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Virtual energy storage model of air conditioning loads for providing regulation service

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Abstract

As the pressure of supply–demand balance increases with the high penetration of renewable energy resources, it is widely accepted that demand side resources including air conditioners (ACs) play an important role in providing ancillary services to the grid. In this paper, air conditioning loads are modeled as a kind of virtual energy storage device based on their inherent thermal storage capacity. It is investigated that air conditioning loads can provide regulation service with certain storage power output and ramping rate limits as a result of minimum on/off time requirements. Simulation studies demonstrate the effectiveness of the proposed method by coordinating ACs to track a regulation signal.

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Keywords: Aggregation of air conditioning loads; Virtual energy storage; Regulation service; Load flexibility; Demand response

1. Introduction

Deep penetration of renewable energy resources into the grid brings great challenge to the balance between supply and demand, which requires substantial reserves from generation side and demand side [1–3]. Studies by Mahmud et al. [4] and Maasoumy et al. [5] indicate that with the development of information and communication technologies, it is well recognized that demand side resources present enormous potential for various services including peak load shaving, load following and frequency regulation. It has been found by Lu [6] and Bashash and Fathy [7] that thermostatically controlled loads (TCLs) such as air conditioners (ACs), who possess heat storage capacity and can still meet the desired comfort level when their power consumptions are varied, are considered as good candidates for providing ancillary services.

In this paper, air conditioning loads are regarded as a kind of virtual energy storage device. Firstly, the virtual energy storage models of individual AC and aggregated ACs are established according to thermodynamic model.

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Then, the power output bound and ramping rate bound of virtual energy storage are derived on the basis of load availability. Finally, the efficacy of the proposed method is validated by tracking a regulation signal in the simulation.

2. Virtual energy storage model of ACs

2.1. Model of individual AC

Thermodynamic model of AC is used to describe the thermal dynamic transition process in a room. The simplified equivalent thermal parameters (ETP) model shows the temperature evolution in (1).

$$C \frac{dT_{in}(t)}{dt} = \frac{T_{out} - T_{in}(t)}{R} - \eta m(t) P^{rated} \quad (1)$$

where $T_{in}(t)$ is the room temperature, C and R are equivalent thermal capacitance and thermal resistance, T_{out} is the ambient temperature, η is the energy efficiency ratio, P^{rated} is the rated power. $m(t)$ is a binary variable that indicates the operating state (1 for open, 0 for closed), which is given as

$$m(t + \Delta t) = \begin{cases} 1 & T_{in}(t + \Delta t) > T_{set} + T_{delta}/2 \\ 0 & T_{in}(t + \Delta t) < T_{set} - T_{delta}/2 \\ m(t) & T_{set} - T_{delta}/2 \leq T_{in}(t + \Delta t) \leq T_{set} + T_{delta}/2 \end{cases} \quad (2)$$

where T_{set} is the temperature setpoint, T_{delta} is the temperature deadband.

Air conditioning system possesses heat storage capacity similar to traditional energy storage, specifically, when its power consumption is varied, the room temperature will not change rapidly at once and can still meet the desired comfort level of user. Hence, it can be constructed as a virtual energy storage. It is noticeable that the concept of virtual energy storage is used to describe the variation process of room temperature and power consumption, which can be analogy with the variation process of stored energy and storage power of traditional energy storage. The drop and rise of room temperature correspond to the storage and release of energy in the storage device. It is intelligible that, with regard to a AC constructed as a virtual energy storage device, the stored energy is maximum when the room temperature is $T_{min}(T_{set} - T_{delta}/2)$ while the stored energy is minimum when the room temperature is $T_{max}(T_{set} + T_{delta}/2)$. According to the model of traditional energy storage, the stored energy $E_{VES}(t)$ and storage power $P_{VES}(t)$ of virtual energy storage are described as

$$\begin{cases} E_{VES}(t) = \frac{C(T_{max} - T_{in}(t))}{\eta} \\ P_{VES}(t) = m(t)P^{rated} - P^0 \\ P^0 = \frac{T_{out} - T_{in}(t)}{\eta R} \end{cases} \quad (3)$$

where P^0 is baseline power that keeps the room temperature at T_{set} .

From (1) and (3), the virtual energy storage model of individual AC can be expressed as

$$\begin{cases} \dot{E}_{VES}(t) = -\frac{1}{RC}E_{VES}(t) + P_{VES}(t) + \frac{T_{delta}}{2\eta R} \\ 0 \leq E_{VES}(t) \leq \frac{CT_{delta}}{\eta}, -P^0 \leq P_{VES}(t) \leq P^{rated} - P^0 \end{cases} \quad (4)$$

The variation of the stored energy during the k th period can be calculated by the integration of $\dot{E}_{VES}(t)$ from $k \Delta t$ to $(k + 1) \Delta t$, thus the stored energy evolution of individual AC can be written as

$$E_{VES}(k + 1) = e^{-\frac{\Delta t}{RC}} E_{VES}(k) + RC(1 - e^{-\frac{\Delta t}{RC}})P_{VES}(k) + \frac{CT_{delta}}{2\eta}(1 - e^{-\frac{\Delta t}{RC}}) \quad (5)$$

Accordingly, the state of virtual charge (SOVC) of individual AC is given as

$$sovc(k + 1) = e^{-\frac{\Delta t}{RC}} sovc(k) + \frac{\eta R}{T_{delta}}(1 - e^{-\frac{\Delta t}{RC}})P_{VES}(k) + \frac{1}{2}(1 - e^{-\frac{\Delta t}{RC}}) \quad (6)$$

2.2. Model of aggregated ACs

For a population of ACs, the heterogeneity of parameters and states would increase pressure on calculation when dispatched. Therefore, virtual energy storage behaviors of aggregated ACs deserve research. The SOVC evolution of the i th AC in a population with n ACs is formulated as

$$sovc_i(k + 1) = e^{-\frac{\Delta t}{R_i C_i}} sovc_i(k) + \frac{\eta_i R_i}{T_{delta,i}} (1 - e^{-\frac{\Delta t}{R_i C_i}}) P_{VES,i}(k) + \frac{1}{2} (1 - e^{-\frac{\Delta t}{R_i C_i}}), i = 1, 2, \dots, n \tag{7}$$

The dispatch period of regulation service is short, e.g. 4 s, the value of $e^{-\Delta t/RC}$ is approximately equal to 1, thus the SOVC evolution of the i th AC in a population with n ACs can be rewritten as

$$\begin{cases} \frac{sovc_i(k + 1)}{b_i} = \frac{sovc_i(k)}{b_i} + P_{VES,i}(k) + \frac{c_i}{b_i} \\ b_i = \frac{\eta_i R_i}{T_{delta,i}} (1 - e^{-\frac{\Delta t}{R_i C_i}}), c_i = \frac{1}{2} (1 - e^{-\frac{\Delta t}{R_i C_i}}) \end{cases} \tag{8}$$

Through summation operation, the SOVC evolution of aggregated ACs is described as

$$\sum_{i=1}^n \frac{sovc_i(k + 1)}{b_i} = \sum_{i=1}^n \frac{sovc_i(k)}{b_i} + \sum_{i=1}^n P_{VES,i}(k) + \sum_{i=1}^n \frac{c_i}{b_i} \tag{9}$$

$SOVC_{sum}(k)$, the state of virtual charge in the virtual energy storage model of aggregated ACs, and P_{sum} , the storage power of aggregated ACs, are defined as

$$\begin{cases} SOVC_{sum}(k) = \sum_{i=1}^n \frac{sovc_i(k)}{b_i} \\ P_{sum}(k) = \sum_{i=1}^n P_{VES,i}(k) \end{cases} \tag{10}$$

From (8)–(9), the virtual storage model of aggregated ACs can be expressed as

$$\begin{cases} SOVC_{sum}(k + 1) = SOVC_{sum}(k) + P_{sum}(k) + C_{sum}, C_{sum} = \sum_{i=1}^n \frac{c_i}{b_i} \\ 0 \leq SOVC_{sum}(k) \leq \sum_{i=1}^n \frac{1}{b_i} \\ -\sum_{i=1}^n P_i^0 \leq P_{sum}(k) \leq \sum_{i=1}^n (P_i^{rated} - P_i^0) \end{cases} \tag{11}$$

3. Flexibility of virtual energy storage

3.1. Priority-based control strategy

Based on virtual energy storage model, a population of ACs can be dispatched like traditional energy storage. A priority-based control strategy is proposed to modulate the storage power of ACs to provide regulation service.

As shown in Fig. 1, on group and off group are constructed according to ACs’ on/off states. In the on(off) group, ACs are sorted by the NT (Normalized Temperature) value from large (small) to small (large). NT values are given as

$$NT_i = \frac{T_{max,i} - T_{in,i}}{T_{max,i} - T_{min,i}}, i = 1, 2, \dots, n \tag{12}$$

Besides, for the sake of avoiding loss of life due to frequent state switching, minimum on/off time requirements are taken into consideration. If a AC satisfies minimum on/off time requirements, it is available, otherwise, it is unavailable. In order to track the regulation signal $r(t)$, storage power of aggregated ACs $P_{sum}(t)$ is compared with it. If $P_{sum}(t) > r(t)$, available ACs in the on group are controlled to turn off in sequence until $P_{sum}(t) \leq r(t)$, accordingly, if $P_{sum}(t) < r(t)$, available ACs in the off group are controlled to turn on in order until $P_{sum}(t) \geq r(t)$.

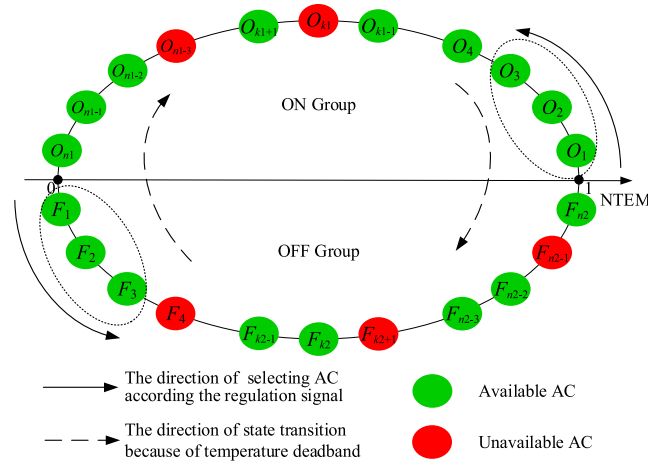


Fig. 1. Schematic diagram of priority lists in on group and off group.

3.2. Limits of storage power consumption and ramping rate

Owing to minimum on/off time constraints in the dispatching, the available storage power bound and ramp rate bound of aggregated ACs would change rather than fixed ones.

(1) storage power output bound

The deviation between regulation signal $r(t)$ and storage power of aggregated ACs before dispatch $P_{stor-before}(t)$ at time t is power imbalance $D(t)$, and the range of power imbalance is

$$\begin{cases} D(t) = r(t) - P_{stor-before}(t) = r(t) + P_{sum}^0 - [P_{ON-after}(t-1) + P_{OFF \rightarrow ON}^{natural}(t) - P_{ON \rightarrow OFF}^{natural}(t)] \\ P_{sum}^0 = \sum_{i=1}^n P_i^0 \end{cases} \quad (13)$$

$$-P_{ON-before}^{ava}(t) \leq D(t) \leq P_{OFF-before}^{ava}(t) \quad (14)$$

where $P_{ON-after}(t-1)$ is the total power of on ACs after dispatch at time $t-1$, $P_{ON \rightarrow OFF}^{natural}(t)(P_{OFF \rightarrow ON}^{natural}(t))$ is the total power of on(off) ACs who turn off(on) naturally because of temperature deadband, $P_{ON-before}^{ava}(t)(P_{OFF-before}^{ava}(t))$ is the total power of available on(off) ACs before dispatch, P_{sum}^0 is the sum of baseline power of all ACs.

Through the derivation, virtual energy storage of ACs can track the regulation signal which is bounded as

$$\begin{cases} r(t) \leq [P_{ON-after}(t-1) + P_{OFF-after}^{ava}(t-1) + P_{OFF \rightarrow ON}^{natural-unava}(t) - P_{ON \rightarrow OFF}^{natural}(t) + P_{OFF}^{unava \rightarrow ava}(t)] - P_{sum}^0 \\ r(t) \geq [P_{ON-after}(t-1) - P_{ON-after}^{ava}(t-1) - P_{ON \rightarrow OFF}^{natural-unava}(t) + P_{OFF \rightarrow ON}^{natural}(t) - P_{ON}^{unava \rightarrow ava}(t)] - P_{sum}^0 \end{cases} \quad (15)$$

where $P_{ON-after}^{ava}(t)(P_{OFF-after}^{ava}(t))$ is the total power of available on(off) ACs after dispatch, $P_{ON \rightarrow OFF}^{natural-unava}(t)(P_{OFF \rightarrow ON}^{natural-unava}(t))$ is the total power of unavailable on(off) ACs who turn off(on) naturally because of temperature deadband, $P_{OFF}^{unava \rightarrow ava}(t)(P_{ON}^{unava \rightarrow ava}(t))$ is the total power of unavailable off(on) ACs who become available at time t .

(2) ramping rate bound

The storage power consumption of ACs after dispatch at time $t-1$ is approximate to the regulation signal value at time $t-1$, thus the limits of ramping rate of regulation signal that ACs are able to track can be obtained

$$\begin{cases} r(t) - r(t-1) \leq P_{OFF-after}^{ava}(t-1) + P_{OFF \rightarrow ON}^{natural-unava}(t) - P_{ON \rightarrow OFF}^{natural}(t) + P_{OFF}^{unava \rightarrow ava}(t) \\ r(t) - r(t-1) \geq -P_{ON-after}^{ava}(t-1) - P_{ON \rightarrow OFF}^{natural-unava}(t) + P_{OFF \rightarrow ON}^{natural}(t) - P_{ON}^{unava \rightarrow ava}(t) \end{cases} \quad (16)$$

4. Case study

The proposed method is applied to follow a one-hour regulation signal. In the simulation, the aggregation consists of 1000 ACs, and the parameters are shown in Table 1. The required minimum on and off time are set as 1 min.

Table 1. Parameters of ACs.

Parameter	Value/Unit	Parameter	Value/Unit
C	[1.5,2.5]/kWh/°C	η	2.5
R	[1.5,2.5]/°C/kW	T_{set}	[21,24]/°C
p_{rated}	[4,7.2]/kW	T_{delta}	1/°C

Fig. 2 depicts the tracking performance of virtual energy storage devices. The storage power output bound and ramp rate bound considering available/unavailable states of ACs are shown in Fig. 3. It can be observed that ACs are able to track the regulation signal with high accuracy when satisfying the constraints of storage power output and ramping rate. Conversely, obvious power errors appear when the constraints are not satisfied. The maximum tracking error is at 2780 s, as shown in Fig. 2(b), the regulation signal at this moment is lower than the minimum value in the available storage output range and the increment of signal is lower than the minimum value in the available ramping rate bound. Therefore, the actual output values of virtual energy storage are corresponding limit values when the constraints are violated, which can be seen in Fig. 2(a). For example, at 2780 s, regulation signal is -1610.64 kW while the lower limit of storage power range is -1268.73 kW and the actual output of virtual storage energy is -1268.73 kW.

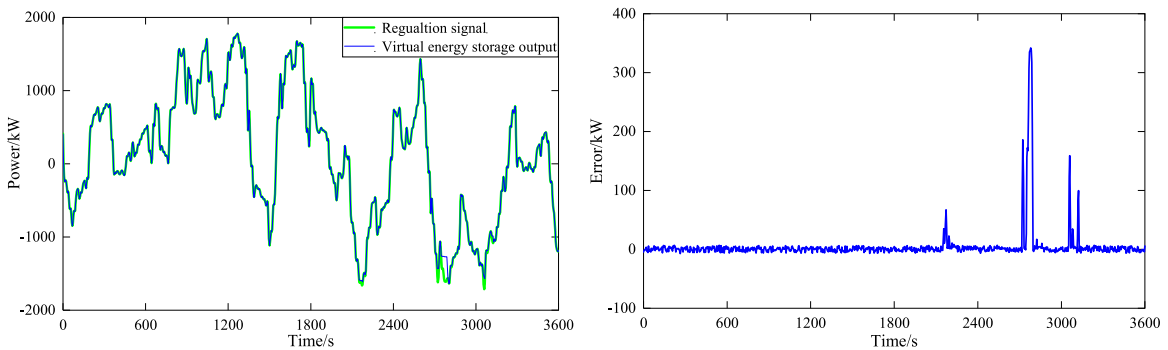


Fig. 2. Simulation results of tracking a regulation signal (a) Comparison of regulation signal and storage power output of ACs (b) Error values.

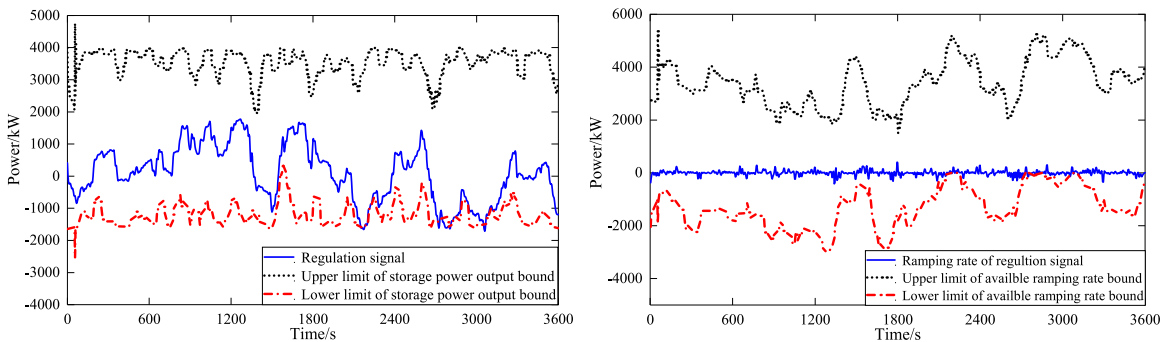


Fig. 3. Constraints of storage power and ramping rate (a) storage power output bound (b) ramping rate bound.

What is more, SOVC performances for virtual energy storage are shown in Fig. 4. In view of the deviation caused by approximation of $e^{-\Delta t/RC}$, the $SOVC_{sum}$ value of aggregated ACs in (10) is updated every 1 min to eliminate

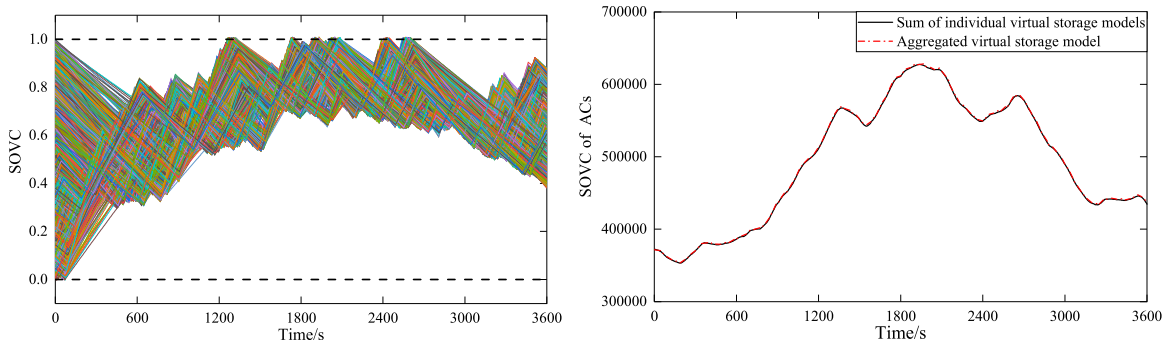


Fig. 4. SOVC profiles of ACs (a) SOVC variation curves of 1000 ACs (b) Comparison of SOVC of aggregation ACs.

distinct error from actual value. In Fig. 4(b), the results of aggregated virtual energy storage model are consistent with those of sum of individual models, which validates the modeling of virtual energy storage of aggregation ACs.

5. Conclusion

In this paper, an aggregation of ACs are utilized to provide ancillary services to the grid. Based on the proposed virtual energy storage model and minimum on/off time requirements, the storage power output limits and ramp rate limits are calculated, and a priority-based control strategy is developed to manipulate the power consumption of ACs. The effectiveness of the proposed method is verified by the simulation results of tracking a regulation signal.

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