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Operating reserve evaluation of aggregated air conditioners

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HIGHLIGHTS

- A novel control strategy for the aggregation model of air conditioners (AC) is proposed.
- A series of indexes are proposed to evaluate the operating reserve performance provided by ACs.
- Operating reserve performance provided by both individual AC and aggregated ACs are analysed quantitatively.
- Operating reserve from demand-side can be dispatched by the system operator similar as conventional generating units.

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ABSTRACT

The penetration of renewable energy sources (RES) in power system is increasing around the world. However, the severe intermittency and variability characteristics of RES make the operating reserve become more and more important for the electric power system to maintain balance between supply and demand. Moreover, the flexible loads, especially for air conditioners (AC), are growing so rapidly that they account for an increasingly large share in power consumption. With the development of information and communication technologies (ICT), ACs can be monitored and controlled remotely to provide operating reserve and respond actively when needed by the electric power system operation. In this paper, a novel control strategy for the aggregation model of ACs based on the thermal model of the room is proposed. By resetting the temperature of each AC, the operation state is adjusted temporarily without affecting customers' satisfaction. The operation characteristics of both individual AC and the aggregation model of ACs are analysed. Furthermore, several indexes are put forward to evaluate the operating reserve performance, including reserve capacity, response time, duration time and ramp rate. The effectiveness of the proposed control strategy is illustrated in the numerical studies.

1. Introduction

The utilization of renewable energy sources (RES) is burgeoning to deal with the rapidly increasing energy consumption and environment deterioration [1]. However, the large fluctuation and severe intermittence of RES make the power generation less predictable and controllable. Furthermore, the high penetration of RES, such as wind power and photovoltaic power, has posed a great challenge to the security and reliability of the power system operation [2]. Therefore, more operating reserve is required for the system to maintain balance between power supply and demand [3]. Operating reserve is the generating capacity available in a short period of time to avoid power shortage that results from emergencies, such as random failures of the generator and load fluctuations [4]. Operating reserve is mainly provided by conventional large generators, especially thermal power generating units and hydro turbines. However, thermal power generation may be phased out in the future. Moreover, the fluctuation brought by the growing share of RES will continuously increase, while the conventional operating reserve providers may not be able to satisfy the requirements of the system with burgeoning RES in the future. Therefore, the shortage of operating reserve has become an urgent issue for both power system operation and planning [5,6].

The development of information and communication technologies (ICT) has made the remote control of flexible loads much easier [7]. Thus it is possible for small end-customers to provide operating reserve to support power system's operation. Studies in [8,9] have illustrated that flexible loads have positive effects on maintaining system balance between supply and demand. Small end-customers can serve as balancing resources through the application of smart controllers and smart meters [10]. By

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Nomenclature

Acronyms

RES	renewable energy sources
AC	air conditioner
ICT	information and communication technologies
HVAC	heating, ventilating and air-conditioning loads
RC	reserve capacity
RT	response time
DT	duration time
RR	ramp rate
COP	coefficient of performance
PER	simulation period

Variables and parameters

H_{gain}	total heat gains of the room
H_{loss}	total heat losses of the room
H_{AC}	heating/cooling generated by AC
$H_{internal}$	heat gain from appliances and occupants
H_{solar}	solar radiation received by the room
c_A	heat capacity of air
ρ_A	density of air
T_A	temperature in the room
T_O	ambient temperature
$T_{set}^{(k)}$	set temperature of the kth AC
$T_{set2}^{(k)}$	reset temperature of the kth AC
ΔT_{set}	temperature adjustment
$T_{hy}^{(k)}$	hysteresis band control of temperature
A	living area of the room
h	height of the room
A_S	surface area of the room envelope
V	volume of the room
ε	coefficient of heat release by appliances and occupants
$P_{incident}$	time-varying coefficient of heat absorbed from the sun
S	operation state of AC
S_{cool}	cooling state of AC
S_{heat}	heating state of AC
S_{styb}	standby state of AC
P	power of AC
$P_{cool}^{(k)}$	power of the kth AC in cooling state
$P_{styb}^{(k)}$	power of the kth AC in standby state
$PD_{cool}^{(k)}$	length of time in cooling state
$PD_{styb}^{(k)}$	length of time in standby state
k	serial number of ACs
N	total number of ACs
t	time
t_{ds}	start moment of duration time
t_{de}	end moment of duration time
α	valid interval of providing operating reserve
P_{max}	maximum power before receiving the control signal
P_{min}	minimum power after receiving the control signal
SS	send control signal
SR	receive control signal
t_{SS}	the moment of sending control signal
t_{SR}	the moment of receiving control signal

utilizing the communication infrastructure of the smart grid, small end-customers are able to control their daily energy consumption and adapt their electricity bills to their actual economic conditions [11].

As one of the most popular and easily controlled flexible loads, air conditioners (AC) account for a large share in power consumption due to the mass application across the world [12]. According to a study carried out in Spain, electricity consumption of residential ACs accounts for about one third of the peak electricity consumption in large cities during the summer [13]. Therefore, ACs have yielded enormous potential in serving as energy storage devices, which can provide operating reserve by reducing power consumption temporarily. In this field, some researches have been conducted. For example, heating, ventilating and air-conditioning (HVAC) loads are controlled to adjust their demand profiles in response to the electricity price [7,14,15]. The potential for providing intra-hour load balancing services using aggregated HVAC loads has been investigated in [16]. Meanwhile, inconvenience to customers should be reduced as much as possible when ACs are controlled to provide operating reserve for power system [17–21]. Fuzzy logic-based approaches have been used in [17–19] to optimize both customer's satisfaction and utility savings. The AC's on/off control time is considered in [20], which introduces a dynamic programming approach to minimize the load reduction in order to reduce the customers' discomfort. Ref. [21] combines the advantages of linear and dynamic programming approaches to enable an acceptable level of services. Moreover, some field demonstration projects in [22–26] have shown the benefits of the demand response. For example, Con Edison, an energy company in New York City, provides customers with free *smart air-conditioning kits*, which help customers control their ACs remotely while earning rewards [25]. Several countries in Europe, e.g. England, Germany and Denmark, have started smart heat pump projects to help balance generation and demand [26].

However, all the above control strategies are based on the on/off control strategy, which comes into effect only by making the ACs switch between the mode of on and off. The on/off control strategy is a rough control method that sheds load directly, which will cause a sudden change in the power, bring a disturbance to the customers involved in demand response programs, and have a negative impact on the operation and performance of ACs. With the development and reform of the electric utility industry, customers' satisfaction with electric services will be increasingly more important.

Furthermore, several unified indexes, including the minimum/-maximum generating capability, the start-up/shut-down time, the minimum/maximum reserve capacity, and the ramp-up/ramp-down rate limit, have been developed for evaluating the operating reserve performance provided by conventional power generating units [27,28]. However, there are few researches which evaluate the performance of operating reserve provided by ACs for maintaining system balance. Only one index, the load-shedding capacity or load reduction, is defined to evaluate the performance of reserves for ancillary services in [16,29–31]. This index may not be comprehensive to evaluate the performance of operating reserve provided by ACs, since it is not clear whether the ACs can meet the requirements of providing operating reserve for the power system, how long the response time of the aggregated ACs is, and how long the load-shedding state of ACs can last. Therefore, the evaluation indexes for operating reserve provided by ACs are not sufficient. Consequently, the operating reserve provided by generation-side and demand-side cannot be dispatched collaboratively. Moreover, the lack of unified evaluation indexes makes it difficult to optimize the control of aggregated ACs, and increases

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