range, the air conditioner remains in its original state.

The actual power of the air conditioner during the period is calculated as follows (1), (2):

$$p_{AC,t} = P_{AC} \times S_{AC,t} \tag{1}$$

$$S_{AC,t} = \begin{cases} 0, & T_{AC,t} < T_{AC,s} \\ 1, & T_{AC,t} > T_{AC,s} + \Delta T_{AC} \\ S_{AC,t-1}, & T_{AC,s} < T_{AC,t} < T_{AC,s} + \Delta T_{AC} \end{cases} \tag{2}$$

Where, $p_{AC,t}$ is the actual power of the air conditioner of time period t; P_{AC} is the rated power of the air conditioner in the cooling state; $S_{AC,t}$ is the working state of the air conditioner in the period (value 0 means "OFF"; value 1 means "ON"); $T_{AC,s}$ is the minimum room temperature setting value; ΔT_{AC} is original set range of room temperature; $T_{AC,t}$ is the temperature of time period t.

In the cooling mode, the room temperature of time t is as follows:

$$T_{AC,t+1} = T_{AC,t} + \Delta t \bullet \frac{G_t}{\Delta c} + \Delta t \bullet \frac{C_{AC}}{\Delta c} \bullet S_{AC,t} \quad (3)$$

Where, $T_{AC,t+1}$, $T_{AC,t}$ represents the room temperature of time period $t+1$ and time period t respectively; G_t represents the outdoor and indoor heat exchange values of time t; Δc represents the indoor temperature coefficient, that is, the heat required for each room temperature increase of 10 °C; C_{AC} represents the air conditioning heat capacity in the cooling state; $\frac{C_{AC}}{\Delta c}$ is the air conditioning in the cooling state effect value on room temperature change; Δt represents time interval.

2.2. Water heater

The actual power consumption of the water heater is related to its operating state, and its operating state is related to the initial water temperature setting value of the user. It can be divided into three cases:

1) when the water temperature of the water heater is higher than the maximum set temperature, the water heater is "OFF" and stops heating;

2) when the water temperature of the water heater is lower than the minimum set temperature, the water heater is "ON";

3) when the water temperature of the water heater is within the comfort range, the water heater maintains its original state. The actual power of the water heater during the period is calculated as follows (4), (5):

$$p_{WH,t} = P_{WH} \times S_{WH,t} \quad (4)$$

$$S_{WH,t} = \begin{cases} 0, & T_{WH,t} > T_{WH,s} \\ 1, & T_{WH,t} < T_{WH,s} - \Delta T_{WH} \\ S_{WH,t-1}, & T_{WH,s} - \Delta T_{WH} < T_{WH,t} < T_{WH,s} \end{cases} \quad (5)$$

Where, $p_{WH,t}$ represents the actual power of the water heater of time period t; P_{WH} represents the rated power of the water heater in the heating state; $S_{WH,t}$ is the working state of the water heater for the time period (value 0 means "OFF"; value 1 means "ON"); $T_{WH,s}$ is the setting value of water temperature; ΔT_{WH} represents the temperature setting range of water heater; $T_{WH,t}$ is water temperature of time t.

The water temperature of the water heater is calculated as shown in the following formula (6):

$$T_{WH,t+1} = \frac{T_{WH,t}(V_{WH} - fl_t \bullet \Delta t)}{V_{WH}} + \frac{T_{in} fl_t \bullet \Delta t}{V_{WH}} + \alpha \bullet p_{WH,t} + \xi \quad (6)$$

Where, $T_{WH,t+1}$, $T_{WH,t}$ respectively, indicating the water temperature of the water heater during the time period $t+1$ and time period t; T_{in} indicates the cold water temperature of the water heater inlet; fl_t indicates the hot water flow of the water heater during the period t, which is related to the living habits of the residents; V_{WH} indicates the volume of the water heater; Δt is the time interval; α indicates the heating temperature coefficient of the water heater, which is the temperature increase value under the rated heating power of the water heater per unit time; ξ indicates the self-cooling temperature decrease value of the hot water inside the water heater in the regular room temperature, which is related to the volume, surface area, room temperature and hot water temperature of the water heater.

2.3. Electric vehicle

The electric vehicle charging load model is related to the initial charging time, the rated charging power of the vehicle battery, the initial state of the battery SOC (battery state of charge), and the final full charge requirement. When the SOC state of the electric vehicle does not reach the power requirement, it will be in the continuous charging phase until the full charge requirement is reached. The actual charging power of the electric vehicle during the period t is calculated as follows (7), (8):

$$p_{EV,t} = P_{EV} \bullet S_{EV,t} \tag{7}$$

$$S_{EV,t} = \begin{cases} 0 & Q_t \geq Q_{\max} \\ 1 & Q_t < Q_{\max} \end{cases} \tag{8}$$

Where, $p_{EV,t}$ is the actual charging power of the electric vehicle for the period t; P_{EV} is the rated charging power of the electric vehicle; $S_{EV,t}$ indicates the charging state of the electric vehicle for the period of time (value 0 means the charging is stopped; value 1 means the power-on state) ; Q_t indicates the electric vehicle battery SOC during the period t; $Q_{\max}$ indicates the maximum SOC of the battery when the electric vehicle reaches the full charge state.

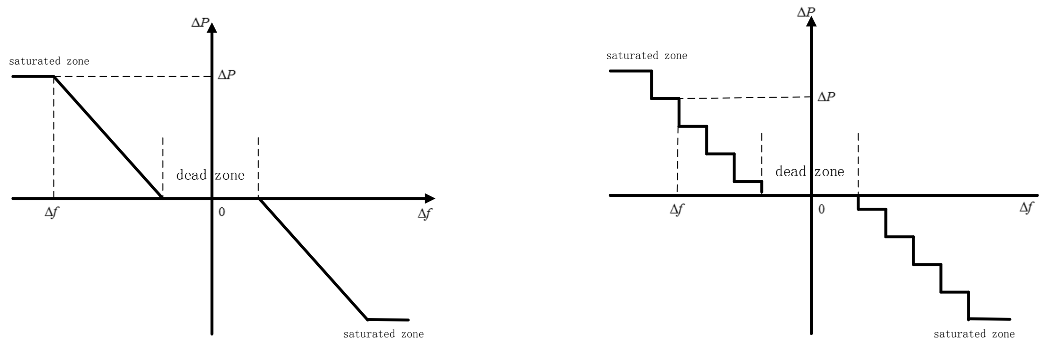
The battery SOC of the electric vehicle during the period $t-1$ is related to the parameters of the electric vehicle during the period t, the rated power of the electric vehicle, and the rated capacity of the electric vehicle battery. The calculation of Q_t is listed in formula (9):

$$Q_t = Q_{t-1} + p_{EV,t} \bullet \frac{\Delta t}{C_{batt}} \tag{9}$$

Where, Q_t and Q_{t-1} indicates the time t and period $t-1$ of the electric vehicle battery SOC; $p_{EV,t}$ is the actual charging power of the electric vehicle during the period t; C_{batt} indicates the rated capacity of the battery; Δt indicates the time interval.

3. Regulation characteristics analysis

The frequency-based load can participate in the system regulation. According to different load control characteristics, they can be divided into continuously regulated and discretely regulated. The energy storage equipment participate in the system frequency regulation in continuous way. And, there is also a type of frequency-based load belongs to the switch control (ON/OFF) type or discrete temperature control type. These devices can only participate in one or more adjustments based on their own electrical characteristics, but cannot achieve free power changes. Discrete adjustment is a more common approach due to the fact that such loads are significant in the system. The regulation characteristics of the frequency-based load in the two modes are shown in Figure.1(a) and Figure.1 (b), respectively.



(a) continuously regulation mode (b) discretely regulation mode

Figure 1. Regulation characteristics of frequency-based load

IOP Conf. Series: Materials Science and Engineering **486** (2019) 012136 doi:10.1088/1757-899X/486/1/012136

In the continuously adjustment mode, the load's frequency regulation characteristics are similar to the primary frequency regulation. However, for the discretely adjustment mode, it is necessary to separately set different frequency response thresholds, response delays, etc.

4. Decentralized strategy

The decentralized strategy of frequency-based load can be divided into four steps:

1) The control center offline simulates the expected fault and performs online matching according to the real-time situation of the grid to calculate the total amount of frequency-based load that needs to participate in the response;

2) The intelligent terminal collects and uploads the user load information to the control center, and the control center evaluates the current load response potential in real time;

3) The control center determines the actual load amount of the current participating response, and the respondable power of each group of loads, and calculates the frequency threshold of each load group in real time according to the decentralized control strategy, and delivers the frequency threshold to the intelligent terminal;

4) The intelligent terminal determines the final frequency threshold, moniters the system frequency in real time, and performs the decentralized action according to the current online or offline frequency threshold.

The detailed flow chart is shown in Figure.2.

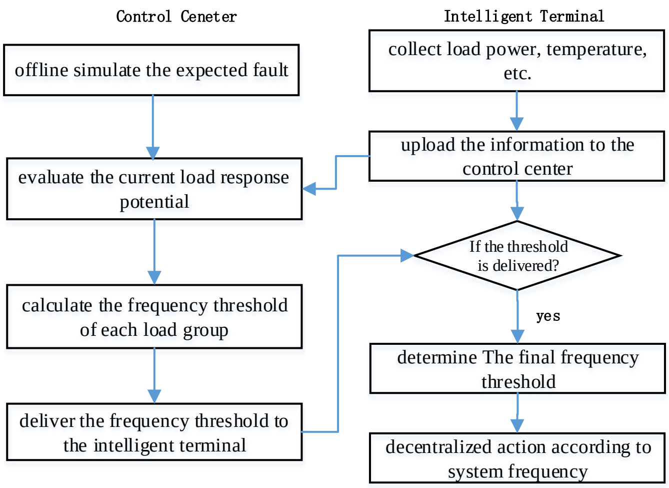


Figure 2. Frequency-based load decentralized strategy

5. Simulation

The frequency-based load adopts different control strategies, and its impact on the power grid is also different. A mathematical model of a single-area power system approximate linearization is shown in Figure.3. Taking this as an example, the influence of the frequency-base load decentralized strategy is analyzed.

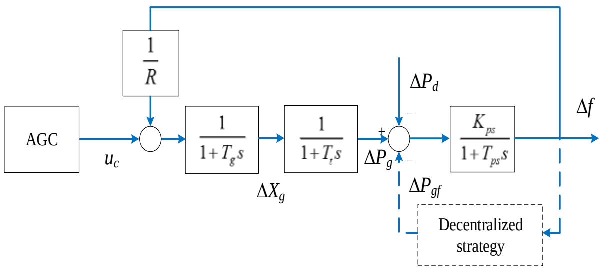


Figure.3 Linearization mathematical model for single-area power system

The values of the parameters of the system are *Tg*=0.08s, *Tt*=0.3s, *Tps*=20s, *Kps*=120, and *R*=2.4. When the frequency-based load is not involved, it is assumed that the 0.2MW active power shortage (ie ΔPd = 0.2 MW) suddenly appears at t =1s, and the power system frequency simulation result is shown in Figure. 4. It can be seen from the figure that when the load of the power system suddenly increases, the frequency of the power grid will decrease. The primary frequency regulation and secondary frequency regulation can make adjustments according to the change of frequency, increase the active output of the generator, and restore the system frequency. However, the maximum frequency drops to 49.73 Hz, and the maximum deviation is about -0.27 Hz, which exceeds the frequency tolerance of ±0.2 Hz.

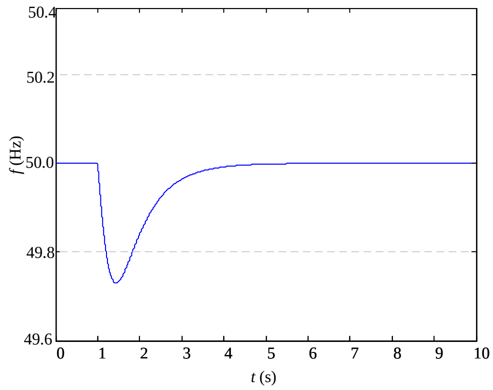


Figure.4 Basic frequency regulation characteristics of power system

5.1. Simultaneous response

Assuming the system's frequency threshold is $\Delta f_0 = -0.1$ Hz. When the frequency-based load monitors the system frequency deviation $\Delta f < \Delta f_0$, turn off the device (Switch="OFF"). When $\Delta f > \Delta f_0$, the device is turned on to continue working (Switch="ON"). Assuming that the system suddenly has a 0.2MW active power deficiency (ie, ΔP_d =0.2MW), the simulation results are shown in Figure.5.

Comparing Figure.5 and Figure.4, it can be seen that after the frequency-based load participates in the frequency regulation, the frequency adjustment characteristic of the power system has been significantly improved. The maximum frequency drops to 49.86 Hz, and the maximum deviation is 0.14 Hz. However, the switch curve in Figure.5 has severe chattering between 1.8s and 3.1s, which will cause the electrical equipment to be in a fast and violent switching state transition. This is absolutely not allowed for electrical equipment. Moreover, the frequency recovery curve is not smooth and affects the frequency quality of the grid.

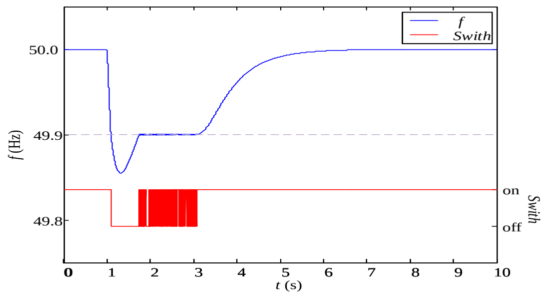


Figure.5 Simultaneously response results of frequency-based load

5.2. Grouping response

The frequency-based loads are divided into 5 groups according to the threshold Δf_{on} and Δf_{off}. The switching thresholds of various types of devices are set to: $\Delta f_{on}^1 = -0.03$ Hz, $\Delta f_{off}^1 = -0.08$ Hz;

$\Delta f_{on}^{2}=-0.05$ Hz, $\Delta f_{off}^{2}=-0.1$ Hz; $\Delta f_{on}^{3}=-0.07$ Hz, $\Delta f_{off}^{3}=-0.12$ Hz; $\Delta f_{on}^{4}=-0.09$ Hz, $\Delta f_{off}^{4}=-0.14$ Hz; $\Delta f_{on}^{5}=-0.11$ Hz, $\Delta f_{off}^{5}=-0.16$ Hz. Assuming that the system suddenly has a 0.2MW active power deficiency (ΔP_d =0.2MW), the simulation results are shown in Figure.6.

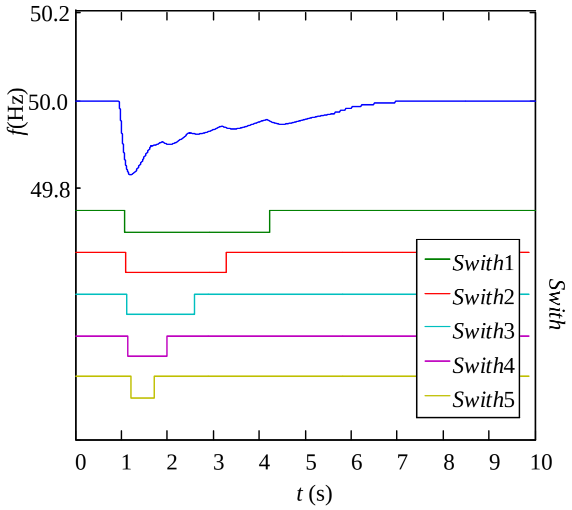


Figure.6 Grouping response result of frequency-based load

It can be seen from the system frequency curve of Figure. 6 that when the switching frequency thresholds of different types of frequency-based loads and different values are taken respectively, the frequency drops to a maximum of 49.84 Hz. From the Switch curve (Switch1-Switch5) of various devices, it can be seen that the grouping response strategy can stagger the opening and closing time of different devices, avoiding a large number of electrical devices to be turned on at the same time, thereby reducing the frequency-based load to the power system. The impact of the power system has a positive effect on frequency regulation.

6. Conclusion

Frequency-based load provides a valuable resource for system frequency regulation. In this paper, the frequency-based load is divided into two types: continuous regulation and discrete regulation. The frequency regulation characteristics of different types of frequency-based loads are analyzed. A decentralized strategy of grouping response is proposed for discrete frequency-based loads. The simulation results show that the grouping response strategy can avoid a large number of loads turned "ON/OFF" at the same time, thus avoiding the phenomenon of "over control" or "under control". However, it should be pointed out that there is a strong uncertainty in the active response of the load, and it still needs to coordinate with other regulation means.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 51677173) and the State Grid Corporation of China project (Research on Coordinated Control Technology of Frequency Regulation Considering Dynamic Demand Response).

References

[1] Y. Wang, B. Liu, T. B. Liu. "Coordinated optimal dispatching of emergency power support among provinces after UHVAC transmission system block fault," *Proceedings of the CSEE*, vol. 35 (11), pp. 2695-2702. 2015.

[2] Q. Zhao, L. M. Wang, Z. X. Liu. "Study on dynamic frequency characteristic and coordinative under-frequency load shedding scheme for nationwide interconnected power grid of China," *Power System Technology*, vol. 33 (8), pp. 35-40. 2009.

IOP Conf. Series: Materials Science and Engineering **486** (2019) 012136 doi:10.1088/1757-899X/486/1/012136

[3] X. F. Xiong, Y. Z. Zhou, J. Q. Zhou. "Study of under-frequency load shedding scheme based on load frequency characteristics," *Proceedings of the CSEE*, vol. 25 (19), pp. 48-51. 2005.
[4] B. Han, J. G. Yao, Y. J. Yu. "Discussion on Active Load Response at Receiving End Power Grid for Mitigating UHVDC Blocking Fault," *Automation of Electric Power Systems*, vol. 40 (18), pp. 1-6. 2016.
[5] Tuan L A, Bhattacharya K. "Competitive framework for procurement of interruptible load services," *IEEE Trans. on Power Systems*, vol. 18 (2), pp. 889-897. 2003.
[6] L. Goel, V. P. Aparna, P. Wang. "A framework to implement supply and demand side contingency management in reliability assessment of restructured power systems," *IEEE Trans on Power Systems*, vol. 22 (1), pp. 205-211. 2007.
[7] B. J. Kirby. "Spinning reserve provided from responsive loads," U.S.: Ridge National Laboratory, 2003.
[8] X. Zhao, J. Ostergaard, M. Togeby. "Demand as frequency controlled reserve," *IEEE Trans. on Power Systems*, vol. 26 (3), pp.1062-1071. 2011.
[9] B. Q. Yu, L. Yang. "FPGA-Based design of grid friendly appliance controller," *IEEE Trans. on Smart Grid*, vol. 5(2), pp.924-931. 2014.
[10] N. Lu, D. Hammerstrom, S. Patrick, "Grid Friendly™ device model development and simulation [EB/OL]," U.S.:PNNL, 2009[2009-11]. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18998.pdf
[11] A. Molina-Garcia, F. Bouffard, D. S. Kirschen. "Decentralized demand-side contribution to primary frequency control, " *IEEE Trans.Power Systems*, vol. 26(1), pp.411-419. 2011.
[12] Z. Xu, J. Qstergaard, M. Togeby. "Demand as frequency controlled reserve," *IEEE Trans. on Power Systems*, vol. 26(3), pp.1062-1071. 2011.