Dynamic Aggregation Model Considering Load Fluctuation and Its Participation in Economic Dispatch of Power System

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Abstract. In order to enable demand side resources effectively participate in the operation of the system, an abstract recognition model of small demand response resource is established which extracts the key parameters such as rated capacity, load fluctuation characteristics and demand response characteristics to help the power system understand more easily. Considering the influence of small load fluctuation and response characteristics, general aggregation and complementary aggregation models are established. An economic dispatching model considering aggregate's dynamic adjustment potential was established where the aggregate with the lowest power generation cost was selected and a load scheduling strategy was developed. The results show that the proposed model can effectively reduce the cost of power generation. It demonstrates that the demand-side resource dynamic aggregation which considers load fluctuation may conductive to the safe and economic operation of the system

1.   Introduction

Demand response technology is one of the core technologies of smart grid, and the application of demand response technology can fully tap the resources on the load side and realize the comprehensive application of resources. A significant number of potential demand response resources are not being developed for small and medium-sized power consumers. Typical load regulation resources include air conditioners, refrigerators, electric vehicles and energy storage. These loads are not only diverse but also have only small requirements for power. Because the power consumption is becoming more and more flexible, it is difficult to explore the microscopic characteristics of a single load when implementing the demand side response measure, but to focus on the external characteristics of the aggregates so that can help improve the efficiency of demand response project conduction.

Because of the diversity of the flexible load, the flexible load model discussed in recent researches focuses on the specific load, especially the power model, such as the distributed power model [1][2] , electric vehicle charge and discharge power model[3]-[6], air conditioning energy consumption model[7]-[8] and so on. Since the power models based on their respective energy consumption characteristics do not have generality, the authors have established some simplified models in the discussion of the regulation of the flexible load. In paper [9], the flexible load interaction model can be

constructed according to the sensitivity of the flexible load to the electricity price. In paper [10], a flexible load agent decision-making model is formed on the basis of establishing the overall framework of flexible load interaction response scheduling. It can be found that the system described above calls the required response capacity within the fixed output range of the flexible load but does not take into account that the demand response potential of the polymer fluctuates with the fluctuation of the load curve so that researches recently is difficult to apply to the actual operation.

Current load aggregation mode is a little bit fixed because more attention is given to the characteristics of the external response capacity of the aggregates. Once the aggregation is finished, it will work through the entire scheduling process. This paper focus deeply into the single load characteristic and overall characteristics of the aggregate combined by them. The following works are done in this paper: firstly, a small load abstract recognition model is established; secondly, a dynamic aggregation model considering specific aggregation objectives is established; finally, according to the requirement of the economic operation scene, the current optimal load group at different time is dispatched to realize the coordination among the three parties of the system, load agent and consumers.

2. Dynamic aggregation principle

For the demand-side resources involved in direct load control, the real-time status of load fluctuations is monitored and combined with the user demand response capacity, time and other key information, the current loads which have the same response capacity are aggregated into different groups for various spare. Due to the existence of load fluctuation, the types and quantities of load contained in the aggregates at different times are changing to achieve various optimization purposes.

In this paper, the system dispatches flexible resources with the help of load agent. Figure 1 shows the basic principles of dynamic aggregation. First of all, the load agency signs a contract with small and medium-sized users to by monitoring the smart meter or interacting with the user to obtain information such as the type of load, the rated power P_N, load fluctuation information $g(t)$, response characteristics $f(t,t_r)$ and the maximum allowable interrupt duration T_{max}. Then, according to the response time T_{req} and the response capacity P_{req}, the dynamic aggregation of the resources in the jurisdiction is carried out, which includes taking the response time as the aggregation center or the response capacity as the aggregation center to get the corresponding aggregated population and put into the system operation. In this paper, two dynamic aggregation strategies are proposed. Strategy 1 divides the whole scheduling process into several small intervals, each time interval T is a new round of aggregation. Strategy 2 is more dependent on intelligent monitoring. Once the current polymer response time or capacity cannot meet system requirements due to load fluctuation, re-aggregate the loads.
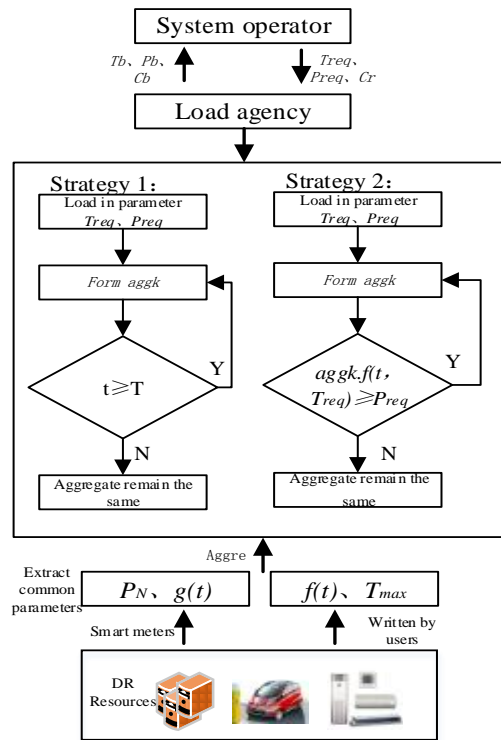
Figure 1. Block diagram of dynamic aggregation.

3.   Physical load identification model

There are many kinds of small load with no uniform load model. In this paper, the general load model is established as in equation (1) and (2), which focuses on identifying the type of small load.

$$Load = \{load_i | 1 \le i \le I\} \tag{1}$$

$$load_i = (Num(t),\ Y_D,\ Y_C,\ Y_S,\ Y_T) \tag{2}$$

where *Load* is a set of various small loads; $load_i$ represents a small load; *Num* is the number of load at time t; Y_D represents the load interaction, when Y_D is 1, the load performance of two-way interaction, when Y_D is 0, the load is unidirectional. Y_C represents the load controllability. When Y_C is 1, the load performance is controllable and when Y_C is 0, the load is uncontrollable. Y_S represents the randomness of the load, Y_S is 1 when the load performance is random, Y_S is 0 when the load performance is deterministic, Y_T is the load's industry type, $Y_T=1$ is the industrial load, $Y_T=2$ is the commercial load, $Y_T=3$ is the resident load and $Y_T=4$ is the other load.

In a certain load set $load_i$, the load components can be described as:

$$load_i = \{l_j | 1 \le j \le J\} \tag{3}$$

$$l_j = (P_N,\ f(t,\ t_r),\ g(t),\ T_{max}) \tag{4}$$

where l_j is a single load of load set $load_i$, P_N is the load rated capacity; $f(t,t_r)$ is the response characteristic curve of the load at time t. $g(t)$ is the load characteristic curve of the load; T_{max} is the maximum response time allowed for the load.

4.   Dynamic load aggregation with different targets

4.1. Common aggregation

For the small controllable load set $load_i$ with $Y_C =1$, common aggregation is to combine the loads

with the similar characteristics together. After obtaining the elasticity curve $f(t,t_r)$ of each load l_j, the K-means algorithm is used to cluster the neighboring points according to the demand of the application scenario or the electricity market.

This process is repeated until the standard deviation measure function converges. Depending on the application scenario, the chosen K-means standard measure functions are also different.

(1)   Based on response time

$$\mathrm{E}^t = \sum_{\mathrm{i}=1}^{I^t}\sum_{j=1}^{J^t}\sum_{load_i.l_j.\mathrm{T}\in C_i^t}\left|load_i.l_j.\mathrm{t}_r - m_i^t\right|^2 \tag{5}$$

where E^t is the sum of the sample mean and the mean square deviation of the cluster center; $load_i.l_j.t_r$ is a point in the space that represents the object; m_i^t is the mean value of the clustering C_i^t based on the time scale.

(2)   Based on response capacity

$$\mathrm{E}^P = \sum_{\mathrm{i}=1}^{I^P}\sum_{j=1}^{J^P}\sum_{load_i.l_j.\mathrm{T}\in C_i^P}\left|load_i.l_j.f(t,\ t_r) - m_i^P\right|^2 \tag{6}$$

where E^P is the sum of the sample mean and the mean square deviation of the cluster center; $load_i.l_j.f(t,t_r)$ is a point in the space that represents the object; m_i^p is the mean value of the clustering C_i^P based on the capacity scale.

4.2. Aggregate integrated model

The aggregate load model after aggregation can be described as:

$$aggre = \{agg_k | 1 \le k \le K\} \tag{7}$$

$$agg_k = \left(P_N,\ F(t,\ t_r),\ G(t),\ \mathrm{T}_{max}\right) \tag{8}$$

where $aggre$ is the aggregate of the same load after aggregation; k is the number of aggregates; usually, for a load set $load_i$ with J loads, aggregation number $k \le 2\ln J$; P_N is the aggregate capacity of agg_k; $F(t,t_r)$ is the adjustable capacity of agg_k at time t; T_{max} is the maximum response time of the aggregate.

Assume that the aggregate agg_k contains the load l_j ($j = 1,2,3, ...,j_k$). For the controllable load ($Y_C=1$), the parameters of the aggregate model are related to the load in the aggregate as in equations (9)-(12):

$$agg_k.P_N = \sum_{j=1}^{j_k} l_j.P_N \tag{9}$$

$$agg_k.\mathrm{T}_{max} \le maxl_j.\mathrm{T}_{max}\ \ j = 1,2,\cdots,j_k \tag{10}$$

$$F(t,\ t_r) = \sum_{j=1}^{j_k} l_j.f(t,\ t_r) \tag{11}$$

$$G(t) = \sum_{j=1}^{j_k} l_j.g(t) \tag{12}$$

5.   Economic dispatching considering the dynamical potential of aggregates

In this paper, based on the traditional scheduling model, the model incorporates the tunable ability of the aggregate. The mathematical model of economic dispatching including polymer load control is established by considering the constraints of system constraints, unit operation constraints and network constraints, taking the total cost of running cost, starting cost and polymer load control as the minimum.

5.1. Objective function

The objective function of the economic dispatch model, which takes the sum of operating cost, starting cost and aggregate load control cost as the optimization target as in equation (13)

$$\min F = \sum_{t=1}^{T}\left\{\sum_{i=1}^{N_G}\left[C_{Gi}\left(P_{Gi}^t\right)\cdot U_{Gi}^t + U_{Gi}^t\left(1 - U_{Gi}^{t-1}\right)S_{Gi}\right] + \sum_{k=1}^{N_k} r\left(agg_k.F(t,\ t_r)\right)\right\} \tag{13}$$

where T is the optimized number of time periods, for example, if a power output value is assigned

to the unit every 15 minutes, $T = 96$; N_G is the number of thermal power units participating in the optimization, P_{Gi}^t is the actual output of thermal power plant i at time t; U_{Gi}^t is the start-up state of thermal power unit i at time t; S_{Gi} is the start-up costs of thermal power units; N_k is the number of aggregates involved in economic scheduling; $agg_k.F(t,t_r)$ is the output of aggregate k in period t; $r(agg_k.F(t,t_r))$ is the cost of aggregate k in period t; $C_{Gi}(P_{Gi}^t)$ is the active production cost function of thermal power unit i, it can be represented by a quadratic curve $C_{Gi}(P_{Gi}^t) = a_{Gi}P_{Gi}^{t\ 2} + b_{Gi}P_{Gi}^t + c_{Gi}$ and a_{Gi}, b_{Gi}, c_{Gi} are cost coefficients of the thermal power unit i.

5.2. Constraints

5.2.1. System constraints. 1) Load balancing constraint

$$\sum_{i=1}^{N_G} P_{Gi}^t \cdot U_{Gi}^t + \sum_{k=1}^{N_k} agg_k.F(t,\ t_r) = P_L^t \tag{14}$$

where $agg_k.F(t,t_r)$ is the output of the aggregate k in t period, and P_L^t is the load demand in period t.
2)System standby constraint

$$\sum_{i=1}^{N_G} P_{Gi,max} \cdot U_{Gi}^t + \sum_{k=1}^{N_k} agg_k.F(t,\ t_r) \geq P_L^t + P_R^t \tag{15}$$

where $P_{Gi,max}$ is the maximum output of thermal power unit i; P_R^t is standby demand of the system at period t.

5.2.2. Thermal power unit constraint. Thermal power unit constraints include upper and lower limits of output of thermal power units, climbing constraint of thermal power unit and thermal power unit turn-off time constraint.

5.2.3. Aggregates constraints. The output of $agg_k.F(t,t_r)$ decides by the response time t_r at period t, and it should be less than the largest response time T_{max} among the aggregate.

$$0 \leq t_r \leq T_{max} \tag{16}$$

when $t_r = 0$, it denotes the aggregate does not involve in system operation at period t.
Besides, the output of $agg_k.F(t,t_r)$ should be less than the rated capacity as in equation (23):

$$0 \leq agg_k.F(t,\ t_r) \leq agg_k.P_N \tag{17}$$

6. Case analysis

6.1. Dynamic aggregation case parameter setting

Load agent signed a contract with 10000 power users to get them involved in the economic dispatch. It is assumed that the response characteristics in this study are directly available, which are the inverse and the proportional functions of the current consumption, respectively. The maximum response time is determined by the user's willingness (randomly generated according to the normal distribution). The abstract model is set table 1 shows.

Table 1. (a)Parameter of $load_1$.   (b) Parameter of $load_2$.

Load Number	$load_1.l_j$	P_N(W)	$f(t,t_r)$	Load Number	$load_2.l_j$	P_N(W)	$f(t,t_r)$
1	1≤j≤5000	1500	$f(t) = g(t)/10t_r$	3	1≤j≤5000	2000	$f(t) = g(t)/10$
2	5000≤j≤10000	2000	$f(t) = g(t)/100t_r$	4	5000≤j≤10000	3000	$f(t) = g(t)/100$

Because the dynamic fluctuation of the load is taken into account in the calculation of the example, four load curves are designed as figure 2 (a), (b), (c) and (d) show. The fluctuation of figure 2 (a) and (b) is a sine function with two different white noise. Figure 2 (c) shows that the load has two levels of power consumption and it has an opportunity to adjust three times a day. Figure 2 (d) shows that the load two power consumption power, but there are many adjustment possibilities.
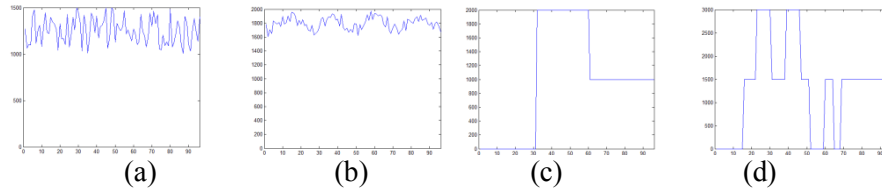
Figure 2. Four typical load fluctuation curves.

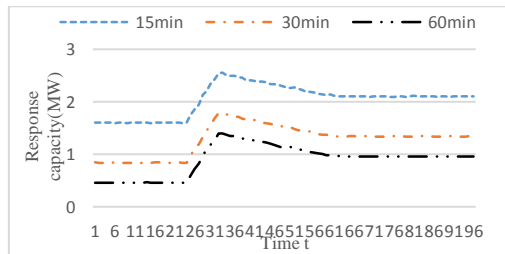### 6.2. Aggregate response characteristic analysis

The demand response characteristics of a single load affect the overall properties of the aggregate. This section aims to clarify the response characteristic of the case set in section 6.1. Table 2 and table 3 show the static response characteristics of all loads in a single time zone. Table 2 shows the results of the static aggregation with the response time as the center. Because of the negative response of $load_1$, the overall load has a tendency of inverse proportion. Table 3 shows the amount of load in the aggregate with different response capacities centered on the response capacity. As the response capacity grows, the aggregator needs to contain more loads

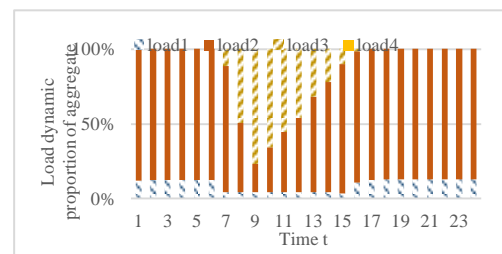**Table 2.** Response capacity of aggregate with different response time.

Response Time (min)	15	30	45	60	75	90	105	120
Response Capacity (MW)	1.6	0.84	0.58	0.45	0.38	0.33	0.29	0.26

Table 3. Load quantity of aggregate under different response capacities.

Response Capacity（MW）	1.0	1.1	1.2	1.3	1.4	1.5	1.6
Load Quantity	5681	6405	7138	7966	8849	9710	20000

Figure 3. Dynamic response characteristics with different response time.


Figure 4. Dynamic load ratio of an aggregate with the 100MW response capacity.

Figure 3 shows the results of dynamic aggregation with the response time as the aggregation center. It can be found that the longer the response time is, the smaller the response capacity is, and the tendency of response characteristics of the aggregates with different response times are consistent, which perform as the response curves of the three response times are parallel. Figure 4 is the dynamic load ratio of an aggregate with the 100MW response capacity. We can see that with time changes, the load composition of the aggregate changes. In the capacity requirements of 100MW, the fourth type of load response capacity is too small and too scattered, so is not involved in this aggregation.

6.3. Analysis of economic dispatch case

In this paper, the RTS96 bus system is selected for analysis. The optimization period T is 96, and the bus 3 is connected to a 96-point load data. The total output of four kinds of load aggregates is shown in figure 5, assuming the cost coefficient k of four kinds of loads is 25 *yuan / MW*, 23 *yuan / MW*, 20 *yuan / MW* and 18 *yuan / MW* respectively.
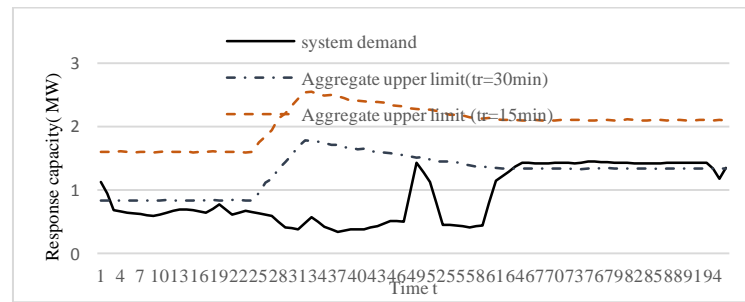
Figure 5. Maximum aggregate output of different response time.

As shown in figure 5, the red curve represents the best response capacity requirements of the system to achieve economic operation. As indicated by the green line, the response capacity of the aggregate is large enough to meet the requirements of the system under the requirement of 15 minutes response time. If the aggregate target is 30 minutes, period 16:30-24: 30 cannot meet the response capacity of the system requirements, that is, the system cannot meet the best purpose of economic operation.
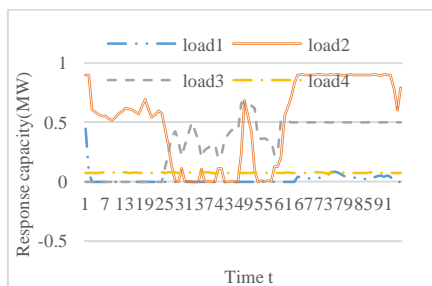
Figure 6. The response capacity under economic dispatch.
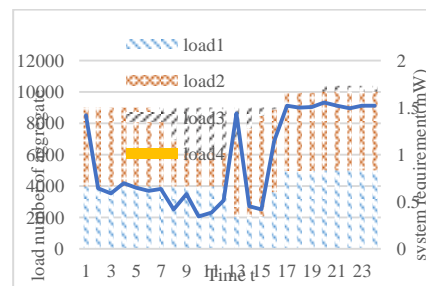
Figure 7. Load number of dynamic aggregate under economic dispatch.

Figure 6 shows under the response capacity of four kinds of loads when the response time is 15 minutes. It can be seen that under the prerequisite of economic dispatching, the system preferentially allocates the fourth type of load with lower cost, so the fourth kind of load maintains a relatively smooth output in the whole process, showing a smooth straight line. Secondly, because of the third type of load curve volatility is strong, its output is mainly affected by its own energy consumption characteristics, and is proportional to its own energy consumption. Since the 15-minute aggregation requirements are sufficient to meet the aggregation requirements of the system, only a fraction of the first and second type of load is invoked. Figure 7 shows the change in the number of loads over time under economic operating.

Comparing the operating costs of systems with and without dynamic aggregates, the costs of both cases are shown in Table 4. The system operating costs of the day are reduced by 720 yuan, and it can be assumed the annual operating cost of about 263,000 yuan to reduce. This is because the dynamic aggregate put into operation take the part of the conventional unit output, thereby reducing the operating costs of conventional units.

Table 4. Comparison of operating costs with/without dynamic aggregate.

Scenes	Total cost(yuan)	Generating cost(yuan)	Start up cost(yuan)	Aggregate dispatch cost(yuan)
Without aggregate	672530	670750	1780	/
With aggregate	671810	669200	1735	1025

7. Conclusion

In this paper, an abstract recognition model of small distributed load is established. Different from the current research of response characteristics for typical response resources such as air conditioning and electric vehicles, it describes and counts the related response parameters of common loads with the help of smart meters so as to reduce the difficulty of the different load identification for power system. The response time and the response time are taken as the aggregation centers, and the small loads are aggregated to establish the demand response synthesis model of the aggregate. Finally, the dynamic tunable potential of the aggregate is incorporated into the economic operation of the power system, and the influence of load fluctuation on the aggregation is analyzed. An example shows that the dynamic aggregation of load fluctuation can reduce the economic cost of power system effectively.

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