Multi-load Groups Coordinated Load Control Strategy Considering Power Network Constraints

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Abstract. Loads with energy storage property can actively participate in power balance for power systems, this paper takes air conditioner as a controllable load example, proposing a multi-load groups coordinated load control strategy considering power network constraints. Firstly, two load control modes considering recovery of load diversity are designed, blocking power oscillation of aggregated air conditioners. As the same time, air conditioner temperature setpoint recovery control strategy is presented to avoid power recovery peak. Considering inherent characteristics of two load control modes, an coordinated load control mode is designed by combining the both. Basing on this, a multi-load groups coordinated load control strategy is proposed. During the implementing of load control, power network constraints should be satisfied. An indice which can reflect the security of power system operating is defined. By minimizing its value through optimization, the change of air conditioning loads’ aggregated power on each load bus can be calculated. Simulations are conducted on an air conditioners group and New England 10-generator 39-bus system, verifying the effectiveness of the proposed multi-load groups coordinated load control strategy considering power network constraints.

1. Introduction
Traditionally, the load following control is used in power systems, and the load is considered as a passive physical terminal [1-2]. In the power system, there are a lot of load, such as air conditioners, refrigerators, water heaters, heat pumps and electric vehicles, with the energy storage characteristics. Short time switching or changing control parameters will not result in significant negative impact. Therefore, this kind of load can take an active participation in power balance control to provide reserve for the system [3]. With the proportion of large-capacity thermal power units and nuclear power units increasing and large-scale intermittent energy paralleling in the grid [4], the capacity cost of generation and the reserve requirements of the system increase significantly. Fully tapping the potential of load reserve is of great significance.

The difficulty of load control is that the loads are with a huge quantity and distributed widely. Implementation of the decentralized control in [5-6], which does not need to communicate with the dispatch center, has high response speed and low cost. However, if the load control is not integrated with the active power control structure of the system, it will lead to the load controls uncertainty and it is easy to result in the phenomenon of over-control or under-control. Implementing feedback control with bidirectional communication in [7-9], the control precision is high. But the load and control center need to communicate the measurement data and control instruction mutually, which reduces the...
response speed of load control and increases the implementation cost. The open-loop control with bidirectional communication is implemented in [10]. The control center sends control instructions to the load and the load receives and executes them, meanwhile the control center collects the information of the sample load and the operating state of the load group is estimated. This kind of load control method can effectively reduce the communication cost of implementing load control and guarantee certain load control precision. Therefore, it is propitious to promote its application in engineering.

Network constraints should be taken into account while the load participating in system power balance control as a backup resource, otherwise it is easy to cause branch overload or even power beyond the limit. Compared to the power supply, the distribution of the load is more extensive, distributed in the load nodes of the power network. When load control is carried out, load nodes are chosen rationally, which is helpful to optimize the power flow distribution of the system. Besides, the tension of the power grid can be relieved on the basis of ensuring the power balance of the system, and the security of the system can be improved.

Taking the air conditioner load as an example, two kinds of load control modes are proposed considering the restoration of load diversity. The control strategy of the air conditioner load restoration is described. Based on above and the inherent characteristics of the two control modes, a coordinated control mode combining two control modes is presented. Moreover, a multi-load group coordinated control strategy is proposed. The index of the safety of the system is established, and the amount of power that needs to be changed of the load group on the load control node is optimized. The simulation of the air conditioner load group and the New England 10-machine 39-node system are carried out to verify the effectiveness of the multi-load group coordinated control strategy considering the grid constraints.

2. Load control strategy

2.1. Air conditioner load model

Air conditioner has a cycle of operating characteristics. Turning on the air conditioner, the room temperature will drop. If the temperature reaches the closing border temperature value, the air conditioner will be turned off. During the air conditioner closed, the temperature rises. If the temperature reaches the opening boundary temperature, the air conditioner is turned on again. According to the principle of heat balance, the physical model of air conditioner load is established. Considering the influence of solar radiation, the direction of the house and the heat capacity of the wall, the model can be expressed by a third-order state space [11].

\[
\frac{d}{dt} \begin{bmatrix} x_{\text{in}} \\ x_{\text{out}} \\ x_{\text{adj}} \\ x_{\text{adj-r}} \end{bmatrix} = [A] \begin{bmatrix} x_{\text{in}} \\ x_{\text{out}} \\ x_{\text{adj}} \end{bmatrix} + [B] \begin{bmatrix} I_{\text{ext}} \\ I_{\text{eq}} \\ I_{\text{adj}} \cdot m(t) \end{bmatrix}
\]

\begin{align*}
A &= \begin{bmatrix}
\frac{1}{C_{\text{in}}} & \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{eq}}} & -2 & 0 \\
\frac{1}{C_{\text{in}}} & \frac{1}{C_{\text{in}} + C_{\text{eq}}} & \frac{1}{C_{\text{in}}} & 0 \\
0 & \frac{1}{C_{\text{in}}} & -\frac{1}{C_{\text{in}}} & \frac{1}{C_{\text{in}} + C_{\text{eq}}} \\
0 & 0 & \frac{1}{C_{\text{in}}} & -\frac{1}{C_{\text{in}} + C_{\text{eq}}} 
\end{bmatrix}
\end{align*}
Figure 1 shows the operating state of the air conditioner load group in the on state and the light blue line represents the probability density of the air conditioner load group in the on state. $\theta^+$ and $\theta^-_t$ are the upper and lower limits of the pre-setting temperature, respectively. $\theta^+$ and $\theta^-$ are the upper and lower limits of the setting temperature after control. $\delta$ is the increment of the setting temperature, and $\Delta$ is the difference between on/off boundary temperature values of the air conditioner.

2.2. Load Control Strategy Considering Load Diversity Recovery

The on/off state of the air conditioner can be controlled by adjusting the setting temperature. If a power shortage occurs in the system, the power demand of the air conditioner load group will reduce by increasing the setting temperature of the air conditioner which in the cooling mode. In the process of load control, the load diversity will be destroyed, causing power oscillation of the aggregated load group and adverse influence on the operation of the system. In this paper, two kinds of load control modes are designed to resume the load diversity. In the below, temperature adjusting up are as an example to analyse the mechanisms of the two control modes.

2.2.1. Control mode 1. Figure 1 shows the operating state of the air conditioner load group in the control mode 1, where the red line represents the probability density of the air conditioner load group in the off state and the light blue line represents the probability density of the air conditioner load group in the on state. $\theta^+_0$ and $\theta^-_0$ are the upper and lower limits of the pre-setting temperature, respectively. $\theta^{+}_0$ and $\theta^{-}_0$ are the upper and lower limits of the setting temperature after control. $\delta$ is the increment of the setting temperature, and $\Delta$ is the difference between on/off boundary temperature values of the air conditioner.
The operation states of the aggregated air conditioner load group can be divided into the following stages of analysis:

- Before the control, the on/off probability density of the air conditioner load group changes in a continuous state, as shown in Fig. 1 (a). The number of air conditioner units turned on and off at a certain time is the same, and the range of the aggregated power of the air conditioner load group is small.

- The air conditioner load is controlled, and all the air conditioners with the indoor temperature between $\theta^+_0$ and $\theta^-$ are closed, as shown in (b) of Fig. 1. The control can immediately reduce the power requirements of the air conditioner load group.

- After the control, there is no air conditioner load operating in the range of $(\theta^-_0, \theta^+)$, as shown in Fig. 1 (c). The control can immediately reduce the power requirements of the air conditioner load group.

- When the operating state of the air conditioner load group reaches the state as shown in (d) of Fig. 1, the air conditioner load, with the indoor temperature between $\theta^-_0$ and $\theta^+$ after control, will not reach the upper temperature limit. Then the indoor temperature continues to rise and the air conditioner enters a closed state until the temperature reaches the upper limit, $\theta^-_1$ and $\theta^-_2$, as shown in Fig. 1 (e) and (f).

- The transition temperature upper limits are set as $\theta^-_1$ and $\theta^-_2$ at the end of the operation cycle and the temperature upper limit of the air conditioner load is adjusted to $\theta^+$, as shown in (g) of Fig. 1. The air conditioner load group runs periodically between the new upper and lower temperature limits, and the on/off probability density of the air conditioner load group is continuously changing with the cycle of the air conditioner. The aggregated power of the air conditioner load group reaches a new steady state one cycle later.

2.2.2. **Control model 2.** The operating status of the air conditioner load group in control mode 2 is shown in Figure 2.

After the implementation of the control, the operation status of the air conditioner load group can be divided into the following stages:

- The upper limit of the setting temperature of the air conditioner is set to $\theta^+$, and the lower limit of the temperature remains unchanged as shown in (a) of Fig. 2.

- In the first operating cycle, when the indoor temperature reaches the lower limit $\theta^-_0$ and the air conditioner load changes the operating state, the lower limit of the air conditioner setting temperature is adjusted to $\theta^-$. The air conditioner load runs between the new upper and lower limits, $\theta^+$ and $\theta^-$, as shown in Fig. 2 (b) and (c).
• When all the air conditioner loads operate between the new temperature limits, the air conditioner load group reaches a new steady state. The on/off probability density of air conditioner load group with the air conditioner cycle is in a continuous state, and the load diversity is not damaged.

2.2.3. *Comparison of two control modes.* From the two control modes, we can draw the following conclusions: the load group diversity can be restored after control model 1 and 2. In the control process of mode 1, power shock occurs. (The aggregated power of load group is greater than the one before control) while it does not exist power shock in mode 2. The response speed of mode 1 is fast which can respond to the control like primary frequency control. The response speed of control mode 2 is slow and can be controlled in response to a longer time scale. The Monte Carlo simulation method is used for the aggregation of the air conditioner group (see parameters in 3.1). The aggregated power curve comparison of control mode 1, control mode 2 and the control mode, which directly adjusts the temperature in accordance with the control command, is shown in Figure 3, which validates the above conclusions further.

![Figure 3. Comparison of air conditioner loads’ aggregated power among three different control modes.](image)

2.3. *Load restoration control strategy*
In order not to cause significant negative impact on the users, it is needed to restore the setting temperature of the air conditioner. In the recovery process, power peak is prohibited. Otherwise, it will lead to adverse impact on the grid operation. At the same time, the diversity of the load is restored in preparation for the next control command. In this paper, load recovery control strategy is proposed according to different period of time. In accordance with the control mode 2, the setting temperature is adjusted to the value before control n cycles later after the control, where n is a random integer, such as an integer between 1 and 3.

3. *Multi-load group coordination control considering network constraint*

3.1. *Multi-load group coordination control framework considering network constraints*
Multi-load group coordination control framework considering network constraints are shown in Fig. 4. The controllable air conditioner load of each load node is divided into groups and different load groups can adopt different control modes. In each load group, a measurement device is installed on the sample air conditioner load to collect the running status information of the sample load in real time, including the terminal characteristics of the load, temperature data, humidity, wind speed, sunshine and so on, and the external control commands. The information is uploaded to the grid control center, and the operating status of the load groups is estimated. The load coordination controller in the control center sets the control command of the load group according to the active power target value to be tracked and the running state of the system. When the load control mode 1 is used, the load groups can participate in the primary frequency regulation or longer time scale control. In order to eliminate the power shock in load control mode 1, load control mode 2 is applied to other partial load groups. Then there will be no power shock in the total power of the load group with different control strategies, and the coordinated control among multiple load groups is realized. In the process of the node selection and the calculation of load control, network constraints are taken into account.
3.2. Multi-load group coordination control

Assume that a load group using control mode 1, at \( t_1 \) moment the load reduces power requirements in response to control command, and the aggregated power curve of the air conditioner load group is shown as the imaginary line in Figure 5. The other load group on the load node is controlled by control mode 2 at \( t_2 \) moment and the aggregated power curve is as shown in the dotted line in Fig.5. \( \Delta P_2 - \Delta P_1 = \varepsilon \), where \( \varepsilon \) is the expected power change of the air conditioner load group, \( \Delta P_1, \Delta P_2 \) as shown in the figure below. The power of the load group with different control strategies is not impulsive after superposition, as shown in the solid line in Fig.5. The key to control the load group coordination in two control modes is to determine the control command \( \Delta P_2 \) and the response time \( t_2 \) of the load group in the control mode 2 according to \( \Delta P_1 + \varepsilon \) and \( t_3 \) after the load group control in control mode 1. According to \( \Delta P_2 \), the change of the setting temperature of the load group can be determined.

![Figure 5. Schematic diagram of coordinated control between control mode 1 and 2.](image)

The total load group of the control mode 1 and the control mode 2 can be coordinated with the load group of the same characteristic or other load groups adopting the control mode 2 to control the external characteristics of the total load group as shown in Figure 6. Load recovery control strategy is included in the control of each load group.

![Figure 6. Schematic diagram of multi-load groups coordinated load control.](image)

3.3. Calculation of load control power based on DC power flow

A PI (Performance Index) that comprehensively reflects operational security is defined as:

\[
PI = \sum_{k=1}^{f} \frac{\omega_k S_C}{(P_k^f - P_k^s)/P_k^s}
\]  

(4)

Where \( P_k \) is the active power flow of the line \( k \) in the current operating state of the system with the actual direction of power flow as the positive direction, \( P_k^f \) is the transmission capacity of the line \( k \), and \( \omega_k \) is the weight coefficient of the line \( k \), which reflects the important degree of the line and can be calculated by the definition index of the maximum flow theory [12]. \( S_C = \sum_{i=1}^{m} \lambda_i S_{C_i} \), \( S_{C_i} \) is the
sensitivity of the injection power of the fault node $i$ to the power flow of branch $k$ in the contingency set, and $\lambda_i$ is the weight coefficient of the predicted fault node $i$, reflecting the severity of the fault and the probability of occurrence, $\sum_{i=1}^{N} \lambda_i = 1$. $m_i$ is $\pm 1$ variable. When the fault node loses power generation (or the load increases suddenly), $m_i=-1$. Otherwise, $m_i=1$. $N$ is the number of fault nodes in the contingency set. It can be seen from equation (4) that PI is a positive value and the system security is poor when the value is large.

Suppose the system has $n$ nodes, $G$ and $D$ are the generator node set and the controllable load node set, respectively. The injection power of node $i$ is $p_i$. When power balance failure occurs, the system regulates the generation and the setting temperature of air conditioner load groups automatically or in accordance with dispatcher’s command to achieve power balance. Taking into account the power balance equation of the system, the load control node can be calculated using the following optimization problem based on DC power flow:

$$\min \text{PI}$$

subject to

$$\sum_{i=1}^{n} \Delta p_i = 0$$

$$P_{gimin} \leq p_i \leq P_{gimax} \quad i \in G$$

$$-\Delta P_{ACmin} \leq \Delta p_j \leq \Delta P_{ACmax} \quad j \in D$$

$$-F_{lmax} \leq F_l \leq F_{lmax}$$

Where $\Delta p_i$ is the power lost by the system failure and the power adjusted by the generator and the controllable load. $P_{gimax}$ and $P_{gimin}$ are the upper and lower limits of the output of the generator $i$, respectively. $\Delta P_{ACmax}$ and $\Delta P_{ACmin}$ are the downward and upward regulating power limits of the aggregated load power of the controllable load node $j$. $F_{lmax}$ is the power transfer capacity of the branch $l$, and $L$ is the line set. The variable to be solved is the change of the injected power of the node, including the variation of the generator output and the controllable load power.

4. Simulation analysis

4.1. Case study system

It is assumed there are 10,000 air conditioners in a load group, the parameters are sampled in the range of values, including the external environment, the initial value and the probability distribution of the parameters [11], the indoor thermal resistance, heat capacity and the probability distribution it obeys. The difference between the on/off boundary temperature of air conditioner is 0.5℃. Taking the New England 10-machine 39-node system as an example, the adjustment of the controllable load node power based on DC power flow is calculated. The generator, load and network parameters are described in [13].

4.2. Simulation results

4.2.1. Verification of multi-load group coordination control strategy. It is supposed there are 8 sets of air conditioner load groups and Monte Carlo simulation is used to simulate its operation. The air conditioner setting temperature is increased by 0.2℃ according to the control mode 2, and restored to the setting temperature after n cycles operation according to the control mode 2, where n is a random integer in the range of (1,3). The reduction of the air conditioner load group power is shown in Fig. 7 after the coordinated control.
4.2.2. Optimal selection of load control node based on DC power flow and calculation of load controlled.

It is supposed that bus 38 of the 10-machine 39-node system loses 200 MW of power generation, and the controllable air conditioner load is set to participate in the power balance control at the 3, 4, 7, 8, 15, 16, 18, and 20 buses. The load control nodes can provide up to 40 MW controllable air conditioner load power regulation. Based on the DC power flow, the load reductions of the load control node are shown in Table 1.

| Load node | 3 | 4 | 7 | 8 | 15 | 16 | 18 | 20 |
|-----------|---|---|---|---|----|----|----|----|
| Power reduction/MW | 40.0 | 12.0 | 40.0 | 37.0 | 17.3 | 24.5 | 40.0 | 0.0 |

5. Conclusion

Two kinds of restoration control modes and restoration control strategies of the air conditioner load are designed. Taking the air conditioner load as an example, the coordinated control mode is proposed considering the inherent characteristics of the two control modes, and multi-load group coordinated control strategy is designed further. In the process of load control, network constraints are taken into account, and indicators reflecting system security are established. The power quantity of load groups that needs to be changed on the load control node is optimized. Based on the balance of power generation and load power, the security of system operation is improved. The air conditioner load group and New England 10-machine 39-bus system are simulated to verify the effectiveness of the multi-load group coordinated control strategy considering grid constraint.

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