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# Cooperation of Demand Response and Traditional Power Generations for Providing Spinning Reserve

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**Abstract**

Spinning reserve in the electric power system is vital in dealing with the sudden drop of electricity supply caused by failure, which used to be provided by traditional power generations. With the development of information and communication technologies (ICTs), demand response (DR) is deployed gradually for providing spinning reserve by shedding flexible loads. Air conditioners (ACs) are one of the most high-quality flexible loads due to its high proportion of capacity in electricity consumption. However, power rebound spike (PRS) of AC loads tend to emerge at the end of DR. Therefore, traditional spinning reserve providers (TSRPs) have to ramp to cooperate with ACs immediately. In this paper, a DR management approach is proposed for controlling DR duration time and capacity by sequent temperature configuration. Meanwhile, the connection between PRS and DR duration time is studied. Reliability indices have also been applied to evaluate different cooperation strategies between ACs and TSRPs. Simulations based on Monte Carlo methods are performed quantitatively.


*Keywords:* demand response; air conditioners; power rebound spike; traditional spinning reserve providers; cooperation;

## 1. Introduction

Ultra-high voltage direct current transmission system (UHVDC) has been constructed among some regions, due to the unfair allocation of primary energy and electricity consumers [1]. For example, in Jiangsu Province of China, it is estimated that 45% electricity consumption will be transmitted by the UHVDC from other provinces [2]. Therefore, the failure of UHVDC will result in a fast and severe shortage of electricity supply, and it may lead to instability of

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frequency and even power grid islanding [3,4]. This puts forward higher requirements for the spinning reserve, which is defined as the extra generating capacity for the balance of power system [5].

Under the contingency of UHVDC failure, traditional spinning reserve providers (TSRP), such as coal-fired generations, do not have sufficient ramp rate to provide abundant reserve capacity in a short time interval. With the development of information and communication technologies (ICT), demand response (DR) can be deployed for spinning reserve by load curtailment [6]. The capacity of air conditioners (AC) is growing steadily, becoming one of the significant resource of DR. In Madrid, ACs account for one-third portion of the energy consumption during the peak hours in extremely hot days [7]. Furthermore, ACs are ideally suited as DR providers due to quick responding speed and easy realization of automatic control [8, 9].

Extensive researches have gained their progress on utilization of ACs for DR. Reference [10] proposes a quantitative evaluation of ACs aggregation, which is equivalent to TSRPs. Meanwhile, DR projects are carried out in some electricity market-matured regions. These projects utilize direct control by end-consumers or load aggregators in exchange for a certain compensation [11, 12]. However, ACs can only work as a temporary spinning reserve, for ACs have to restart in order to maintain customers' satisfaction, where a power rebound spike (PRS) of AC loads will emerge at the end of DR [13, 14]. Therefore, the improper usage of DR with PRS results in low reliability performance of the system rather than improve it, and the TSRPs should provide sufficient power generation to cooperate with the rebound of AC loads.

This paper proposes cooperation strategies between ACs and TSRPs and is organized as follows. A DR duration control strategy is proposed in Section 2. Based on that, the relationship between PRS index and DR duration is analyzed in Section 3. In Section 4, theoretical model of TSRPs-ACs cooperation system is illustrated, while reliability indices are applied to evaluate the cooperation strategies. Simulations are performed based on Monte Carlo methods and conclusions are drawn in Section 5 and Section 6, respectively.

**Nomenclature**

| | | | |
|---|---|---|---|
| AC | air conditioner | PRS | power rebound spike |
| TSRP | traditional spinning reserve provider | $P_{ns}$ | power of ACs in normal state |
| DR | demand response | $P_{tlrs}$ | tolerance of DRC in the control strategy |
| DRC | demand response capacity | RU | ramp-up rate |
| DRD | demand response duration | RD | ramp-down rate |
| EENS | expected energy not supplied | UHVDC | ultra-high voltage direct current |
| ICT | information and communication technology | $T_{set}^{k}$ | setting temperature of AC for $k_{th}$ alteration |
| LOLP | loss of load probability | $T_{setmax}$ | the maximum setting temperature of AC |

## 2. DR duration control strategy

Based on the AC aggregation model in [10] and the thermal model of the room in [15], the power curve of the AC aggregation in summer is shown in Fig. 1. In the initial state, all the ACs are running normally. At the time $t_s^{\,0}$, ACs receive the control signal of starting DR, and the setting temperatures of ACs increase from $T_{set}^{\,0}$ to $T_{set}^{\,1}$ individually, which leads to the decrease of power consumption. However, the total power of ACs starts to increase when the air temperatures in each room have reached $T_{set}^{\,1}$. For maintaining a certain amount of response capacity for a controller-defined period, this paper designs a control strategy of the ACs to avoid the power rebound:

$$T_{set}^{\;k+1} = \begin{cases} T_{set}^{\;k} + 1, P_{AC} > \alpha * DRC \,\&\&\, T_{set}^{\;k} < T_{set\max} \\ T_{set}^{\;k}, P_{AC} \le \alpha * DRC \,\|\, T_{set}^{\;k} \ge T_{set\max} \end{cases} \tag{1}$$

where $T_{set}^{\;k}$ and $T_{set}^{\;k+1}$ denote the setting temperatures before and after the alteration of each individual AC, respectively. $P_{ACs}$ and DRC are the real-time power of all ACs and the DR capacity, respectively. $\alpha$ is a triggering parameter, depending on the tolerance of the capacity fluctuation for ACs aggregation as spinning reserve. $T_{set\max}$

represents the highest setting temperature of each AC depending on the specific characteristics of AC device.

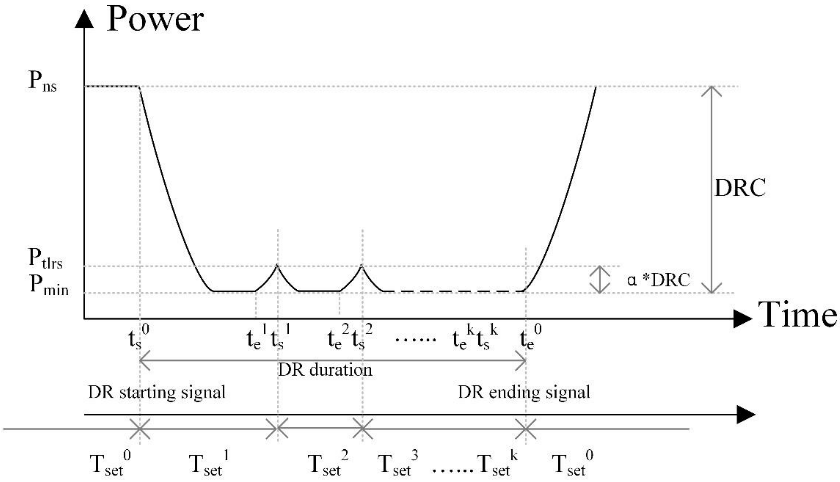


Fig. 1. The operating power curve of ACs in proposed strategy

## 3. Analysis on power rebound spike phenomenon

The controllers of ACs have trends to reset their setting temperatures to the original states at the end of the DR, in order to maintain the satisfaction of the customers. Therefore, if there is no regulation of ACs re-commitment, numerous ACs are likely to restart during a very short time interval, where the PRS will emerge, as showed in Fig. 2(a).

The PRS can be quantified by the index of the maximum power. Many factors can have influence on the maximum power, such as the heat capacity of rooms, ambient temperatures, rated power of the ACs, etc. [16]. Among the factors above, the duration of DR is a significant factor, as shown in Fig. 2(b).

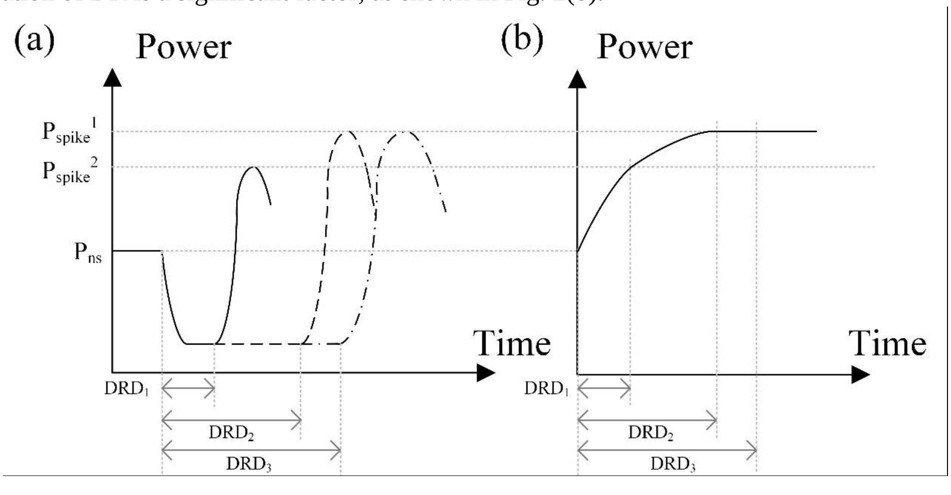


Fig. 2. (a) Several PRS phenomena; (b) the relationship of maximum power of PRS and DR duration

## 4. Analysis on TSRPs-ACs cooperation system

When a sudden drop of generation occurs, TSRPs, such as coal-fired generators, cannot improve the output of power sufficiently fast to provide abundant reserve capacity in a short time interval. The generation power constrains of TSRPs can be formulated as follows [16]

$$P_{s,t} \le P_{s\max} \tag{2}$$

$$P_{s,t} - P_{s,t-1} \le RU * T \tag{3}$$

$$P_{s,t} - P_{s,t-1} \ge RD * T \tag{4}$$

where $P_{s,t}$ , $P_{s,t-1}$, $P_{s,\max}$ denote the power output of the TSRPs at time t, time t-1, and the maximum power output of the TSRPs, respectively. RU and RD are the ramp-up rate and the ramp-down rate, respectively. T is the corresponding ramp time.

Fig. 3(a) shows the cooperation of ACs as spinning reserve and the TSRPs in a state of contingency. Red line illustrates that at the time $t_s$ , a sudden decrease of generation by $P_{ns}$ happens. Ignoring the delay or the package loss of communication system, ACs and TSRPs are triggered immediately. Green solid line and the green dash line represent two strategies of TSRPs behaviour. In strategy A, PRS are neglected. The ramp process of the TSRPs terminates at the time $t_A$ , when the power output of TSRPs reaches to the original power $P_{ns}$ . While in strategy B, the TSRPs continue ramping until their power output reaches $P_B$ .

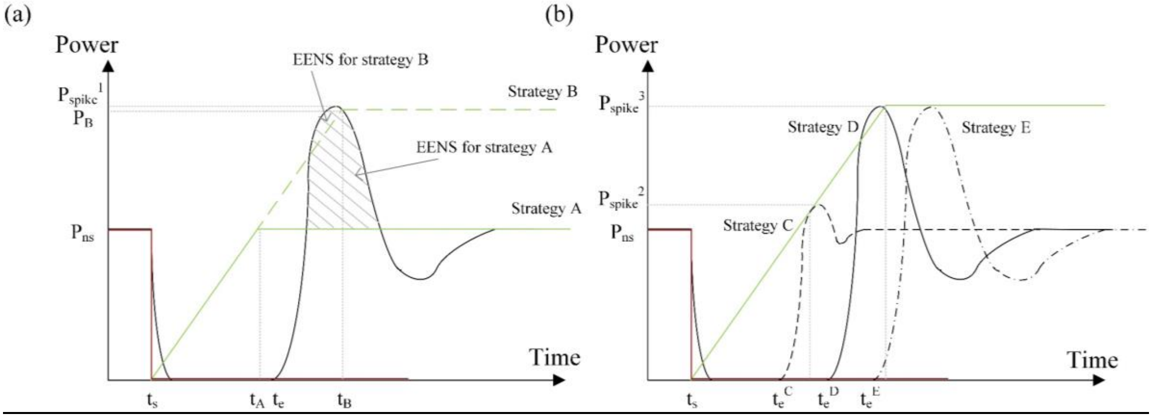


Fig. 3. (a) Cooperation of TSRPs-ACs system with different ramp strategies; (b) Cooperation of TSRPs-ACs system with different DR strategies

The reliability indices are applied to evaluate different strategies. Simulations are ought to be performed for sufficient amount of times, as to suppress the fluctuations caused by the randomized the room thermal model and the AC model parameters. Expected energy not supplied (EENS) and loss of load probability (LOLP) can be calculated by following equations [17].

$$EENS = \frac{1}{n}\sum_{k=1}^{n}\sum_{i\in T}\varepsilon_i * (P_{load,i} - P_{gen,i}) * t_i \tag{5}$$

$$LOLP = \frac{1}{n}\sum_{k=1}^{n}\sum_{i\in T}\varepsilon_i * t_i \tag{6}$$

where $n$ denotes the total simulation times, and $T$ is the set of the period to be studied. $P_{load,i}$ and $P_{gen,i}$ are the values of generation and the load during the time interval $t_i$ , respectively. $\varepsilon_i$ is a Heaviside step function:

$$\varepsilon_i = \begin{cases} 0, P_{gen,i} \ge P_{load,i} \\ 1, P_{gen,i} < P_{load,i} \end{cases} \tag{7}$$

EENS represents the relative area of the shade part in Fig. 3(a). From this aspect, the parameter to be controlled is the ramp duration. The process of ramp stopped according to certain judgement conditions. Obviously, the judgment conditions determine the reliability performance of TSRPs-ACs cooperation system in different strategies.

In another aspect, the strategies vary in the DR duration, as shown in Fig. 3(b). Compared between strategy C and strategy D, former strategy has both shorter DR duration and better reliability performance. It can be concluded that there is an optimum point of DR duration at a constant TSRPs ramp time. In another word, DR duration and ramp time can be co-optimized to achieve both the best reliability performance and relatively low DR cost.

## 5. Simulation and discussion

ACs aggregation is deployed to conduct the simulation. The parameters of ACs and TSRPs are listed in Table 1.

Table 1. The parameters of ACs and TSRPs.

| | Amount of ACs | Tolerance parameter | COP | Air temperatures (℃) | Ambient temperature (℃) | Heat capacity of air (kJ/kg*℃) |
|---|---|---|---|---|---|---|
| distribution | constant | constant | normal | uniform | constant | constant |
| value/range | 500 | 0.3 | (3,3.7) | (28,34) | 32 | 1.5 |
| | Hysteresis temperature(℃) | Rated power (W) | Max setting temperature(℃) | Setting temperature(℃) | Capacity of TSRPs(MW) | Ramp rate (percentage of capacity/min) |
| distribution | uniform | constant | constant | normal | constant | constant |
| value/range | (1,2) | 6000 | 30 | (24,26) | 3 | case2: 6% |

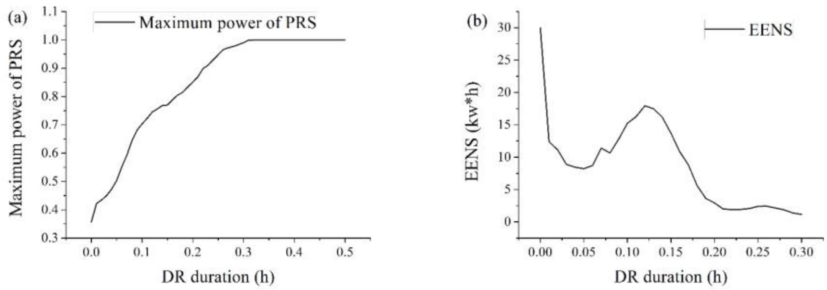


Fig. 4. (a) Relationship of DR duration and maximum power of PRS (b) Relationship of DR duration and EENS

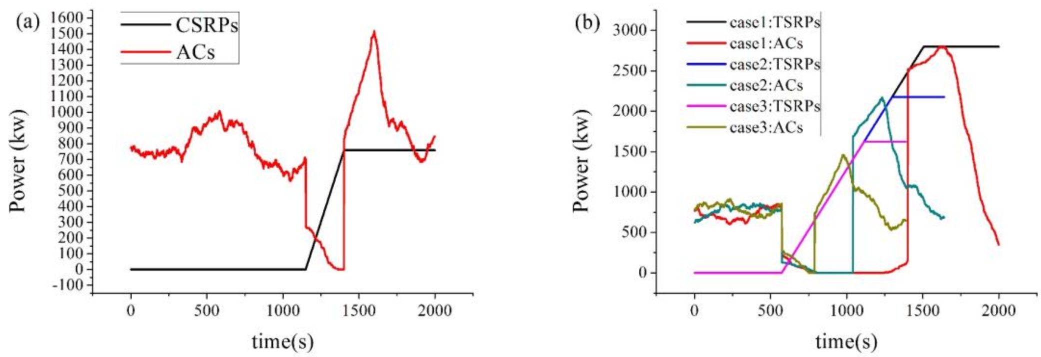


Fig. 5. (a) Scenario 1: cooperation of TSRPs-ACs system without considering PRS (b) Scenario 2: Cooperation of TSRPs-ACs system with different DR strategies considering PRS

The simulation results verify the theories proposed in previous sections. As illustrated in Fig. 4(a), Y-axes represents the relative value of maximum power of PRS, which is normalized based on the total capacity of ACs. When DR duration equals zero, the relative average power in normal state is 0.36. While DR duration reaches to 0.31 hour, the relative value of maximal PRS reaches 1. It indicates that there are severe side-effects of DR if the DR duration is over or near 0.31 hour, when AC is the only DR resource and no PRS-suppressing measures are taken. As shown in Fig. 4(b), EENS is not monotonic, which decreases first and then increases. It can be inferred that the improper extension of DR duration will lead to worse reliability performance of TSRPs-ACs system rather than improve it.

As shown in Fig. 5 (a), cooperation of TSRPs-ACs system is conducted without considering PRS. While in Fig. 5(b), the terminating condition of TSRPs ramp is the time when the power output of TSRPs reaches the maximum power of PRS. The DR duration are 0.23, 0.13, 0.06 hour in case 1, case 2 and case 3, respectively. The reliability indices are calculated for 4 hours after the end of DR process for 1000 times using Monte Carlo method. The results of each cases are presented in Table 2. It can be deducted from the results that different ramp ending judgement conditions lead to different reliability performance of TSRPs-ACs cooperation system. The simulation results verify the conclusions drawn from Fig.4(b), and vice versa.

Table 2. Comparison of reliability performances with different strategies.

| | | EENS(kW*h) | LOLP |
|---|---|---|---|
| stage1 | | 43.489 | 0.568 |
| | Case 1 | 1.927 | 0.004 |
| stage2 | Case 2 | 17.489 | 0.017 |
| | Case 3 | 8.726 | 0.018 |

## 6. Conclusion

With the growing portion of capacity of renewable energy generating units, ACs are deployed in several regions as DR providers for suppressing the imbalance between electricity suppliers and consumers. In this paper, the specific strategies for TSRPs-ACs cooperation system have been studied, considering the influence on reliability performance by the PRS phenomenon.

## Acknowledgements

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