Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 104 (2016) 50 – 55

Energy Procedia

CUE2016-Applied Energy Symposium and Forum 2016: Low carbon cities & urban energy systems

# Quantitative Analysis of Air Conditioner Aggregation for Providing Operating Reserve

Hongxun Hui[a], Weidong Liu[b], Yi Ding[a,*]

*a. College of Electrical Engineering, Zhejiang University, Hangzhou, China*
*b. Economy Research Institute of State Grid Zhejiang Electric Power Company, Hangzhou, China*

**Abstract**

With the increasing penetration of renewable energy around the world in recent years, requirements of operating reserve for maintaining system balance have become more and more important. Moreover, the development of information and communication technologies has made flexible demands, such as air conditioners (AC), heat pumps and plug-in electric vehicles provide operating reserve possible. However, characteristics and potential of these flexible demands for providing operating reserve have not been further studied. In this paper, a quantitative analysis method of air conditioner aggregation for providing operating reserve is proposed. Several evaluation indices for evaluating AC aggregation's potential of providing operating are proposed and quantified, including reserve capacity (*RC*), response time (*RT*), duration time (*DT*) and ramp rate (*RR*). Numerical studies illustrate the proposed method.


Peer-review under responsibility of the scientific committee of the Applied Energy Symposium and Forum, CUE2016: Low carbon cities and urban energy systems.

*Keywords*: quantitative analysis, air conditioner aggregation, operating reserve.

## 1. Introduction

The growing increase of energy consumption and the severe deterioration of the environment have brought huge challenges around the world [1-2]. In order to achieve sustainable development, international communities and governments have made commitments and progress on the emission reduction. For instance, the Chinese government declared a goal of decreasing $CO_2$ emissions by 40-45% each unit GDP till 2020, compared with that in 2005 [3-6].

* Corresponding author. Tel.: +86 186-6804-3033; fax: +86 0571-87951625.
*E-mail address:* yiding@zju.edu.cn.


Peer-review under responsibility of the scientific committee of the Applied Energy Symposium and Forum, CUE2016: Low carbon cities and urban energy systems.
doi:10.1016/j.egypro.2016.12.010

Renewable energies, e.g. wind & photovoltaic are considered significant for securing energy supplies and reducing pollution [7-8]. However, the high penetration of renewable energy sources (RES) has brought extra pressure of power system secure operation. Different from traditional generators, RES' power production are less predictable and controllable. The high fluctuation and intermittence of RES put forward more significant requirements of operating reserve for maintaining system balance between generation and demand.

The development of information and communication technologies has made small end-consumers for providing operating reserve possible. Flexible demands, such as air conditioners, heat pumps and plug-in electric vehicles, are fast growing and account for a larger share in power consumption side. Many studies have illustrated that flexible demands have positive effects on system balance between generation and demand [9-10]. However, the research on operating reserve performance of flexible demands is not sufficient. In this paper, a quantitative analysis method of air conditioner aggregation for providing operating reserve is proposed, since air conditioners are one of the most popular and significant flexible demands. Similar to the operating reserve provided by conventional generating units, several indexes for operating reserve provided by flexible demands are quantified, including reserve capacity (*RC*), response time (*RT*), duration time (*DT*) and ramp rate (*RR*) [11-12].

The remaining of this paper is organized as follows. AC operating reserve and AC aggregation operating reserve are analyzed quantitatively in Section 2 and Section 3, respectively. Numerical studies are presented in Section 4. Finally, Section 5 concludes the paper.

**Nomenclature**

| | | | |
|---|---|---|---|
| AC | air conditioner | *PWR* | power of ACs |
| *RC* | reserve capacity | *REFR, refr* | refrigeration state of ACs |
| *DT* | duration time | *STBY*, *stby* | standby state of ACs |
| *RT* | response time | *Sig* | control signal |
| *RR* | ramp rate | *rs* | *RT* start |
| *k* | serial number of ACs | *re* | *RT* end |
| *T, t* | time | *ds* | *DT* start |
| *RTEMP* | room temperature | *de* | *DT* end |
| *hy* | temperature hysteresis of control | $\alpha$ | bottom margin of *RC* |

## 2. Quantitative Analysis of AC Operating Reserve

### 2.1. Normal operation characteristics of AC

Fig. 1 presents the normal operation characteristics of an AC. The $RTEMP_{set}$ is set by the consumers who are living in the room. However, the *RTEMP* cannot strictly equal to the $RTEMP_{set}$ all the time. There is a temperature hysteresis of control ($RTEMP_{hy}$), which means the highest difference between the *RTEMP* and the $RTEMP_{set}$ is $RTEMP_{hy}$. The *k*th *RTEMP* interval can be expressed as

$$RTEMP^{(k)} = \left[ RTEMP_{set}^{(k)} - RTEMP_{hy}^{(k)}, RTEMP_{set}^{(k)} + RTEMP_{hy}^{(k)} \right] \tag{1}$$

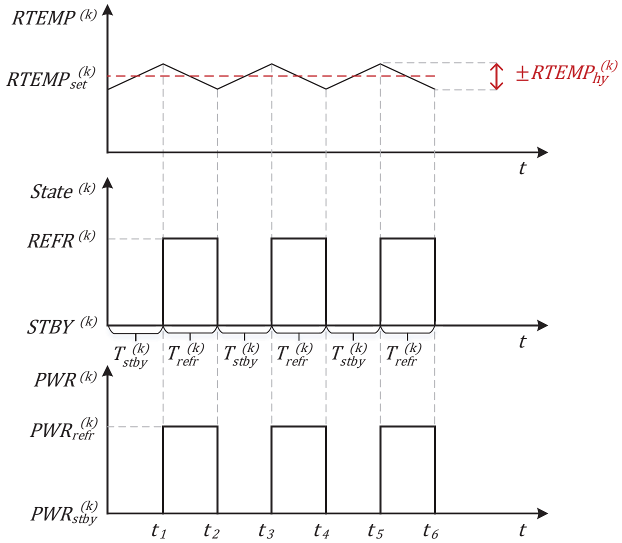


Fig. 1. Normal operation characteristics of AC

In this paper, it is assumed that all the ACs operate in the refrigeration state. When the *RTEMP* is not higher than the lower limit value $(RTEMP_{set} - RTEMP_{hy})$, the AC is turned to standby state. Conversely, when the *RTEMP* is equal to or higher than the upper limit value $(RTEMP_{set}+RTEMP_{hy})$, the AC is turned on. The *k*th AC's operating state can be expressed as

$$State^{(k)} = \begin{cases} REFR^{(k)}, & RTEMP^{(k)} \geq RTEMP_{set}^{(k)} + RTEMP_{hy}^{(k)} \\ STBY^{(k)}, & RTEMP^{(k)} \leq RTEMP_{set}^{(k)} - RTEMP_{hy}^{(k)} \end{cases} \tag{2}$$

Different from the power $(PWR)$, as shown in Fig. 1, the refrigeration power $(PWR_{refr})$ is not a constant and the standby power $(PWR_{stby})$ is not zero in practice. $PWR_{refr}$ is related to a lot of factors, such as the room area, the house internal construction, the ambient temperature and the power limit of AC. Therefore, $PWR_{refr}$ and the length of refrigeration time are variable at different times of the day.

## *2.2. Operating reserve performance of AC*

Air conditioners can provide operating reserve by cutting down the consumption of power. Compared with the on/off control strategy, resetting the temperature of AC is a softer approach to influence the consumers [13]. By increasing the set temperature from $RTEMP_{set}$ to $RTEMP_{set2}$, the AC can extend the standby time and decrease the power consumption. Notably, the AC is available to provide operating reserve when it has been turned on and the corresponding room temperature is lower than the preset highest tolerable temperature.

However, there are obvious differences of the AC operating reserve performance, due to different control signal time. It can be divided into two typical cases: control signal (*Sig*) is received in the AC's refrigeration state period $(T_{refr})$ or in the standby state period $(T_{stby})$. Three indexes for one AC operating reserve are defined, which are *RC*, *RT* and *DT*. The most important principle to calculate these indexes is comparison analysis between normal operation and after-*Sig* operation, as shown in Figure 2.

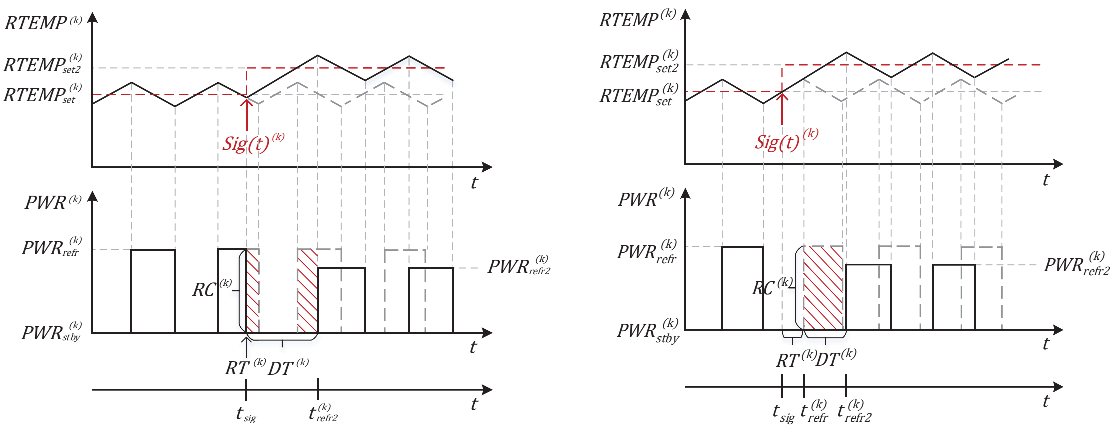


Fig. 2. Operating reserve performance of AC (a) *Sig* is received in $T_{refr}$ ; (b) *Sig* is received in $T_{stby}$

The operating reserve, provided by the *k*th AC, can be quantified as

$$RC^{(k)} = PWR^{(k)}_{refr} \tag{3}$$

$$RT^{(k)} = \begin{cases} 0 & , t_{sig} \in T^{(k)}_{refr} \\ t^{(k)}_{refr} - t_{sig} & , t_{sig} \in T^{(k)}_{stby} \end{cases} \tag{4}$$

$$DT^{(k)} = \begin{cases} t^{(k)}_{refr2} - t_{sig} & , t_{sig} \in T^{(k)}_{refr} \\ t^{(k)}_{refr2} - t^{(k)}_{refr} & , t_{sig} \in T^{(k)}_{stby} \end{cases} \tag{5}$$

## 3. Quantitative Analysis of AC Aggregation Operating Reserve

AC aggregation contains N number of ACs, which have different rated powers, *Energy Efficiency Ratios* (EER) and set temperatures. Correspondingly, there are N rooms. Each room's area and internal construction are different. Moreover, every consumer has his/her own way of life. That is, the number of ACs which have been turned on is variable at different times of the day.

In analogy to the generators that provide operating reserve, four indexes for AC aggregation operating reserve performance are quantified, which are *RC*, *RT*, *DT*, and *RR*, as shown in Figure 3.

$$RC = PWR_{\max} - PWR_{\min} \tag{6}$$

$$PWR(t) = PWR_{\max} - RC \cdot (1 - \alpha\%) \tag{7}$$

The equation (7) have two solutions

$$t_{ds}, t_{de} \ (t_{ds} \le t_{de}) \tag{8}$$

Hence, *RT*, *DT*, and *RR* can be calculated as

$$RT = t_{re} - t_{rs} = t_{ds} - t_{sig} \tag{9}$$

$$DT = t_{de} - t_{ds} \tag{10}$$

$$RR = RC \cdot (1 - \alpha\%) / RT \tag{11}$$

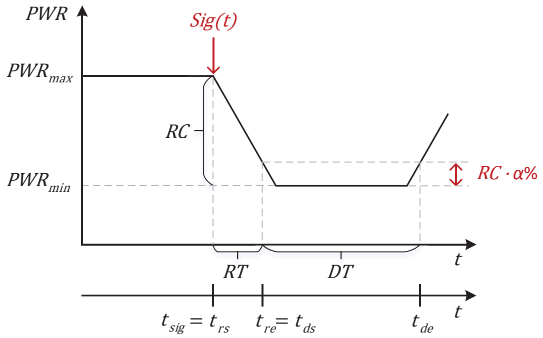


Fig. 3. Operating reserve performance of AC aggregation

## 4. Case Studies and Discussions

N independent ACs are aggregated to validate the indexes. It is assumed that all the *N* ACs belong to the residential consumers and operating normally. The initial set temperatures of each room distribute randomly between $23^{\circ}C$ and $26^{\circ}C$, and the temperature hysteresis of control is $1^{\circ}C$. The control signal time is 12:00 PM, and each AC's $RTEMP_{set}$ will increase $1^{\circ}C$ to $RTEMP_{set2}$ after receiving the signal. In this case study, $\alpha$ % is set to 10%. Table 1 present the simulation results of four indexes with different number of ACs.

Table 1. The simulation result

| Indexes | N=100 | N=500 | N=1,000 | N=5,000 |
|---|---|---|---|---|
| RC (MW) | 0.0977 | 0.2480 | 0.5493 | 2.7396 |
| RT (Min) | 2.75 | 2.67 | 3.00 | 4.08 |
| DT (Min) | 13.42 | 13.25 | 13.92 | 12.42 |
| RR (MW/Min) | 0.0319 | 0.0836 | 0.1648 | 0.6043 |

It can be noticed that the *RT* is short enough to provide operating reserve, since the AC aggregation is able to reach the maximal reserve capacity within ten minutes. As the number of ACs gets larger, the *RT* has an increasing trend with slight changes in comparison with *RC* and *RR*. The *RC* and *RR* have a marked increase along with the variable N. The effect of communication delay is not considered in this case. Hence, the *RT* may be longer in practice. It is also unpractical that all the ACs will increase $1^{\circ}C$ after receiving the signal, because different consumers have different requirements in comfort. Therefore, the *RC* depends on user acceptance seriously.

## 5. Conclusions

With the increasing pressure of power system balance with the high penetration of RES, the flexible demands have huge potential for providing operating reserve. This paper proposed a method for quantitatively analyzing potential of AC aggregation for providing operating reserve.

## 6. Acknowledgements

This work was supported in part by the China NSFC under Grant 51577167 and the State Grid Zhejiang Electric Power Company (Research on peak-shaving abilities and operation mechanisms of flexible loads, 5211JY15001S).

## 7. References

[1] Zhang X P, Cheng X M. Energy consumption, carbon emissions, and economic growth in China. Ecological Economics, 2009; 68(10): 2706-2712.

[2] Wang T, Chen G T, Qian Z A, et al. Situation of sand-dust storms and countermeasures in North China. Journal of Desert Research, 2001; 4: 002.

[3] Protocol K. United Nations framework convention on climate change. Kyoto Protocol, Kyoto, 1997; 19.

[4] Ott H E, Sterk W, Watanabe R. The Bali roadmap: new horizons for global climate policy. Climate Policy, 2008; 8(1): 91-95.

[5] Ramanathan V, Xu Y. The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues. Proceedings of the National Academy of Sciences, 2010; 107(18): 8055-8062.

[6] Dong F, Yang Q, Long R, et al. Factor Decomposition and Dynamic Simulation of China's Carbon Emissions. China Population, Resources and Environment, 2015; 4: 001.

[7] Akella A K, Saini R P, Sharma M P. Social, economical and environmental impacts of renewable energy systems. Renewable Energy, 2009; 34(2): 390-396.

[8] Urmee T, Harries D, Schlapfer A. Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific. Renewable Energy, 2009; 34(2): 354-357.

[9] Ding Y, Pineda S, Nyeng P, et al. Real-time market concept architecture for EcoGrid EU—A prototype for European smart grids. Smart Grid, IEEE Transactions on, 2013; 4(4): 2006-2016.

[10] Ding Y, Nyeng P, Ostergaard J, et al. Ecogrid EU-a large scale smart grids demonstration of real time market-based integration of numerous small DER and DR//2012 3rd IEEE PES International Conference and Exhibition on. IEEE, 2012; 1-7.

[11] Wang J, Wang X, Wu Y. Operating reserve model in the power market. Power Systems, IEEE Transactions on, 2005; 20(1): 223-229.

[12] Kueck J D, Kirby B J, Laughner T, et al. Spinning reserve from responsive load. Oak Ridge National Laboratory, 2009.

[13] Huang K Y, Huang Y C. Integrating direct load control with interruptible load management to provide instantaneous reserves for ancillary services. Power Systems, IEEE Transactions on, 2004; 19(3): 1626-1634.

**Biography**

Hongxun Hui received the B.Eng. degree from the College of Electrical Engineering in Zhejiang University, Hangzhou, China, in 2015. He is currently pursuing Ph.D. degree in Zhejiang University. His research interests include electricity markets and demand response.