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Optimal Dispatching Strategy for Residential Air Conditioning Loads Based on Hierarchical Group Method

Fei Zhao [1*], **Jinsha Yuan** [1], **Ning Wang** [1], **Ping Liu** [2]

[1] School of Electrical and Electronic Engineering, North China Electric Power University, Baoding 071003, CHINA

[2] State Grid Huludao Electric Power Supply Company, Huludao 125000, CHINA

[*] Corresponding author: zhaofei@ncepu.edu.cn

Abstract

With the rapid development of energy internet, demand response technology provides a new solution to stabilize the active power fluctuation in power system. This paper creates the equivalent thermodynamic parameter model of an air conditioning, and then carries the Monte Carlo method to simulate residential power consumption behavior. After that, a load dispatching strategy which is based on the hierarchical group method is firstly proposed to suppress active power fluctuation in a community level power grid. At last, the simulation case is carried out to verify the effectiveness of the proposed strategy, through the result and the statistical data, the strategy proposed can effectively suppress the power fluctuation and shave peak for a community level power grid which contains photovoltaic power and wind power. In addition, if it was carried out in the community level power grid, the carbon emissions can be reduced and significant effectively environmental benefits can be obtained.

Keywords: air conditioning, demand response, load dispatching, Monte Carlo simulation, hierarchical group, carbon emission

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INTRODUCTION

In recent years, the rapid growth of residential loads, especially for thermostatically controlled loads, has caused too many serious problems for the economical operation and stable of power system (Callaway and Hiskens 2010, Wang *et al.* 2012). Reasonable dispatching of the thermodynamic loads is conducive to optimize the resource allocation, and it plays an important role in consumption of new energy and reducing operation stress of power grid. As a kind of thermodynamic load, air conditioning has merits of stable power consumption, outstanding characteristic in energy storage, and excellent controllability, and has a great potential to achieve peak shaving and valley filling in power grid (Wang *et al.* 2014). Because of the former advantages, a growing number of researches which are related to optimize air conditioning loads dispatching strategy have been conducted. In addition, an effective air conditioning loads control strategy is in need not only for optimize energy utilization but also for relieving power system operational stress (Carolina Barbosa *et al.* 2017, Fu and Liu 2017, Yang *et al.* 2017).

An effective way to dispatch thermodynamic loads is to guide users change their behavior of electricity consumption with the demand response technology (U 2006). Meanwhile, it is necessary to dispatch controllable loads to meet power system requirements quickly. Direct load control (DLC) is a kind of demand response based on incentive mechanism, it tries to reduce power consumption at peak demand/ price time in a day through monitoring power signal or price signal.

The study of large groups of thermostically controlled loads (TCLs), namely TCL populations, started in the 1980s with the works of (Malhamé and Chong 1985, Mortensen and Haggerty 1988, Satoru and Fred 1981). The important result in realizes the mathematical aggregation of a homogeneous population of stochastic hybrid systems as a system of partial differential equations with boundary conditions (Ben Mariem and Chaieb 2017, Vicente-Molina *et al.* 2018, Wani *et al.* 2018).

At present, there are some deep discussions on modeling some thermodynamic loads and scheduling

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demand response load. In Walker and Pokoski (2007), a residential load dispatching model is developed and it takes psychological factors which can affect domestic users' power consumption habit into consideration. Based on domestic electric water heater's thermodynamic characteristics and parameter diversity, a precise model of single electric water heater is proposed in Lane and Beute (1996); Nehrir *et al.* (2007); Orphelin and Adnot (1999), which can reflect different conditions of electric water heater but is too complex to be applied to load dispatching. In Yebai *et al.* (2015), a thermodynamic model representing the power system load due to hot water consumption from storage water heaters is provided which makes it possible to predict the effects of load control, and it is also useful for evaluation of the response which could be expected from demand-side management options. Some literatures focus in the area of load dispatching of demand response. Some centralized or hierarchical control strategies for thermodynamic loads are proposed and verified in HongJie and YunFei (2013); Rui *et al.* (2016); Wang *et al.* (2014); Yajing *et al.* (2015); Zhang *et al.* (2014) respectively. A dynamic frequency regulation strategy which uses residential thermostatically controlled loads to alleviate frequency deviations caused by high penetration of renewable energy sources in the power system is demonstrated in Kondoh (2011). A direct load control strategy for domestic electric water heater is proposed to accommodate wind power generation in Hokkaido, which indicates that the acceptable wind power generation increases almost three times.

Based on the aforementioned papers, this paper creates the equivalent thermodynamic parameter model of an air conditioning, and then carries the Monte Carlo method to simulate residential power consumption behavior. After that, this paper proposes a load dispatching strategy which is based on the hierarchical group method to suppress active power fluctuation in an community level power grid. At last, the simulation case is carried out to verify the effectiveness of the proposed strategy.

AIR CONDITIONING LOAD MODEL

As mentioned in the previous section, air conditioning loads have great potential in peak shaving. In addition, an optimal air conditioning loads control strategy can reduce domestic users' total electricity consumption and bills. Therefore, it is critical to propose an air conditioning power flow model and an air conditioning load control model for optimizing the operation of air conditioning systems in residential buildings. In this section, a simplified air conditioning load model is introduced.

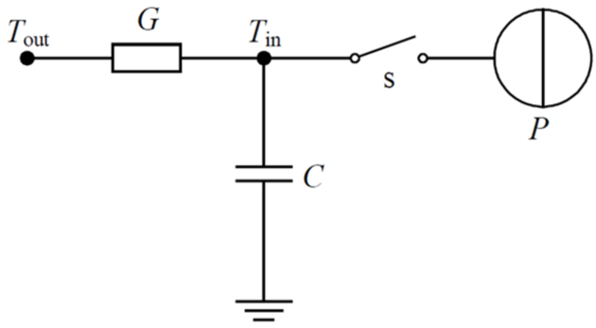

Fig. 1. Thermodynamic parameter model of air conditioning

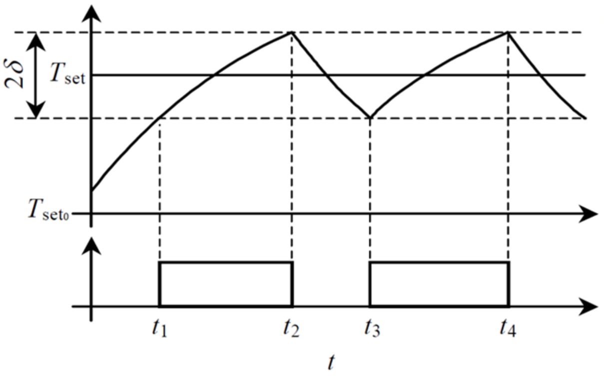

Fig. 2. Thermal process of single air conditioning

Fig. 1 shows equivalent thermodynamic parameter model of an air conditioning load, for this kind of load, this paper proposed a 1 order differential equation to describe the temperature change:

$$\begin{cases} \dot{T}_{on}(t) = \frac{G(T_{out}(t) - T_{in}(t) - P}{C}, s(t) = 1 \\ \dot{T}_{off}(t) = \frac{G(T_{out}(t) - T_{in}(t)}{C}, s(t) = 0 \end{cases} \tag{1}$$

where, *T*on(*t*) is the room temperature of t when air conditioning turn on, *T*off(*t*) is the room temperature of t when air conditioning turn off,(°C).; *T*out is the temperature of outside; C is the caloric(kW·h); G is the thermal conductivity, kW/°C; *s*(*t*) is the operation state of air conditioning at t; during the operation state , the air conditioning is keeping the room temperature within a preset range [T_L,T_H] which is shown as **Fig. 2**, P is the operation power.

The group air conditioning is conducted N number of (1), for this group, the power of *t* is expressed by (2), it is the sum of all single equipments.

Table 1. Air Conditioning system parameters' probability distributions

Parameter Symbols	Distribution
G	*ln*G- *N* (0.6,0.05)
C	*ln*G- *N* (10,0.1)
P	*ln*G- *N* (3.5,0.08)
N	1000
*T*out	*N* (30,0.01)

$$P_{ACLs}\ (t) = \sum_{i=1}^{N} P_i S_i(t) \tag{2}$$

Assumed that the group air conditioning loads can adjust based on Tset immediately:

$$T_{set}(t) = T_{set0} + \Delta T_{set}(t) \tag{3}$$

where, *T*set0 is the initial temperature, (°C); Δ*T*set is the group temperature change value. An group is conducted by (1)-(3), it is an nonlinear dynamic system with single input(Δ*T*set) and single output(*P*ACLs). For such system, it's complicated to carry a dynamic real-time simulation, so in the next section, this paper simulate the group air conditioning loads' characteristic by Monte Carlo method.

MONTE CARLO SIMULATION FOR A GROUP OF AIR CONDITIONING LOADS

The previous section has introduced single model and group model of air conditioning loads. However, the operation of a single air conditioning has great uncertainty; therefore, it is inappropriate to use a single air conditioning load curve to represent water heater load characteristics. In addition, the great uncertainty of a single air conditioning operation makes it difficult to predict the load, which makes it difficult to implement day-ahead load control for power systems.

In this paper, multiple domestic air conditioning loads in a group are used as samples to simulate load characteristics by the Monte Carlo method based on the single and group air conditioning model proposed in Section 2, and the result will be used in Section 5.

For Monte Carlo simulation, the parameters should be determined frist, **Table 1** show the parameters and their probability distributions, and the table is based on handbook, user preference and experience validation. *N*(*u*,*v*) represents standard normal distribution, *u* is expectation and *v* is variance.

Before simulation, an assumption need to be highlighted: The aim of Monte Carlo simulation is to simulate the group characters for optimal operation of air conditioning group, so if the simulation result had some differences with reality, it is still can be used for strategy verification. That is to say, the Monte Carlo simulation ensures the randomness of data for strategy verification. The simulation result is shown in **Fig. 3**.

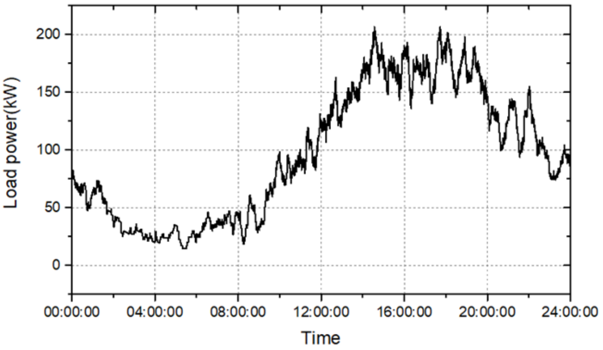

Fig. 3. Monte Carlo simulation result

In this section, the Monte Carlo load characteristics simulation method has been introduced to model controllable loads. In the next section, the hierarchical group control method is proposed to optimize load scheduling for a group air conditioning loads.

HIERARCHICAL GROUP CONTROL METHOD FOR LOAD DISPATCHING

Hierarchical group control method means the air conditioning loads are divided into different groups to be hierarchy. When these loads are in optimal dispatching, they are sorted by some rules, and they will be controlled in order.

In community level power grid, the air conditioning loads are divided into three levels according to users' willing for participating in demand response. The priority level can also be determined by this:

$$\begin{aligned} H &= \{h_1, h_2, h_3, \cdots h_i \cdots, h_{N_H}\} \\ L &= \{l_1, l_2, l_3, \cdots l_i \cdots, l_{N_L}\} \\ R &= \{r_1, r_2, r_3, \cdots r_i \cdots, r_{N_R}\} \end{aligned} \tag{4}$$

where, *H*, *L*, *R* represents the users participating in high level demand response, low level demand response and refusing to participate in demand response respectively. h_i, l_i, r_i represent the index of air conditioning in each group. $N_H{}^t$, $N_L{}^t$ and $N_4{}^R$ are the numbers of domestic electric water heaters in each group, respectively and satisfy:

$$N_H + N_L + N_R = N \tag{5}$$

where, *N* is the sum of the number of air conditioning loads in each group.

In a community, there are many users participating demand response at *t*. Air conditioning in their home

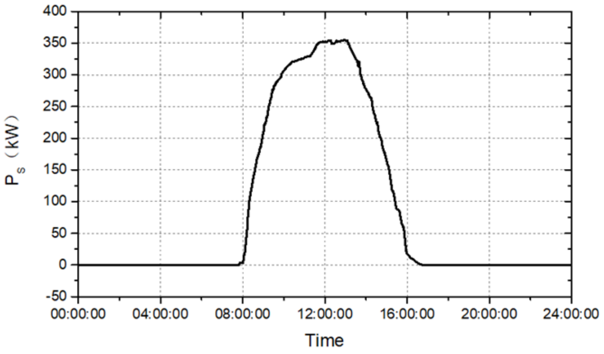

Fig. 4. Power of P_S

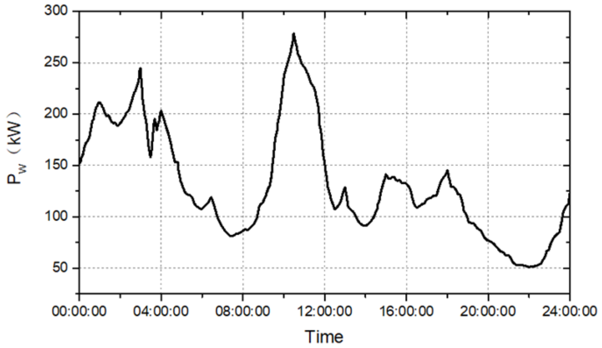

Fig. 5. Power of P_W

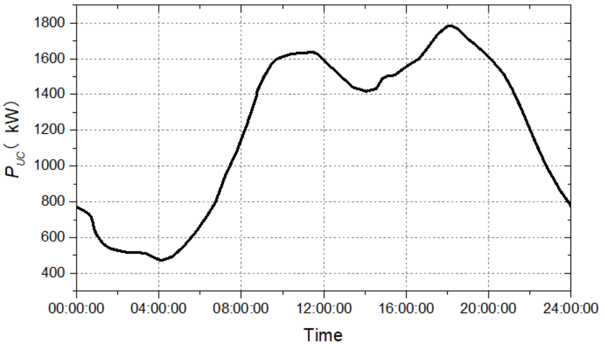

Fig. 6. Power of uncontrollable loads (P_{UC})

can communicate with community energy management system (CEMS) by home energy management system (HEMS). The CEMS-HEMS-ACL (air conditioning load) communication system is conducted. During the operation of this system, the order in each group can be determined as a certain rule. The sorted group:

$$\begin{aligned} H^t &= \{h_1^t, h_2^t, h_3^t, \ldots h_i^t, \ldots h_{N_H^t}^t\} \\ L^t &= \{l_1^t, l_2^t, l_3^t, \ldots l_i^t, \ldots l_{N_L^t}^t\} \\ R^t &= \{r_1^t, r_2^t, r_3^t, \ldots r_i^t, \ldots r_{N_R^t}^t\} \end{aligned} \tag{6}$$

These hierarchy groups are the core of hierarchical group dispatch method. In each group, the loads are sorted by the temperature by the value of ξ:

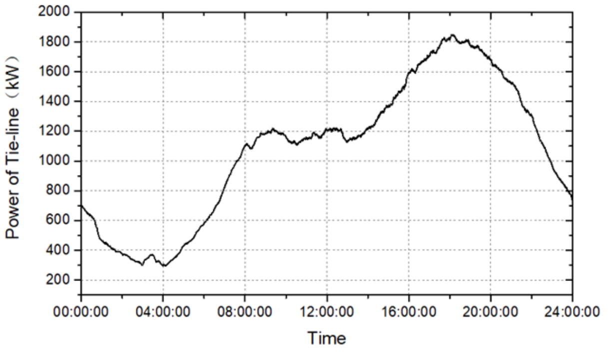

Fig. 7. Power fluctuation of tie-line

$$\xi = \frac{T(t)}{T_{set}} \tag{7}$$

The next thing is to get the active power fluctuation of community level power system:

$$\delta = \frac{P_L^t - P_L^{t-1}}{P_L^{t-1}} \times 100\% \tag{8}$$

where, $P_L{}^t$ is the community active power at time t and δ is the power fluctuation rate. If $\delta > 0$, the community active power at time t tends to increase, otherwise the community active power tends to decrease. Therefore, air conditioning loads should be switched off to shave peak demand when the net active power tends to increase and switched on to fill valley demand when the net active power tends to decrease. This control method can be applied to reduce power system active power fluctuations.

CASE STUDY

This case is a community level power grid, there are photovoltaic power (400 kW, SUNTECH), wind power (600 kW, CART3) and residential loads (uncontrollable and controllable) connected. These original power data are measured. **Fig. 4** shows the power of photovoltaic power (P_S). **Fig. 5** shows the power of wind power (P_W). **Fig. 6** shows the power of residential uncontrollable loads (P_{UC}). PC is the power of air conditioning loads.

Thus, the power of the tie-line in this community level power grid can be expressed as (9). The curve is shown in **Fig. 7**.

$$P = P_C + P_{UC} - P_S - P_W \tag{9}$$

In this community level power system, carry the CEMS-HEMS-ACL simulation for 24 hours. The simulation step is set as 1s, the strategy is carried out per 5 minutes, that is to say, some air conditionings change their operation states per 5 minutes. The active power

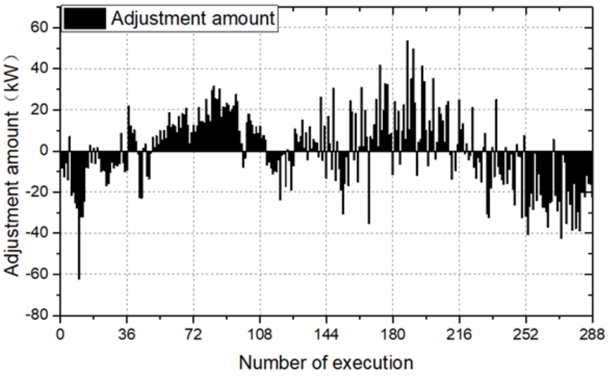

Fig. 8. Power adjustment amount of every execution

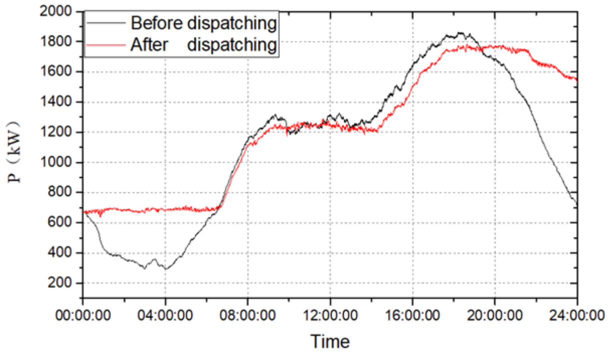

Fig. 9. Power fluctuation of tie-line before and after dispatching

adjustment amount of every execution is shown in **Fig. 8**. The result of tie-line power is shown in **Fig. 9**.

Some discussions can be proposed from the result:

(1) 0:00-6:00 is a valley decade of the power grid. The proposed dispatching strategy achieve the valley filling which can effectively mitigate the harm caused by excess power in the power system. The curve of tie-line power in this decade is nearly a straight line, the dispatching strategy is really stable. In addition, the wind power is in peak, but the uncontrollable load is too low to eliminate the new energy which cause the wind power curtailment period. The strategy proposed effectively mitigate this wind power curtailment; if the strategy is slightly improved, it can be applied to the demand response dispatching of partially transferable load, and it will achieve better effect of peak shaving and valley filling.

(2) 6:00-9:00: the power of tie-line before dispatching increase sharply, but the effect is not obvious after the optimal dispatching, mainly because the air conditioning loads amount is less in the whole community, and it is not enough for the short time and large active load growth tracking.

(3) 9:00-14:00 is similar to 0:00-6:00, and the former of 14:00-24:00 is similar to 0:00-6:00. During 18:00-21:00, the peak value of the tie line decreases, and the peak time goes backward, and keeps stable in about two hours. During 21:00-24:00, the active power of tie-line falls sharply, but withr the regulation of the demand response strategy proposed, the contact line has a slow decline in power, which avoiding the unbalanced three-phase voltage and the low efficiency of the equipment. It has some positive significance to the stability and economically operation of the power system.

Table 2. Statistical data of tie-line active power

	Before Dispatching	**After Dispatching**
Mean value (kW)	1078.437	1220.439
Standard deviation (kW)	469.726	403.405
Peak value (kW)	1849.111	1784.524
Valley value (kW)	293.197	637.962
Peak valley difference (kW)	1555.913	1146.562

(4) As shown in **Table 2**, the peak value of active power decreases by 3.49%, the value of active valleys increases by 117.59%, peak and valley difference is reduced by 26.31%, and the standard deviation is reduced by 14.12%, and the peak and valley difference is reduced effectively and the load fluctuation is reduced.

CONCLUSIONS

This paper creates the equivalent thermodynamic parameter model of an air conditioning, and then carries the Monte Carlo method to simulate residential power consumption behavior. After that, this paper firstly proposes a load dispatching strategy which is based on the hierarchical group method to suppress active power fluctuation in a community level power grid. At last, the simulation case is carried out to verify the effectiveness of the proposed strategy, through the result and the statistical data, the strategy proposed can effectively suppress the power fluctuation and shave peak for a community level power grid which contains photovoltaic power and wind power. In addition, if it was carried out in the community level power grid, the carbon emissions can be reduced and significant effectively environmental benefits can be obtained. However, the strategy proposed can not have good performance both on peak shaving and valley filling, due to the amount of dispatchable loads, it can be improved in the further research.

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