An emergency control strategy considering variable frequency air conditioning load

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Abstract. As a high-quality flexible load, variable frequency air conditioning load has the potential to respond quickly to emergency control without significantly negative impact on users. This paper presents an emergency control strategy considering aggregated variable frequency air conditioning load. First, the operation principle of air conditioning is introduced, and a single air conditioning model is established. On this basis, the two control methods are compared and analyzed, and the impact of location on emergency control strategy is considered. The effectiveness of the emergency control strategy is verified by an example simulation.

1. Introduction

With the access of large-scale new energy generation to power grid and the wide application of direct current transmission, the safe and stable operation of power system will face a great challenge when DC blocking failure occurs[1]. Measurements such as DC power boost, accurate load shedding and generator tripping are common emergency control measures to ensure rotor angle stability, frequency stability and voltage stability of power system. At present, most of the emergency load shedding is cut to the feeder level, regardless of the type of load contained in the feeder, which has a greater negative impact on social life after power outage. Air conditioning converts electrical energy into heat energy with a larger time constant and a higher proportion in summer and winter [2], transient excision does not have a significant negative impact on the user. Currently, the existing research is mainly focused on fixed-frequency air conditioning, while the research on variable-frequency air conditioning is insufficient. However, variable-frequency air conditioning has occupied 70% of the market, and the response of fixed-frequency air conditioning is not timely when it is controlled, and the variable-frequency air conditioning can respond quickly. In view of the problems in the current emergency control load shedding strategy, this paper presents an emergency control strategy considering aggregate frequency conversion air conditioning. Different control methods are analyzed and compared, and the validity of the proposed control strategy is verified by simulation.

2. Modeling and Control Methods for Air Conditioning

2.1. Formatting the title

Currently, the common models to simulate the energy consumption of air conditioning are the heat and cold exchange model and the equivalent thermal parameter (ETP) model [3]. This work is based on the first-order equivalent thermal parameter model of air conditioning. This model is described below and the expression formula is as follows.
\[ C \frac{dT_{in}(t)}{dt} = \frac{1}{R} \left[ T_{out}(t) - T_{in}(t) \right] - Q_{AC}(t) \]  
\[ (1) \]

Formula \( T_{in} \) denotes indoor ambient temperature in units °C, \( T_{out} \) denotes outdoor ambient temperature in units °C, \( R \) denotes equivalent thermal resistance of buildings in units °C/Kw, \( C \) denotes equivalent heat capacity of buildings in units kWh/°C; \( Q_{AC} \) denotes refrigeration capacity of air conditioning in units of kW. Simplify the above:

\[ T_{in}^{t+1} = T_{out}^{t+1} - Q_{AC}^{t} \cdot R - \left( T_{out}^{t} - Q_{AC}^{t} \cdot R - T_{in}^{t} \right) \cdot e^{-\frac{dt}{RC}} \]  
\[ (2) \]

Data of refrigeration capacity and power varying with frequency during operation are recorded from low frequency to high frequency under standard refrigeration conditions[4]. Fitting the relationship between refrigeration capacity, power and compressor frequency yields the following function relations:

\[ Q_{AC} = af + b \]
\[ P_{AC} = cf + d \]  
\[ (3) \]

In formula, \( f \) is the air conditioning compressor frequency(unit of Hz), \( a,b,c,d \) is a constant fitted to the data and is related to the air conditioning model. Common compressor control logic calculates the target frequency by the difference between user-set temperature and indoor temperature.

\[ f = \begin{cases} f_{max} & \Delta T \geq T_1 \\
f_{min} + (\Delta T + 1)(f_{max} - f_{min}) & T_2 \leq \Delta T < T_1 \\
f_{min} & T_3 \leq \Delta T < T_2 \\
0 & \Delta T < T_3 \end{cases} \]  
\[ (4) \]

\( f_{max} \) is the highest rated frequency of air conditioning and \( f_{min} \) is the lowest rated frequency of air conditioning. \( T_1 > T_2 > T_3 \), settings are relevant to the air conditioning model.

2.2. Frequency Conversion Air Conditioning Control Method

Air conditioning load participates in emergency control by adjusting air conditioning setting temperature[5] and directly adjusting compressor frequency. The following two control methods are analyzed separately.

2.2.1. Temperature Adjustment Method.

Increase temperature during stable operation, room temperature and frequency changes as shown in Fig.1 After increasing the set temperature of the air conditioner, the frequency of the compressor first drops to the lowest value. As the indoor temperature is gradually increased by the influence of outdoor high temperature, the frequency of the compressor also gradually increases and tends to be stable. When the air conditioner runs at the lowest frequency, the operating power decreases significantly. Assume user set temperature to \( T_{set1} \) before control, set temperature to \( T_{set2} \) after control . Assume that the user’s comfort temperature range is \([T_{min}, T_{max}]\) According to the formula (4), Room temperature changes between \([T_{set1} - T_2, T_{set2} + T_1]\), then there are \([T_{set1} - T_2, T_{set2} + T_1] \in [T_{min}, T_{max}]\), therefore, the temperature regulation method needs to meet the following equation

\[ T_{min} + T_2 \leq T_{set1} < T_{set2} \leq T_{max} - T_1 \]  
\[ (5) \]
2.2.2. Frequency Adjustment

Assuming that in the stable operation process before control, it can be considered that the indoor temperature is equal to the set temperature \( T_{in} = T_{set} \). According to the formula (1-4)

\[
\begin{align*}
Q_{AC}(t) &= \frac{1}{R}[T_{out}(t) - T_{in}(t)] \\
f_{set} &= \frac{T_{out} - T_{set} - b}{a} \\
P_{AC} &= c \cdot \frac{T_{out} - T_{set} - b}{a} + d
\end{align*}
\]

(6)

Where \( f_{set} \) is the frequency of smooth operation of the air conditioning compressor when the user sets the temperature as \( T_{set} \). When the outdoor temperature is constant, the power \( P_{AC} \) is inversely proportional to the set temperature \( T_{set} \). The lower the set temperature before control, the greater the potential of reduction. Set \( P_{AC}(T_{out}, T_{set}) \) to indicate that the outdoor temperature is \( T_{out} \) and the user set the temperature of \( T_{set} \). The power consumption of the air-conditioner running smoothly will run smoothly with \( P_{AC}(35, 25) \) at first, then adjust to \( P_{AC}(35, 28) \). The change of indoor temperature and air conditioning consumption power is shown in Figure 2.

After the regulation, the power drops instantaneously, and the room temperature rises slowly with the outdoor high temperature and approaches the set value infinitely. The user comfort zone is \([T_{min}, T_{max}]\) according to the formula [6], the compressor frequency operation zone \([f_{min}, f_{max}]\)

\[
\begin{align*}
(f_{min} &= ((T_{out} - T_{min}) / R - b) / a, f_{max} &= ((T_{out} - T_{min}) / R - b) - a)
\end{align*}
\]

is calculated under the condition of satisfying the comfort degree.

The adjusted frequency should be within \([f_{min}, f_{max}]\) set the operating frequency of the compressor before control as \( f_{set1} \), and that of the compressor after control as \( f_{set2} \), which meets the requirements of \( f_{max} \geq f_{set2} \geq f_{set1} \geq f_{min} \).
3. Selection of control air conditioning area

According to EEAC theory, when the system breakdown, the system dominant image is generated, the motion track of the multi-generator system is mapped, the advanced generator group S and the backward generator A are determined, and the image $P - \delta$ curve shown in Figure 4 is calculated.

$$\delta_{sa} = \sum_{i \in S} M_i \delta_i \sum_{j \in A} M_j \delta_j \sum_{i \in S} M_i$$

$$P_{m,sa}, P_{e,sa}, \delta_{sa}$$ The formula is as follows:

$$P_{m,sa} = \frac{M_a \sum_{i \in S} P_{mj} - M_s \sum_{j \in A} P_{mj}}{M_T} \quad P_{e,sa} = \frac{M_a \sum_{i \in S} P_{ei} - M_s \sum_{j \in A} P_{ej}}{M_T}$$

Among them, $M$ is the inertia of the generator, $P_m$ and $P_e$ are the mechanical power and electrical power of the generator, and the subscripts $s, a, s_a$ represent the corresponding variables of the leading group, the backward group and the image system respectively, $M_T = M_s + M_a$. In Figure 3, the system fails at point B, at point C it is removed, at B-C the system is in the acceleration phase of forward swing, and at DE the deceleration phase of forward swing. If the aggregate air conditioning load is in group A and the compressor frequency $f$ is reduced at point E, then the load of group A decreases and $\delta_{sa}$ decreases, and the increase of $P_{e,sa}$ is known by formula. The $P - \delta$ curve of the image system changes from point E to point F, the deceleration area increases from $S_2$ to $S_2 + \Delta S$, and the system transient stability margin $\eta_\delta = (S_2 - S_1) / S_1$ also increases.

Only when the system is in the forward swing phase and the aggregate air conditioning load is in the backward group, can reducing the compressor frequency be conducive to the system transient voltage stability and transient frequency safety at the same time. If these conditions are not met, reducing the compressor frequency will reduce the transient stability.

4. Simulation validation

4.1. Analysis of Load Control Method for Aggregate Air Conditioning

In the aggregation of variable frequency air conditioning load group, the diversity of air conditioning equipment type, building parameters and the flow of people in the room is considered. However, for the air conditioning load in the same building group, the structure of the house is similar to the model of air conditioning equipment. It can be concluded that the key parameters obey a certain probability distribution. Monte Carlo simulation can be used to study the aggregated air conditioning load group. There are 10,000 air conditioners in the same building group participating in the control. The parameters in Table 1 obey the positive-too distribution.
| Unit | Numerical value and distribution |
|------|---------------------------------|
| R°C/kW⁻¹ | N(10,1) |
| CkJ/°C⁻¹ | N(200,0.5) |
| Tm°C | N(25,1.12) |

Table 1. Parameter Distribution.

Assuming that the outdoor temperature tout is maintained at 35 ° during the control period and the rated power of the air conditioner is 2kW, the control effects of different methods are compared under the condition of meeting the requirements of comfort. At the time of 300 seconds, adjust the set temperature to 28 °C and set the compressor frequency to 22.53Hz. The load power variation of aggregate air conditioning under the two control modes is shown in Figure 3.

When the temperature control is adjusted, the aggregated power drops instantly and runs at the lowest power for a period of time, then the curve rises and finally tends to be stable; when the frequency control is adjusted, the aggregated power drops instantaneously and runs stably at the lower aggregate power.

Define the aggregate power reduction \( \Delta P = P_{AC} - P_{AC0} \), according to formula (6):

\[
E(\Delta P) = N \cdot \frac{E(a)}{E(c) \cdot E(R)} \cdot \left( E(T_{set1}) - E(T_{set2}) \right)
\]

(7)

It can be seen that the reduction is negatively correlated with the set temperature of the air conditioner before control. The lower the set temperature of the air conditioner before control, the greater the capacity can be reduced. The aggregate power before control is about 4300kw, and the aggregate power after control is 3223kw, with a reduction of 25%. It is consistent with the value of 3200kW calculated by formula (7).

Comparing the performance of the two control methods, the load power of the polymerization air conditioner controlled by adjusting the temperature has a drop process and a rise process, and the low-power operation time is different with the maximum temperature allowed by the user, which has fluctuation; while the power curve of the frequency control has no fluctuation, which can accurately reduce the control amount and the control time, but the reduction is relatively low, which can be controlled by adjusting more Regional aggregate air conditioning load to make up for the reduction.

4.2. Verification of control method

The PSASP7.53 WEPR136 bus system is used as a simulation example to verify the proposed emergency control location and its impact on user comfort. It is assumed that each load node has air conditioning load aggregation. The three-phase short-circuit grounding occurs at 100% of the i-side outlet between nodes 19-30, and the fault time is 0.2S.

If the fault is removed in 0.2S and no emergency control measures are taken, the system is unstable. After the fault is removed, the rotors of No. 7 and No. 8 units accelerate and lose stability. No. 7 and No. 8 units are the leading group, and No. 1 to No. 6 units are the lagging group.

(1) Scenario 1: 200ms after the fault is removed, by reducing the operating frequency of the air conditioning compressor at nodes 29, 30 and 31 of the leading fleet, 22wm, 42wm and 53wm are reduced respectively, accounting for 13%, 8% and 14% of the total load of the node.

(2) Scenario 2: 200ms after the fault is removed, by reducing the operating frequency of the air conditioning compressor at nodes 16, 18 and 19 of the backward fleet, 50wm, 43wm and 22wm are reduced respectively, accounting for 10%, 19% and 15% of the total load of the node.

The power angle curves of case 1 and case 2 without any emergency control are shown in Figure 5 above.
In case 1, when the air conditioning power is reduced in the leading group, the deceleration area is reduced, and finally the system is unstable. In case 2, when the air conditioning power is reduced in the lagging group, the deceleration area is increased, and the system tends to be stable.

5. Conclusion
In order to give full play to the potential of air conditioning load group, reduce the impact on users and reduce the cost of emergency control, this paper proposes an emergency control strategy considering variable frequency air conditioning load group. Firstly, the physical model of air conditioning is established, and the two control methods are compared and analyzed. On this basis, the location of controlled air conditioning load group is considered. Finally, the effectiveness of the proposed method is verified by a practical example.

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