Research on abundance adaptive frequency control strategy of household temperature-control load

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Abstract. Based on the method of space state, state division of household temperature-control load group is proposed. State sequence method is used to analyze the influence of load group abundance on aggregated power. Based on the minimum cost and maximum flow algorithm, the temperature-control load group's abundance recovery strategy is proposed, which could achieves the goal of fast and smooth recovery load group abundance. The simulation of household temperature-control load respond to the power system primary frequency adjustment is carried out under the circumstances of good abundance, excess abundance and lack of abundance. The simulation results show that the effect of temperature control load on the power grid primary frequency adjustment is fine. and the effectiveness of the proposed frequency adjustment control strategy is verified.

1. Introduction

In traditional power system, the generation side actively tracks the load to achieve active power balance and the user side is in a passive state during the whole process[1][2]. Besides, due to its randomness, volatility and unpredictability, the loads in user side is considered as one of the main causes of the imbalance between supply and demand[3]. The generation side will provide the corresponding frequency control reserve capacity to deal with the potential faults in the power grid. There are a large number of thermal energy storage devices in the power grid, such as air conditioners, water heaters and refrigerators[4][5]. The controlling of these devices will not give a significant impact on the users in short time. Therefore, these devices have a good potential to participate in active power balance regulation of power grid[6][7].

In this paper, temperature-control load is taken as the research object. Abundance adaptive frequency control strategy is proposed to solve the system abundance deficiency when the temperature-control load group participates in the primary frequency control in the power grid. And the effect of temperature-control load participating in the frequency control is verified.

2. Impact analysis of load group abundance on aggregated power

The aggregated power of the load group changes in real time on the time scale. The variation rule is related to the working characteristics of single temperature-control load particle and the initial distribution state of the particle swarm[8]. In order to explore the variation characteristics of the aggregated power about temperature-control load group, the concept of load group abundance is introduced in this paper.

The temperature range and working state of temperature-control load particles are different in the working process. According to the state space method[9], the temperature-control load can be divided

into several state groups. When the load state distribution of each state group is average, it can be considered that the current load group has good abundance. When a large number of loads are operating, for those loads that have the same operating characteristics, the ratio between the number of particles in working state and the total number of particles in this temperature range should be equal to probability, which is the ratio of the working time and operating time of a single air conditioner. On the contrary, if the ratio is less than the probability, it can be considered that the current load group has lack abundance. If the ratio is larger than the probability, it can be considered that the current load group has excess abundance. The concept of abundance is relatively vague. Based on the Hill inequality and the state characteristics of load group[10][11]. This paper constructs an assessment formula for the abundance of load group and the abstract abundance is measured as overall abundance and interval abundance[12].

According to different temperatures, the load group is divided into equal parts between high and low temperature thresholds. According to the load working state, the same temperature range can be divided into working state and standby state, this constitutes the spatial state of the load group. According to the actual spatial state and ideal spatial state, the overall abundance of load group can be calculated by formula (1) to evaluate the distribution of load group.

$$S = 1 - \frac{\sqrt{\dfrac{1}{N}\sum\limits_{i=1}^{N}(y_i - y_i')^2}}{\sqrt{\dfrac{1}{N}\sum\limits_{i=1}^{N}y_i^2} + \sqrt{\dfrac{1}{N}\sum\limits_{i=1}^{N}y_i'^2}} \tag{1}$$

Where, S is the score of overall abundance evaluation, $S \subseteq [0,1]$; N is the total number of spatial states in this evaluation; y_i' is the standard number of the i spatial state in the load group and y_i is the actual number of the i spatial state in the load group; In this paper, an abundance of 0.9 is considered to be applicable.

The overall abundance can reflect the stability of the aggregated power of the entire load group. The load groups with different state intervals may have the same overall abundance, which means that overall abundance does not reflect well on individual states. Therefore, this paper proposes to compare and evaluate the load number and ideal load number in a single temperature interval, namely interval abundance.

$$S_i = (1 + (y_i - y_i') \div y_i') \div M \tag{2}$$

Where, M is the total number of temperature intervals, S_i is the abundance of the i temperature interval. Formula 2 can be used to compare the load number of a single temperature range with the ideal load number, which can better reflect the abundance of a single temperature interval.

3. Abundance adaptive frequency control strategy of temperature-control loads

3.1. Characteristic analysis of adaptive frequency control strategy

When the frequency event occurs in the power grid, traditional adaptive frequency control strategy of temperature control load changes operating state by changing the setting temperature of the air condition. In this way, traditional strategy can achieve the goal of changing the aggregated power of the load group to help the power grid regulate frequency. The changes of the high and low temperature thresholds of the temperature control load are expressed by equation 3.

$$T_{high}' = T_{high} + \Delta T$$
$$T_{low}' = T_{low} + \Delta T \tag{3}$$

$$\Delta T = K_f \times (f - f_0) \tag{4}$$

Where, K_f is the frequency response coefficient $(^\circ \text{C/Hz})$; f is power system frequency (Hz); f_0 is rated frequency of power system (Hz); T_{high} is the high temperature threshold ($^\circ\text{C}$) before modification; T_{low} is the low temperature threshold before modification ($^\circ\text{C}$); T'_{high} is the modified high temperature threshold ($^\circ\text{C}$); T'_{low} is the modified low temperature threshold ($^\circ\text{C}$). The temperature setting point changes with frequency as shown in figure. 1.

Figure 1. Variation of temperature setting point with frequency

If we assume that the setting temperature of a load group with 1000 water heaters is changed. Under the traditional adaptive frequency control strategy, the set point of the temperature of the water heater load decreases by 1°C to 5°C respectively, and the variation curve of the aggregated power of the water heater is shown in figure. 2.
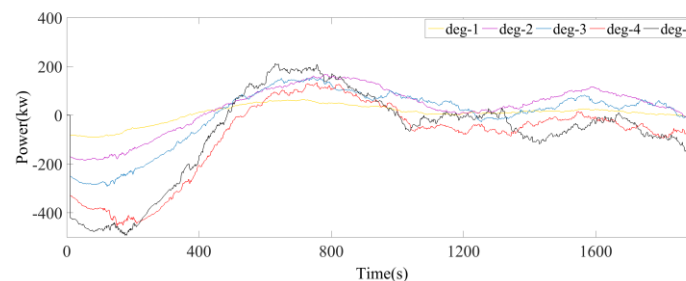

Figure 2. Variation of aggregated power under different temperature settings at low frequency events

According to the simulation results in figure. 2, at the early stage of responding to low frequency events, after lowering the temperature setting point, the aggregated load of the electric water heater can immediately provide the frequency adjustment backup to response frequency events. After a period of time reach the maximum variation of aggregated power, which can effectively help the power system achieve the balance between supply and demand. However, after a period of time, the load group aggregated power recovery process will occur in the temperature control load, during this process the power peak will be generated, exceeding the original aggregated power. Therefore, adaptive frequency control can help the power grid respond to frequency events, but due to the destruction of load group abundance, the aggregated power peak phenomenon will occur in the recovery process, which means that it may cause harm to the power grid.

3.2. The influence of abundance on frequency modulation reserve capacity of load group

The high and low temperature thresholds are divided into 10 temperature state spaces. When low frequency events occur, the spatial state of the load group is shown in figure.3. When low-frequency

events occur, the adaptive frequency control strategy is triggered. Both high and low temperature thresholds are reduced. At this time, the load power changes instantaneously. The changed particles are transferred from states 8, 9 and 10 to states 11, 12 and 13. As what is shown in figure 3, it can be clearly seen that if the number of heated state particles between the original threshold and the new threshold is different, the frequency control reserve capacity generated will be different. As a result, the traditional adaptive frequency control strategy has a hidden trouble. The trouble is the same type load group with different initial state may provide different number of reserve.
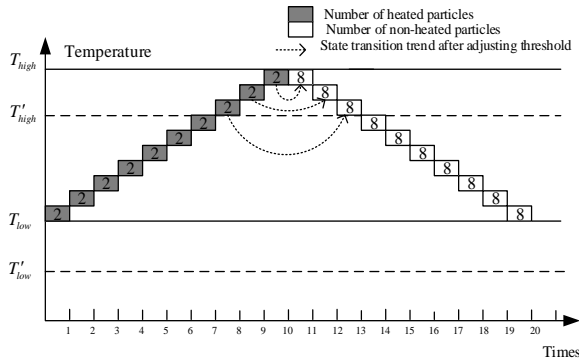

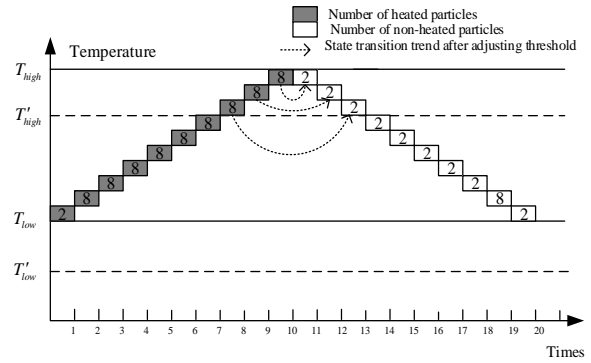Figure 3. The spatial state of the water heater with excess abundance

Figure 4. The spatial state of the water heater with lack abundance

3.3. Abundance adaptive frequency control strategy

In view of the above analysis of adaptive frequency control strategy for load group of abundance differences caused by controlled/owe problem, this article put forward the abundance adaptive control strategy. The temperature set point is no longer just about frequency offset and frequency modulation coefficient, but largely depends on the assessment results of load group state. The calculation process of temperature setting change value is shown in figure.5.
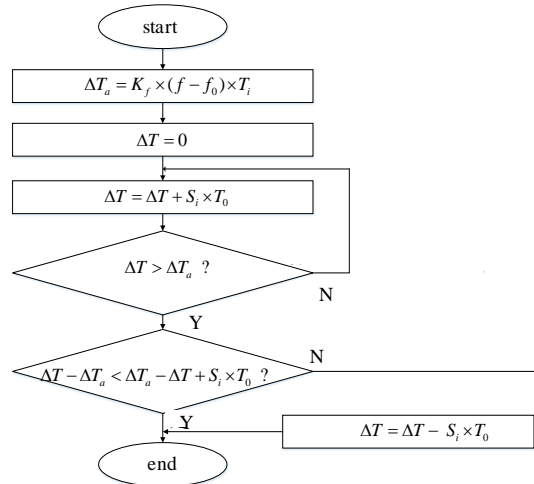

Figure 5. Calculation process of setting temperature

In figure.5, ΔT_a is the temperature change under traditional adaptive control, ΔT is the temperature change calculated under the abundance adaptive control, K_f is the frequency response coefficient, T_0 is the minimum temperature interval, S_i is the interval abundance. The abundance adaptive method is based on the traditional adaptive frequency control, and the temperature interval of

load group is divided into several equal parts. According to the abundance of the interval load group, the optimal temperature variation value is found.

4. Frequency control strategy of home temperature-control load group abundance recovery

In order to solve the problem that the spatial state abundance of load group is missing after the adaptive frequency adjustment control strategy, the temperature control load group abundance recovery control strategy is proposed. Smoothly restore the aggregated power to the average power and avoid recovery peaks/troughs. At the same time, determine the minimum recovery duration and prepare for the next frequency event. The working time required for the change of the load state is converted into the weight, the amount of allowed load for the conversion among the spatial states is equivalent to the flow. The load abundance recovery process is constructed into the fee flow network and the minimum cost and maximum flow algorithm combined with the dichotomy is adopted. Determine the minimum recovery time and ensure aggregated power of the temperature-controlled load changes smoothly throughout the recovery process and no recovery peak will occur. After the control is over, the load group will have a good abundance. The minimum cost maximum flow algorithm is shown in figure.6.
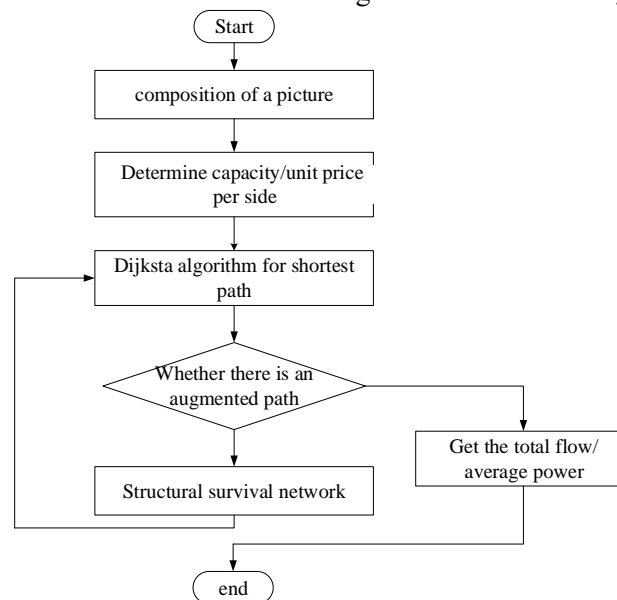

Figure 6. Minimum cost maximum flow algorithm flow

It can be seen from figure. 6 that the entire minimum cost and maximum flow process is realized on the composition, which is made based on the current spatial state of load group and the ideal spatial state of load group. After the composition, turning the problem into graph theory. The composition is the basis of solving the problem of expense flow, which is shown in figure. 4. Taking the state recovery process of a load group as an example, each side has two attributes, the left side represents the flow, which is analogized by the number of units converted from the load state, the right side represents the cost, which is analogized by the cost of the work required hours. Initial states are randomly distributed between high and low temperature thresholds, according to the working characteristic of load, the amount of work that move from the initial state position to the final state position is translated into the concept of working hours. The sum of working hours of all loads is the total cost between the super source point and the super junction point, which can be used to determine whether the given hours are the minimum hours. The total flow from the super source point to the super junction can determine whether the load group abundance state is restored successfully within a given aggregated power and time.
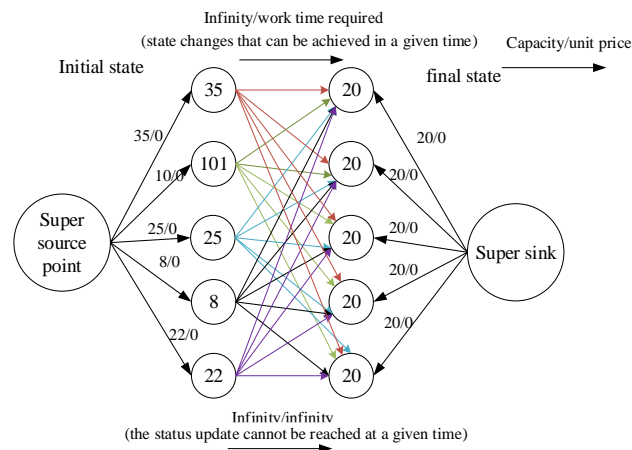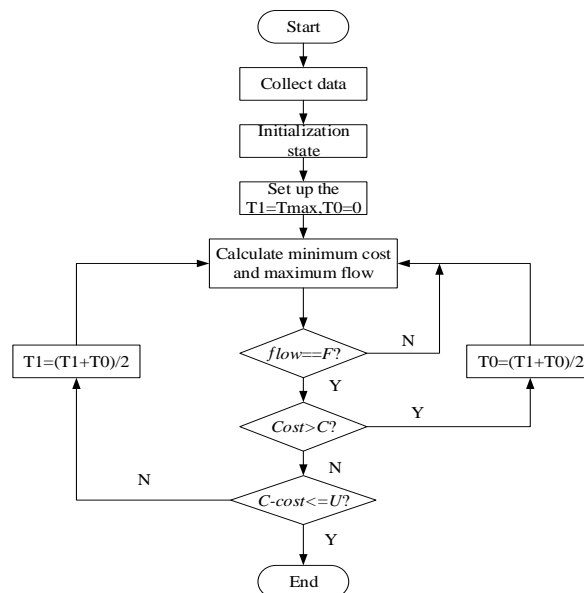
Figure 7. Cost flow diagram

Figure 8. Dichotomy judgment process

As shown in figure.7, the total cost and flow calculated by the single cost flow algorithm, which are further judged by combining the dichotomy method. If the calculated flow does not satisfy the condition of finish, the duration needs to be determined again. If it does, the time accuracy can be judged. If the time precision is not satisfied, the recovery can be done in a shorter time. If it is satisfied, it means that the optimal solution has been found.

The load group abundance control strategy guides the particle abundance restore from chaotic initial state. The control is completed within the shortest time with the given recovery power. During the control process, the state of the load group is kept between the high and low temperature thresholds and the load group abundance is good after the recovery. After adjusting the aggregated power of load group through the abundance control strategy, the peak/trough of wave can be effectively avoided, the abundance recovers well and the aggregated power is stable after the control.

5. The simulation of household temperature-control loads participation in the system primary frequency control

The simulation time is 40 seconds and 4 percent of the power generation loss occurred in the power system at 10 seconds. Selecting four scenario, namely no load participates and the proportion of temperature-control load is 0.1pu, 0.2pu and 0.35pu. The simulation result is shown in figure.9.
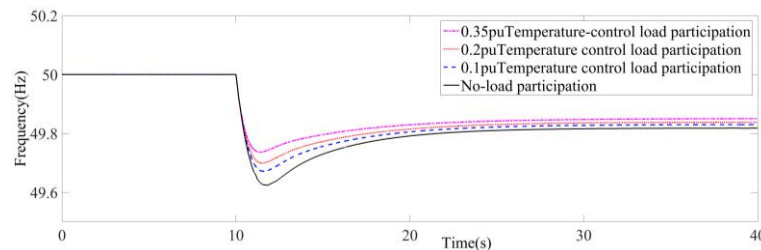

Figure 9. Load groups with different proportions participate in frequency adjustment

When the low frequency event occurs in 10s, the temperature-control load participates in the frequency control system and responds rapidly to the frequency control and the frequency drops is suppressed significantly. With the increase proportion of the temperature-control load in the whole load, the frequency control effect keeps getting better from the aspects of the maximum frequency change and the stable time.

In the case of excess abundance, the simulation time is 40 seconds and 4 percent of the power generation loss occurred in the power system at 10 seconds. Three groups of scenarios are selected for simulation. The first group without load side frequency control strategy, the second group uses the traditional adaptive control strategy and the third group uses the abundance adaptive control strategy. The frequency variation is shown in figure.10.
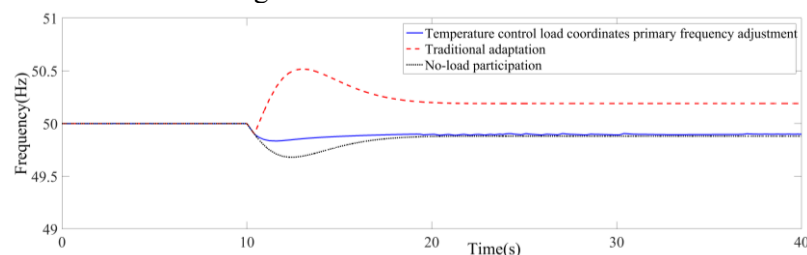

Figure 10. Load group with excess abundance participates in frequency deficiency

In the simulation, the phenomenon of over control is obviously. By adopting the abundance adaptive frequency control strategy responds to low frequency event, the abundance is taken into consideration when adjusting the temperature setting point. The simulation results show that abundance adaptive frequency control strategy can avoid the over control phenomenon and effectively providing the reserve capacity of frequency control.

In the case of lack of abundance, the simulation time is 40 seconds and 4 percent of the power generation loss occurred in the power system at 10 seconds. Three groups of scenarios are selected for simulation. The first group without load side frequency control, the second group uses the traditional adaptive control strategy and the third group uses the abundance adaptive control strategy. The frequency variation is shown in figure.11.
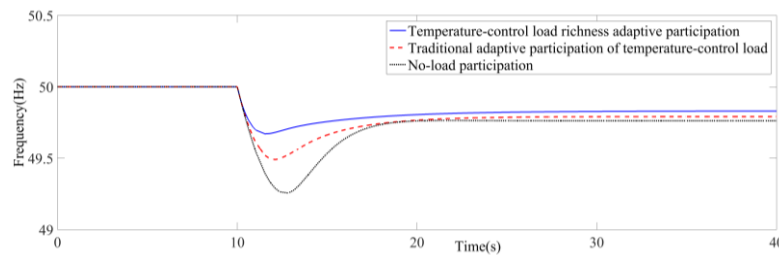
Figure 11. Load group with lake of abundance participates in frequency deficiency

The load group is in the state of lack of abundance, it is easy to produce under control phenomenon through the traditional adaptive frequency control strategy, which leads to insufficient frequency control reserve when frequency events occur. Under the circumstance of adopting abundance adaptive frequency control strategy, the adaptive frequency control strategy is more effective.

6. Conclusion

Based on the state space method, the method of state division of household temperature-control load group is proposed. Based on this method, the load group abundance evaluation model is constructed. When adaptive frequency control strategy helps the power grid to respond to frequency events, it will damage the load group abundance and generate the phenomenon of aggregated power wave peak in the recovery process. A fast and smooth recovery load group abundance control strategy based on minimum cost maximum flow algorithm is proposed to solve the problem. The effectiveness of the proposed temperature control load group response to the power system primary frequency control is verified. Simulation results show that the proposed adaptive frequency control strategy for temperature control load is effective in maintaining system temperature-control load group abundance and responding to the frequency events.

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