Quantitative Analysis of Air Conditioner Aggregation for Providing Operating Reserve

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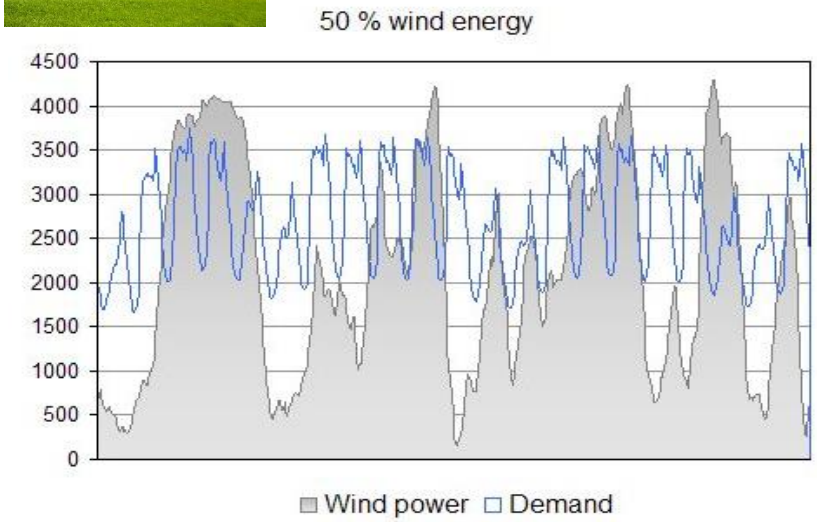
Background: Operating reserve



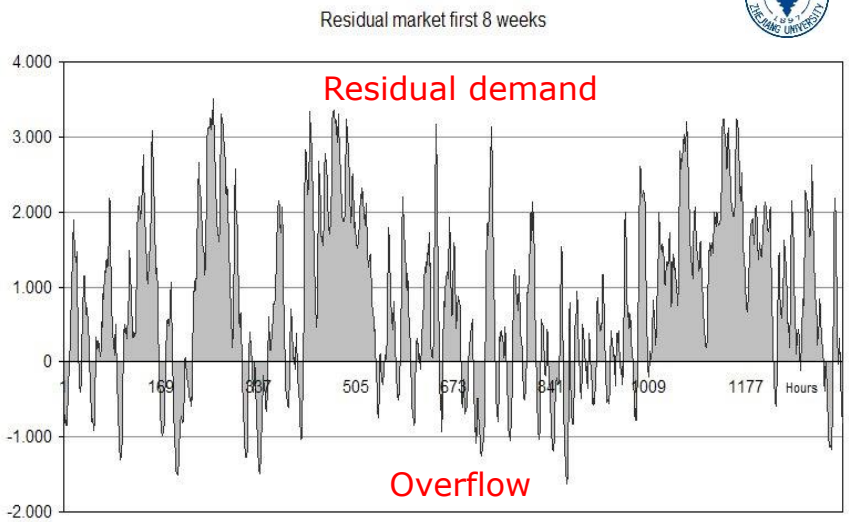


Fig.1. EcoGrid EU-assumed wind power capacity in 2025[1]

[1] 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

Fig.2. Smart house

Fig.3. Conventional generating units

Background: Interaction between generation and consumption

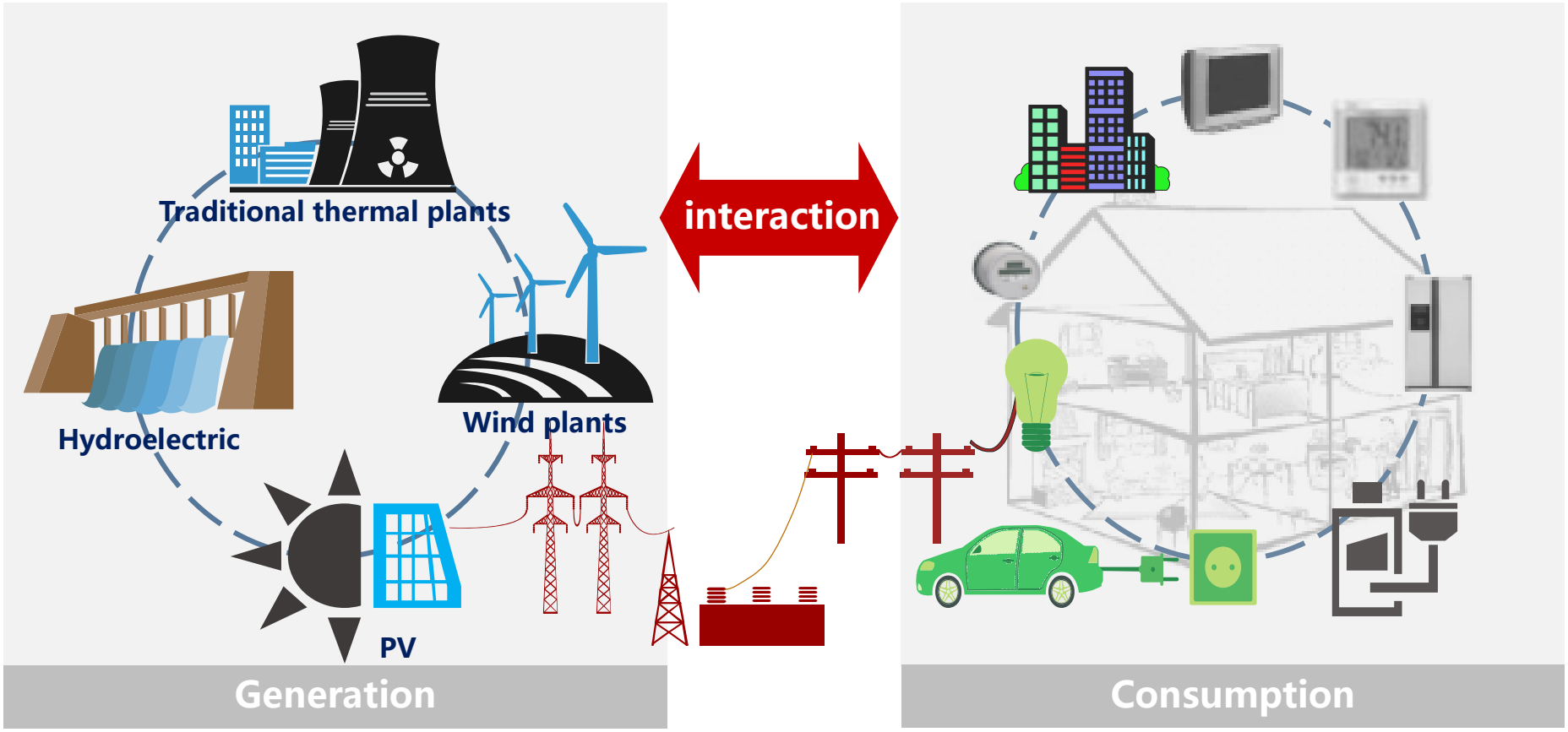


Fig.4. Interaction between generation and consumption

- Air conditioners are one of the most popular and significant flexible demands.
- Several indexes for operating reserve provided by flexible demands are quantified, including reserve capacity, response time, duration time and ramp rate.

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Normal operation characteristics of AC

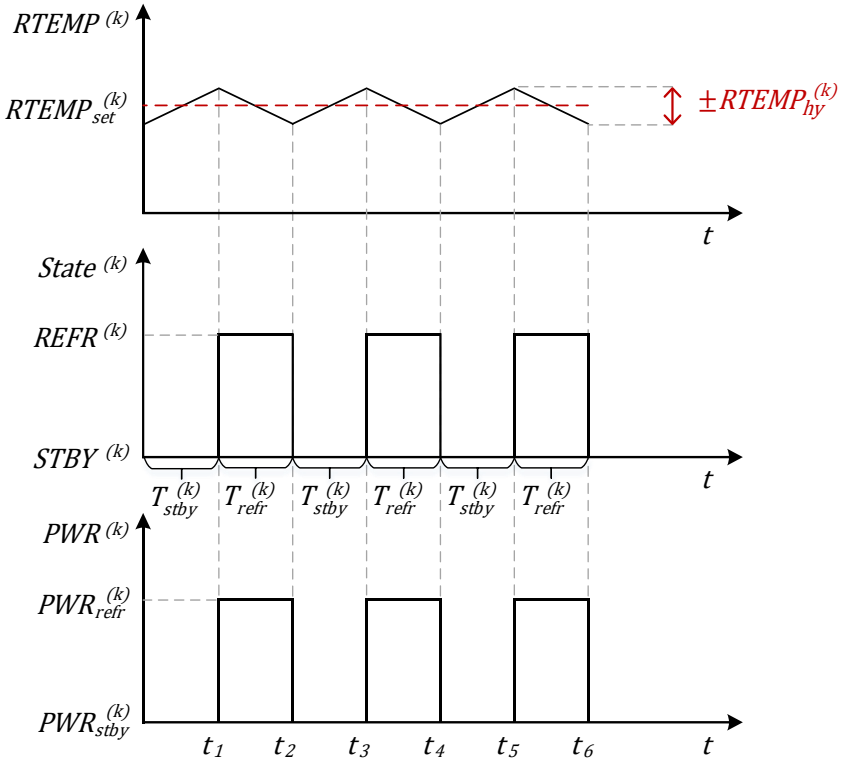

Fig.5. Normal operation characteristics of air conditioner(AC)

- **The kth room temperature(RTEMP) interval can be expressed as**

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

- **The kth AC's operating state can be expressed as**

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

Operating reserve performance of AC

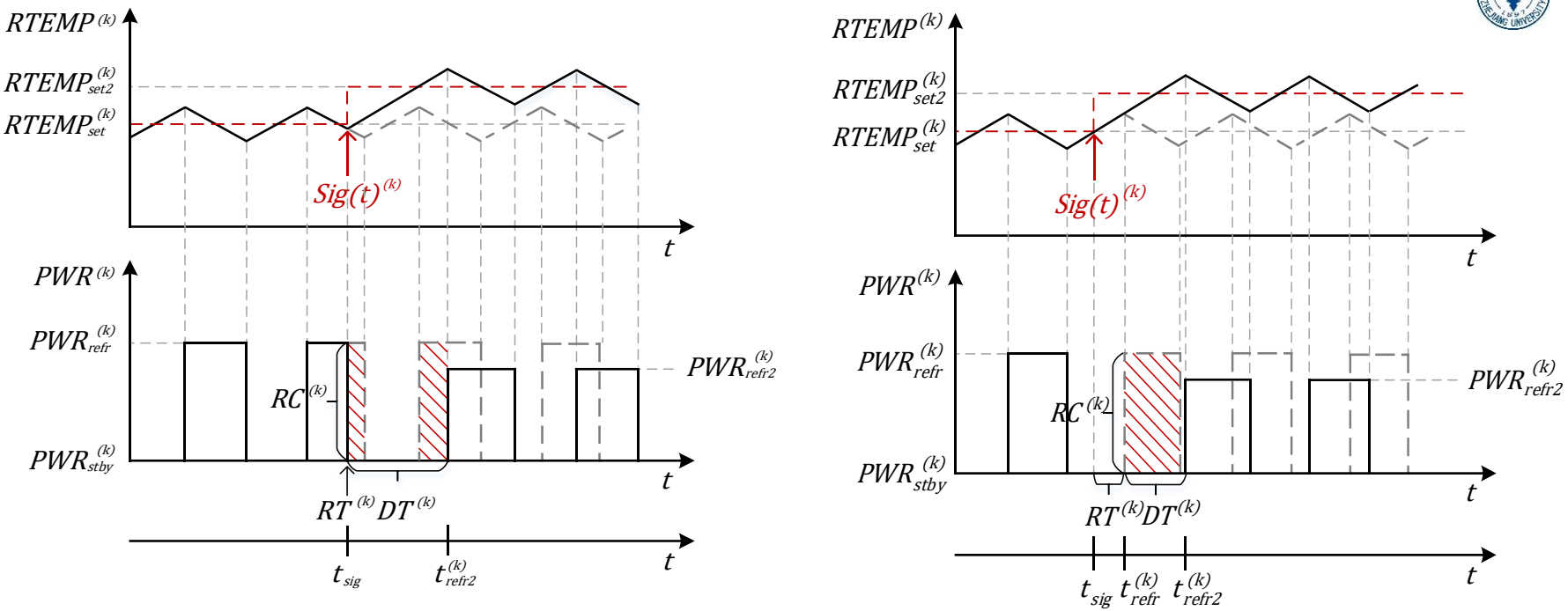

Fig.6. Operating reserve performance of AC

(a) Sig is received in T_{refr} ; (b) Sig is received in T_{stby}

- **The operating reserve can be quantified as**

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

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

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

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Quantitative Analysis of AC Aggregation Operating Reserve

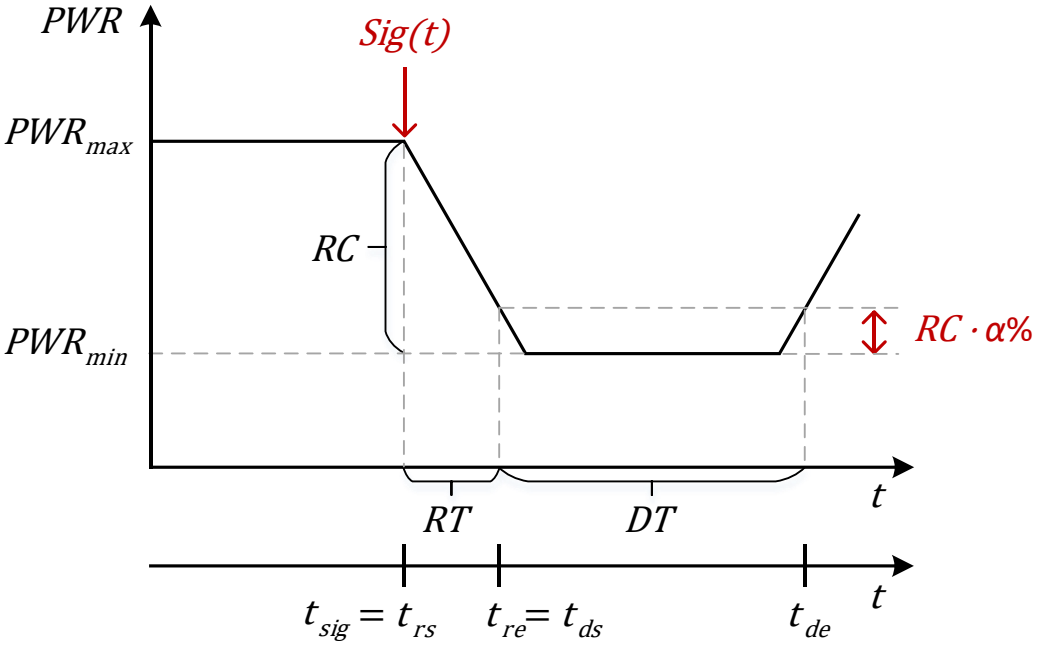

Fig.7. Operating reserve performance of AC aggregation

- **Reserve capacity of AC aggregation can be calculated as**

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

- **Duration time can be calculated as**

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

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

$$DT = t_{de} - t_{ds} \tag{9}$$

Quantitative Analysis of AC Aggregation Operating Reserve

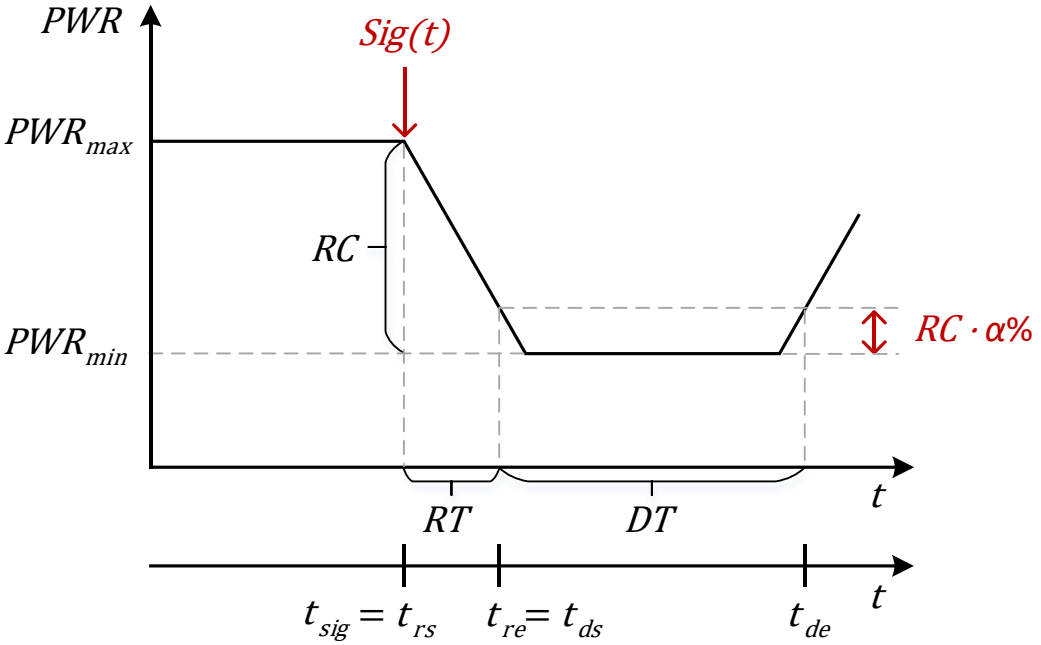

Fig.8. Operating reserve performance of AC aggregation

- **Response time can be calculated as**

$$RT = t_{re} - t_{rs} = t_{ds} - t_{sig} \tag{10}$$

- **Ramp rate can be calculated as**

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

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Case Studies and Discussions

Initialization of parameters-1

- **The initial temperatures:**
  - Set temperatures of each AC distribute randomly between 23℃ and 26℃.
  - The temperature hysteresis of control is 1℃.
  - Each AC's $RTEMP_{set}$ will increase 1℃ to $RTEMP_{set2}$ after receiving the signal.

- **Each room's parameters:**
  - The area of each room is generated as N values in the normal distribution (the mean value is 100m², and the standard deviation is 40m²).
  - The height of each room is 2.5m.
  - The heat capacity is $288\frac{kJ}{m^2 \cdot ^\circ C}$.

- **Each air conditioner's parameters:**
  - Assumed that each AC's rated power equals to sixtyfold area. That is, the rated power is 1800W if the corresponding room area is 30m².
  - The Energy Efficiency Ratios (EER) distribute randomly between 3.0 and 3.6.

Case Studies and Discussions

Initialization of parameters-2

- **Table A-1. The ambient temperature on August 1 in Hangzhou, China[3]**

Time(CST)	Temperature	Time(CST)	Temperature	Time(CST)	Temperature	Time(CST)	Temperature
12:00 AM	86.0 ° F	6:00 AM	82.4 ° F	12:00 PM	96.8 ° F	6:30 PM	95.0 ° F
12:30 AM	86.0 ° F	6:30 AM	84.2 ° F	12:30 PM	98.6 ° F	7:00 PM	93.2 ° F
1:00 AM	82.4 ° F	7:00 AM	86.0 ° F	1:00 PM	98.6 ° F	7:30 PM	93.2 ° F
1:30 AM	84.2 ° F	7:30 AM	86.0 ° F	1:30 PM	98.6 ° F	8:00 PM	91.4 ° F
2:00 AM	84.2 ° F	8:00 AM	89.6 ° F	2:30 PM	98.6 ° F	8:30 PM	91.4 ° F
2:30 AM	82.4 ° F	8:30 AM	89.6 ° F	3:00 PM	96.8 ° F	9:00 PM	91.4 ° F
3:00 AM	82.4 ° F	9:00 AM	91.4 ° F	3:30 PM	96.8 ° F	9:30 PM	91.4 ° F
3:30 AM	82.4 ° F	9:30 AM	93.2 ° F	4:00 PM	93.2 ° F	10:00 PM	91.4 ° F
4:00 AM	82.4 ° F	10:00 AM	93.2 ° F	4:30 PM	95.0 ° F	10:30 PM	89.6 ° F
4:30 AM	80.6 ° F	10:30 AM	95.0 ° F	5:00 PM	95.0 ° F	11:00 PM	87.8 ° F
5:00 AM	80.6 ° F	11:00 AM	95.0 ° F	5:30 PM	96.8 ° F	11:30 PM	86.0 ° F
5:30 AM	80.6 ° F	11:30 AM	96.8 ° F	6:00 PM	95.0 ° F		

- **α%=10%**
- **N=100, 500, 1000, 5000**

[3] https://www.wunderground.com/

Case Studies and Discussions

The simulation results-1

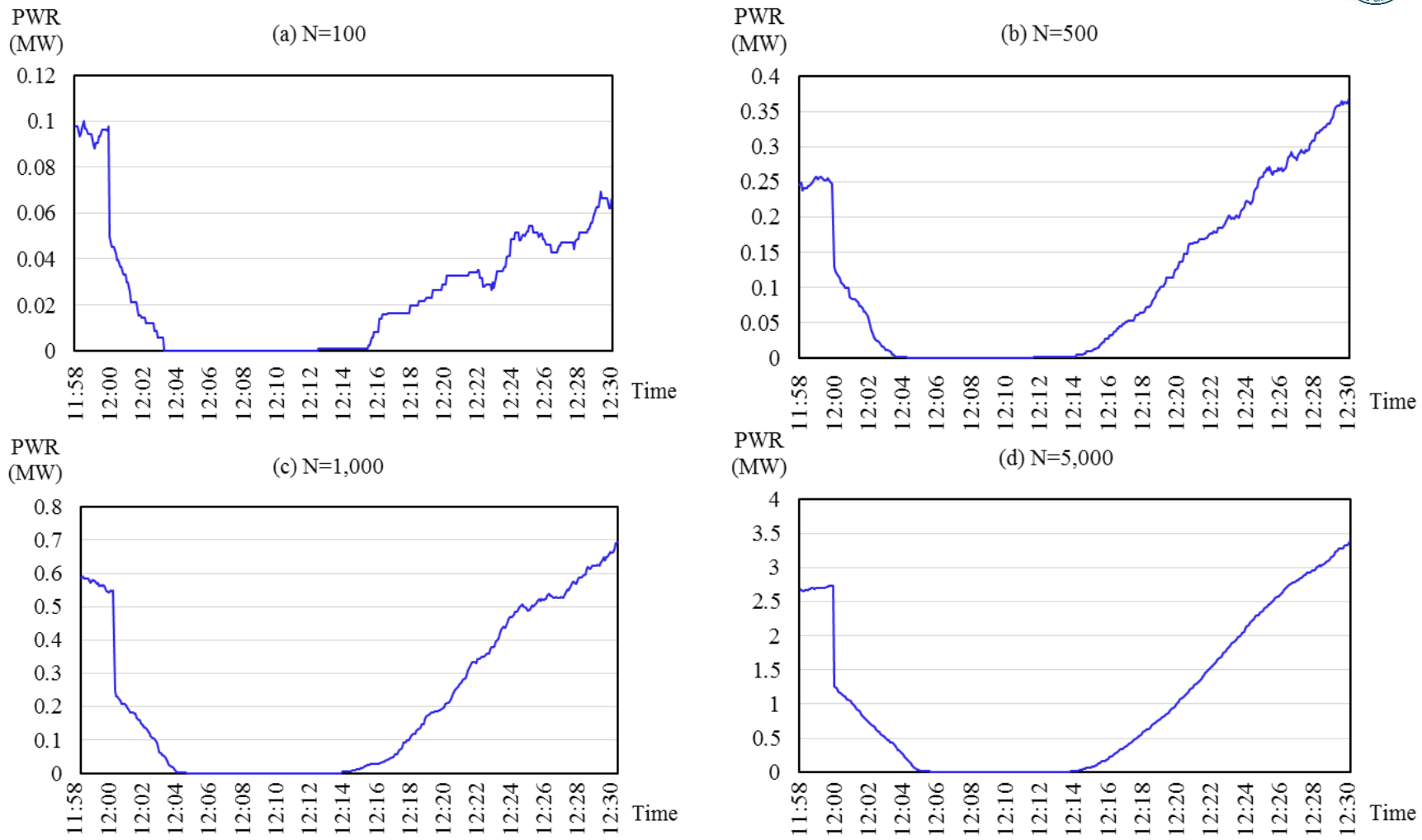

Fig.9. The simulation curves

(a) N=100; (b) N=500; (c) N=1,000; (d) N=5,000

Case Studies and Discussions

The simulation results-2

- **Table 1. The simulation result**

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

- **Discussions and Conclusions:**
  - RT is short enough to provide operating reserve. (RT≤10min)
  - DT is nearly invariable.
  - RC and RR increase proportionally to the variable N.

  - 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.

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Thank you for your attention!

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