Dispatching Potential Evaluation of Thermostatically Controlled Loads Based on Realistic Customer Electricity Data in China

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***Abstract*—With the development of the information and communication technologies, demand response (DR) can be realized more easily and considered as one of effective methods to provide regulation services for the power system. Among the flexible loads for DR, thermostatically controlled loads (TCLs) are regarded as one of the most important loads, because of the large share of power consumption and suitable regulation characteristics without impacting customers' comfort. However, the dispatching potential of TCLs is difficult to be evaluated due to the limitation of measuring equipment. Faced with this issue, this paper proposes a method for evaluating the dispatching potential of TCLs based on the realistic customer electricity data in China. The relationship between the dispatching potential of TCLs and the ambient temperature is obtained. In this way, the system operator can calculate the dispatching potential of TCLs according to the weather forecast. The effectiveness of the proposed model and method are verified in the case studies.**

***Keywords—demand response, thermostatically controlled load, dispatching potential*.**

I. Introduction

The development of smart grid is facing more challenges, such as the increasing penetration of renewable energy sources, the larger peak-valley difference of loads and the insufficient regulation reserve capacities [1]. Besides, the power consumption of thermostatically controlled loads (TCLs), e.g., air conditioners, is rising rapidly. For example, the power consumption proportions of air conditioners in Beijing, Shanghai, and Guangzhou Cities in China have exceeded 40% or 50%, which still shows an increasing trend year by year [2]. These seasonal and periodical high power demand may lead to the shortage of power supply, and cause serious threat to the safe and stable operation of power systems [3].

With the development of the information and communication technologies, the source-gird-load interactive control technologies are paid more attention, which is called demand response (DR) to provide regulation services for the power systems by adjusting the power consumption of loads [4]. Among the flexible loads for DR, TCLs are regarded as one of the most important loads, because of the large share of power consumption and suitable regulation characteristics without impacting customers' comfort [5]. It has been proved that short-term increase or decrease of TCL's electricity consumption in a few minutes has little impact on customers' electricity demand [6]. Therefore, the TCLs are considered as the high-quality and valuable dispatching resources for the power systems [7]. Some researches on TCLs for DR have been done. For example, reference [8] aims at minimizing the maximum load or operating cost of the system. Reference [9] combines DLC dispatching model and unit combination model. In Reference [10], consideration of user comfort and load prediction error is added. Reference [11-12] proposed the state queuing (SQ) model to describe the air conditioning running state changes, providing ideas for the centralized control of a large number of air conditioning loads. Based on the load aggregator, reference [13] proposed a double-layer optimal dispatching strategy for distributed air-conditioning load grouping wheel control.

However, all the above studies consider that the dispatch-ing potential of air conditioning is infinite, and the optimal control strategies are designed on this basis. In reality, the dis-patching potential of TCLs is limited and generally unknown to the system operator, which is exactly this paper wants to fill.

In March 2015, with the release of further deepening the electric power system reform (hereinafter referred to as document No.9), China started the new round of electric power system reform.[14] Document No.9 clearly points out that the State Grid Corporation of China should actively increase the flexible regulation capacity of the power system and carry out DR.[15] In 2016, the National Key Research and Development Program "Friendly Interactive System of Supply and Demand" was launched in Jiangsu Province. The goals of this project are to reduce the regional comprehensive energy consumption and decrease the peak-valley difference of loads by DR. Suzhou Jinji Lake District and Changzhou Wujin District are taken as demonstration areas, which will become one of the largest DR demonstration projects in the world.[16]

Based on the realistic customers' electricity data in the Jiangsu Province, this paper proposes a dispatching potential evaluation method of TCLs, where the relationship between the dispatching potential of TCLs and the ambient temperature is obtained. In this way, the system operator can calculate the dispatching potential of TCLs according to the weather fore-cast. The effectiveness of the proposed model and method are verified in the case studies.

II. The Model of Thermostatically Controlled Loads

The equivalent thermal parameters (ETP) model is the most common TCL model in the previous studies on DR.[17-19] The ETP model takes into account the power of TCLs, the environment temperature, the room thermodynamic parameters and some other factors, which can be expressed as

$$\frac{d\theta(t)}{dt} = -\frac{1}{\tau}\left[\theta(t) - \theta_a(t) + sm(t)RP_c\right] \tag{1}$$

$$\tau = RC \tag{2}$$

$$P_c = \alpha P_N \tag{3}$$

where $\theta(t)$ is the indoor temperature and measured by the controller at time *t*, °C; $\theta_a(t)$ is the indoor temperature without TCL at time *t*, which can be approximately considered as equal to the outdoor environment temperature, °C; *s* is the operating mode of the air conditioner, and the value is equal to 1 or -1, respectively, indicating that the air conditioner is operating in the cooling or heating mode; $m(t)$ is the switching state of TCLs, and the value is set as 1 or -1, respectively, indicating that TCLs starts or stops; τ is the thermal time constant of the house, hour; C and R are the equivalent thermal capacitance and equivalent thermal resistance of TCLs respectively, kWh/°C and °C/kW; P_c is the cooling/heating power, kW; P_N is the rated power, kW; α is the coefficient of performance(COP).

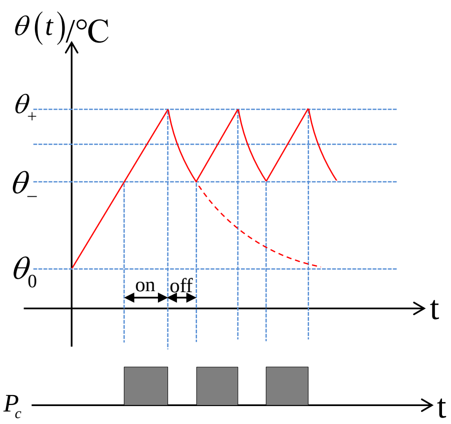

Fig. 1. Dynamic Change Process of TCL

In order to avoid TCL's compressor start-stop frequently and ensure the user's comfort, the TCL is controlled to maintain the indoor temperature in the dead zone. In refrigeration mode, when the indoor temperature reaches the upper limit, the compressor starts to work and TCL starts refrigeration. When the indoor temperature reaches the lower limit, the compressor stop working.

$$m(t) = \begin{cases} 0 & ,\theta(t) \le \theta_- \\ 1 & ,\theta(t) \ge \theta_+ \\ m(t-\varepsilon), & \text{other} \end{cases} \tag{4}$$

where ε is an extremely small time interval, and is a step in simulation analysis. $m(t-\varepsilon)$ represents previous state. The dynamic change process is shown in Fig. 1.

III. Dispatching Potential Evaluation Method of Thermostatically Controlled Loads

The dispatching potential of TCLs is defined as the power consumption of the TCLs that can be regulated to participate in the DR. Obviously, the most accurate way is to install load identification equipment with communication systems, which can accurately monitor the user's power consumption of TCLs, and send the measured data back to the dispatching center. However, the cost of this method is too high, and the maintenance is very complicated. Facing this issue, this paper proposes the evaluation method based on the realistic electricity consumption data.

The TCLs in cooling mode in summer are taken as the example. First of all, according to the meteorological temperature data in the summer, select the coolest *N* days in each month. Then take the average of the daily load curve of these *N* days as the baseline load curve of this month. That is to say, the baseline load curve is regarded as the load which is not affected by high temperature, which is expressed as

$$Load_{base} = \frac{1}{N}\sum_{i\in S} \mathrm{Load}_i \tag{5}$$

where $Load_{base}$ is the baseline load. $Load_i$ is the selected load curves.

Based on the equation (5), the dispatching potential of TCLs in each day can be obtained by subtracting the baseline load curve from the original load curve, which is expressed as

$$Load_{TCL,j} = Load_j - Load_{base} \tag{6}$$

where $Load_{TCL,j}$ is the dispatching potential curve of TCLs; $Load_j$ is the daily load curve excluding the above *N* days.

The maximum dispatching potential of TCLs in each day can be calculated as

$$Load_{TCL,j}^{\max} = \max\left\{Load_{TCL,j}, 0\right\} \tag{7}$$

Based on the equation (7) and the corresponding ambient temperature, the relations between these two values can be obtained and listed in the form of scatter diagram, which can be fitted to obtain the corresponding function of the maximum dispatching potential of air conditioners with respect to the ambient temperature:

$$Load_{TCL}^{\max} = f(T) \tag{8}$$

where T is the average temperature for any given day; $Load_{TCL}^{\max}$ is the corresponding maximum dispatching potential of TCLs on the predicted day.

IV. Case Studies

The customers' electricity consumption data in Galaxy International Community in Wujin District, Changzhou City, Jiangsu Province in September 2018, are adopted in the case studies. These data come from the National Key Research and Development Program of China "urban users and power grid supply and demand friendly interaction system". The electricity consumption data are collected every 15 minutes.

A. *Data Screening*

Considering the on-line rate of the metering devices and the loss of data in the transmission process, the electricity consumption data of residents are firstly screened before calculating the dispatching potential of TCLs. If a user's data meets one of the following three criteria, the user's data will be discarded:

(1) The user's power consumption data is not 30 days.

(2) The user has at least 36 zeros for 96 collection points on a given day.

(3) The user's total power consumption in a day is less than 0.01kWh.

After the data screening, 1174 households are considered as having the valid data.

B. *Baseline Load Curve Calculation*

According to the weather conditions in Wujin district, in September 2018, seven days from September 24th to September 30th were selected as the baseline days. Therefore, based on the equation (5), the baseline load curve $Load_{base}$ can be calculated, as shown in Fig. 2.

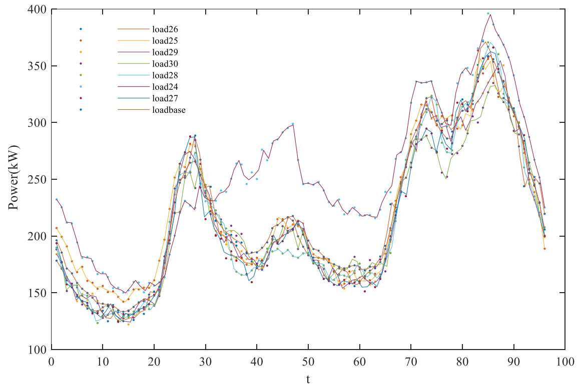

Fig. 2. $Load_i$ and $Load_{base}$

C. *Dispatching Potential of Daily Thermostatically Controlled Load*

Based on the equation (6), the dispatching potential curve in each day $Load_{TCL,j}$ can be obtained by subtracting $Load_{base}$ from the daily load curve, as shown in Fig. 3-Fig. 9. The highest value is the maximum dispatching potential of the TCLs on each day, which is 510.7613kW, 642.1873kW, 592.0390kW, 478.7189kW, 440.9631kW, 463.5427kW, 294.1166kW on September 1st to 7th, respectively. Similarly, the maximum dispatching potential of TCLs from September 8th to September 23th can also be obtained in this method, as shown in Table I.

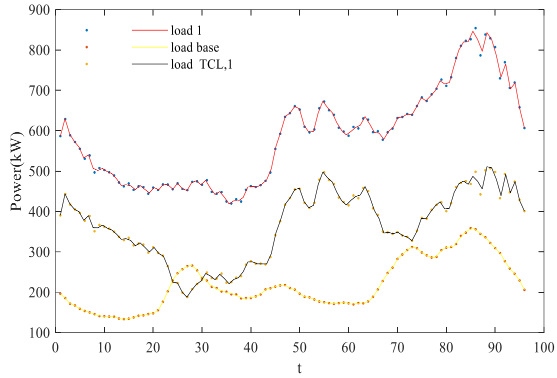

Fig. 3. $Load_{TCL1}$

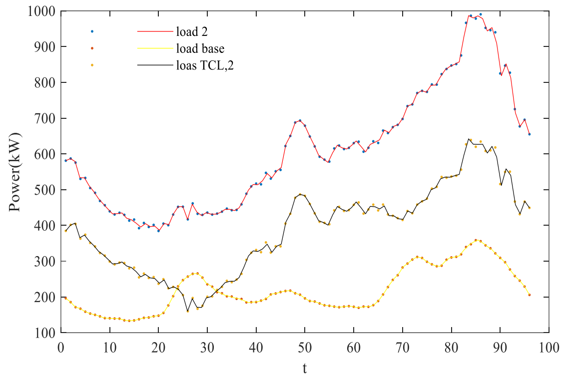

Fig. 4. $Load_{TCL2}$

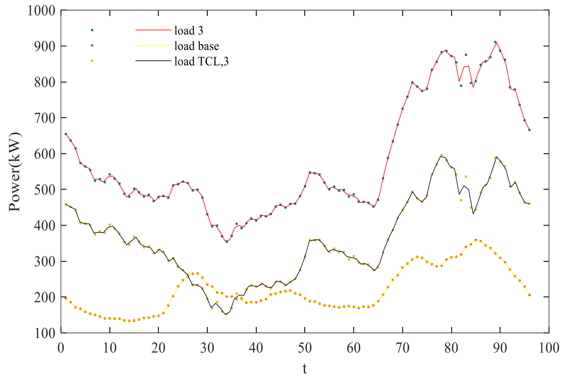

Fig. 5. $Load_{TCL3}$

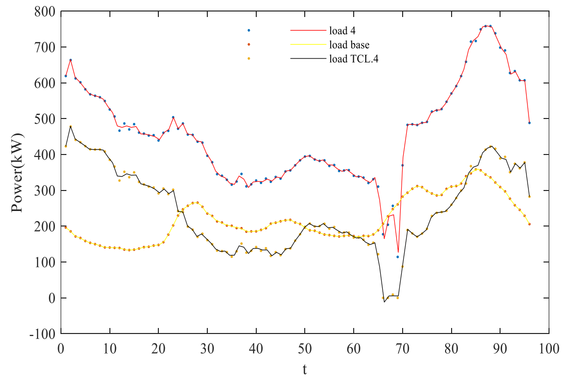

Fig. 6. $Load_{TCL4}$

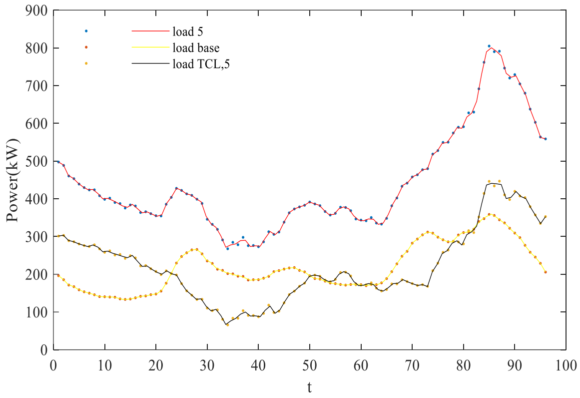

Fig. 7. $Load_{TCL5}$

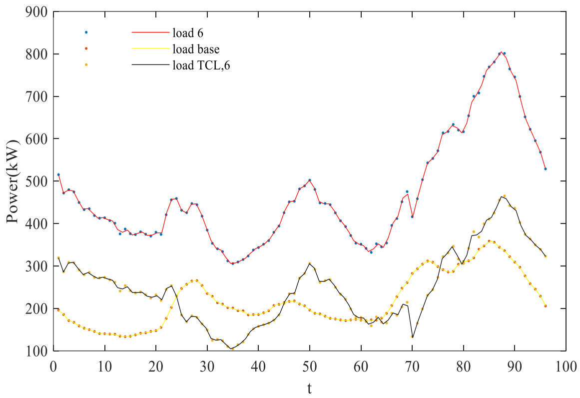

Fig. 8. $Load_{TCL6}$

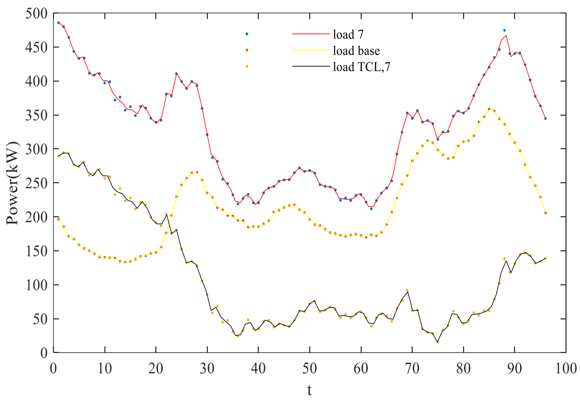

Fig. 9. $Load_{TCL7}$

TABLE I. THE AVERAGE TEMPERATURE AND THE MAXIMUM DISPATCHING POTENTIAL OF TCLS

Date	Average Temperature /°C	Maximum Dispatching Potential of TCLs/kW
9.01	28.5	510.7613
9.02	29	642.1873
9.03	29	592.039
9.04	28	478.7189
9.05	27.5	440.9631
9.06	28	463.5427
9.07	23.5	294.1166
9.08	24	127.1775
9.09	24	80.2612
9.10	23.5	60.6914
9.11	24.5	64.755
9.12	26	74.5795
9.13	25	79.8618
9.14	26.5	173.0368
9.15	26.5	242.5138
9.16	27.5	391.7966
9.17	25.5	249.0181
9.18	27	391.7038
9.19	28	487.5575
9.20	26.5	371.3941
9.21	23	223.1098
9.22	24.5	110.319
9.23	23.5	90.5332

It can be seen that when the average temperature is lower than 26℃, the maximum dispatching potential of the TCLs is small and fluctuates irregularly. When the average temperature is higher than 26℃, the maximum dispatching potential of the TCLs is positively correlated with the temperature as a whole. Therefore, it can be considered that the cooling demand will occur when the average temperature is higher than 26℃. The fitting curve is shown in Fig. 10.

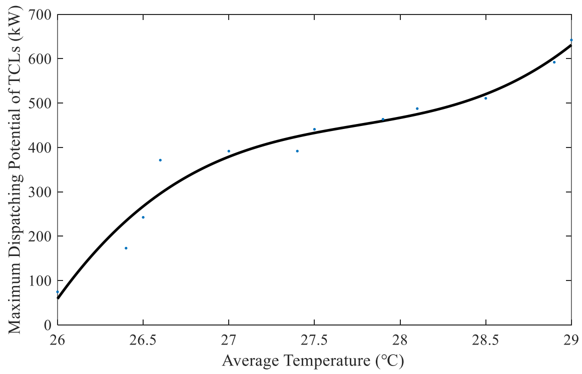

Fig. 10. Relationship Between the Average Temperature and Maximum Dispatching Potential of TCLs

The regression coefficient of this curve is 0.9602, which indicates that the regression model has a good fitting characteristic. Substitute the data of September 4 for verification. It can be seen that the maximum dispatching potential of TCLs obtained by the fitting curve is 466.9805kW, when the average temperature is 28℃. The actual maximum dispatching potential is 478.7189kW. The error is 2.45%, which is accurate enough for evaluating the maximum dispatching potential of TCLs in practice.

V. CONCLUSIONS

This paper puts forward a method for evaluating the dispatching potential of TCLs based on realistic customer electricity data in China. First of all, the average loads in low-temperature days are taken as the baseline load curve. Then the dispatching potential of TCLs can be obtained by subtracting the baseline load curve from the load curves on high-temperature days, where the maximum value on the curve is the maximum dispatching potential of TCLs. Finally, the maximum dispatching potential of TCLs is fitted with the ambient temperature. This evaluation method is verified by the actual electricity data in China. In this way, the dispatcher can evaluate the dispatching potential of TCLs in the next few days according to the weather forecast, which is useful for carrying out DR in smart grid.

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