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A strategy for contingency management with aggregated thermostatically controlled loads in china's electricity market

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Abstract. Faced with the deregulation of power grid in China, the traditional operation dispatch of system and the management of customers will change enormously. In the new environment, the power consumption of customers could be adjusted with the information and communication technology, which provide a new approach for system operator to maintain the power balance between supply and demand during contingencies. In China, thermostatically controlled loads (TCLs) account for a large proportion of power consumptions and have a great potential to provide regulating reserve for system. Therefore, a strategy for contingency management with TCLs is proposed in this paper to guarantee the reliable operation of power system. Firstly, the regulating capacity models of aggregated TCLs are proposed by the aggregation of the model for one individual TCL considering the customer behaviour and electric-thermal characteristics. What's more, an optimization model integrating the aggregated TCLs and conventional generators is proposed to determine the operation dispatch during contingencies. The proposed methods are validated using the modified IEEE 30-bus system.

1. Introduction

The power industry in China is experiencing restructuring nowadays. In 2015, the Chinese government has issued "No. 9 Document" and launched a new round of power industry reform [1, 2]. One of the objectives in the "No. 9 Document" is to transform the State Power Corporation (SPC) to public utility organization and develop competitive, efficient and dynamic electricity market. Besides, the customers in demand side are permitted to buy electricity directly from the generation companies or electricity markets instead of SPC [2]. Hence, customer choices will have great impacts on the system operation, electricity pricing and emergency control.

In conventional power system, the planning mechanism of power industry in China remain vertical monopoly [3]. During the real-time operation, the SPC determines the dispatch plans of different generators based on their predefined production quota and tariff results [4]. When the system transits from stable state into contingency state caused by random failures, the contingency management plans will be developed by SPC to guarantee the reliable operation of system. The corresponding contingency management plans mostly focus on the adjustments of generation output, and usually ignore the regulation of power consumption in demand sides. In the new environment, the system operator will determine the dispatching plans based on the bids and offers submitted by the customers and generators. Besides, customers will adjust their behaviors of power consumption based on the change of electricity price [5]. If the cost paid for the demand is higher than the benefits produced by the same amount of electricity, the customers will accordingly reduce their demand. Hence, similar to the reserve provided by conventional generators, the demand side resources could provide the system operator with a strategy for contingency management by reducing or shifting loads.

As important demand side resources, thermostatically controlled loads (TCLs), such as heaters and air conditioners, account for a large proportion of power consumptions. It is estimated that the share of TCLs in the power consumptions approach 40% during peak loads in China [6]. Under the premise that consumer's comfort are not affected, the operating status of TCLs could be adjusted in cooperation with the power output of generators by system operator. Many studies [6-8] have agreed the feasibility and effectiveness of TCLs for providing operating reserve. The literature [6] proposes a quantitative evaluation methods to evaluate the operating reserve of aggregated TCLs without sufficient measurement data. In the literature [7], a novel strategy is proposed for the aggregation of TCLs based on resetting the temperature of each TCL. Besides, many studies investigate the method and strategy to integrate the aggregated TCL models into operation control of power system [9-11]. In the literature [11], the centralized load controllers to control TCLs are proposed to provide operating reserve. An operation planning framework for the dispatch of large-scale TCLs is proposed to improve the efficiency in real-time operation [10]. The previous studies mainly investigate the evaluation and control of TCLs at the level of end-users. However, faced with the deregulation of power grid in China, how the aggregated TCLs cooperate with conventional generators at system level to determine the operation dispatch in contingency states have not been discussed.

In this paper, a new strategy integrating the aggregated TCLs with generation sources to deal with the contingencies of system is proposed. Firstly, the regulating capacity model for one individual TCL is proposed based on customer behavior and electric-thermal characteristics. These models for different TCLs in one region are aggregated to determine the regulating capacity of aggregated TCLs. Moreover, the capacity models for aggregated TCLs are integrated with conventional generators to obtain the operation dispatch based on optimal power flow model during contingencies.

2. A strategy for contingency management with aggregated TCLs

During contingencies such as transmission line failures, based on the bids and offers submitted by generators and customers, operation dispatch will be determined by system operator using optimal power flow [12]. Figure 1 shows the framework for optimal dispatch integrated with aggregated TCLs during contingency state. As shown in figure 1, the loads in demand side can be divided into two categories: conventional loads and aggregated TCLs. Given that the capacity of one individual TCL is relatively small which cannot participate in the electricity market directly, a number of TCLs in one region could be aggregated together as an aggregator. Compared to conventional loads, the power consumption of aggregated TCLs can be regulated with smart devices equipped in each household. The system operator could control the working states of aggregated TCLs by sending signals to their smart devices. Therefore, similar to generators, the aggregated TCLs could submit its regulating capacity and price in electricity market.

In the clearing of electricity market, optimal power flow model will be applied to determine the dispatch results for both the power generation and aggregated TCLs. Based the clearing results in the market, system operator will send control signals to the aggregated TCLs to regulate their power consumption. The regulation of power consumption of TCLs could be implemented by regulating their set temperature. Generally, adjusting the set temperature of TCLs to a higher level in cooling state could reduce their power consumption. If the aggregated TCLs are regulated during real-time operation, the owners of TCLs could earn the corresponding benefits.

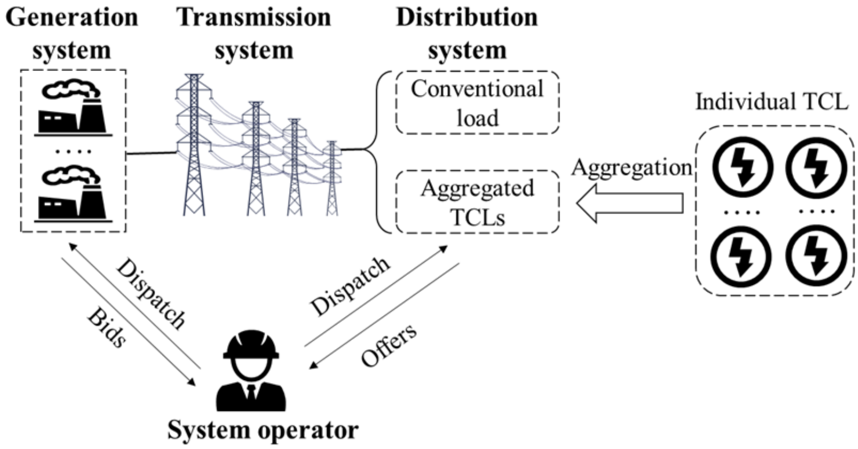

Figure 1. A framework for optimal dispatch integrated with aggregated TCLs.

2.1. Regulating capacity evaluation of individual TCL

The regulating capacity of one individual TCL is related to the customer behaviour and the electric-thermal characteristics. With regard to customers, their preferences for the room temperature and the benefits earned from raising the set temperature of TCL are different. According to the thermal model in the literature [7], the regulating capacity of individual TCL P_{TCL} can be determined by the reduction of power consumption with the regulation of the set temperature from initial temperature to final temperature, as shown in Figure 2.

$$P_{TCL} = \frac{R(T_{set}^{k+1} - T_{set}^{k})}{EER} \quad (1)$$

where P_{TCL} represents the regulating capacity provided by TCL by regulating temperature from T_{set}^{k+1} to T_{set}^{k}. R is the equivalent thermal conductance and EER is the energy efficiency ratio.

Considering the difference of the TCLs' operation state when receiving control signals, the duration time that TCLs provide regulating capacity can be different [7]. Generally, the operating states of TCLs can be divided into two categories: cooling state and standby state. Hence, the duration time DT_{TCL} depends on the operating state of TCL receiving control signals, which can be represented as:

$$DT_{TCL} = \begin{cases} t_{de} - t_{SR}, t_{SR} \in PD_{cool} \\ t_{de} - \left(t_{SS} + RT\right), t_{SR} \in PD_{styb} \end{cases} \quad (2)$$

where t_{de} is the end moment of duration time, t_{SS} is the moment of sending control signal and t_{SR} is the moment of receiving control signal. RT is the response time which denotes the time delay of TCL starting to provide regulating capacity after control signal is sent. PD_{cool} and PD_{styb} represent the time periods of cooling state and standby state, respectively.

It should be noted that the duration time DT_{TCL} has a positive relationship with the regulating range of set temperature. That is to say, the more set temperatures are regulated, the longer duration time is.

With the regulation of set temperature from T_{set}^{k+1} to T_{set}^{k}, different customers with TCLs have various references for benefits. For example, the benefits paid for customer m to regulate the set temperature 1°C can be low. However, with the adjusting magnitude of set temperature increase, the benefits paid for customers will inevitably increase. Generally, the cost C_k corresponding to the regulating capacity of TCL m can be represented as a ladder [6], as shown in Figure 2.(c). When the set temperature of TCL m is regulated from T_{set}^{k+1} to T_{set}^{k}, the customer could be paid by the corresponding cost C_{k+1}. The cost C_{k+1} is the expectation of benefits that customers can get by regulating their set temperatures of TCL, which is related to their living standards and their preferences for the room temperature.

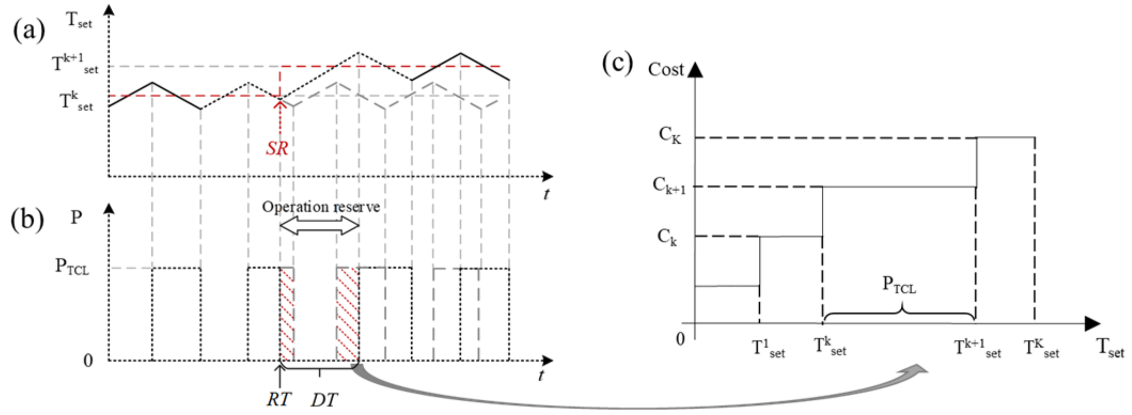

Figure 2. The regulating capacity provided by one individual TCL and its cost: (a) the variation curve of the temperature in the room, (b) the power consumption of TCL and (c) the costs paid for TCL.

2.2. Regulating capacity evaluation of aggregated TCLs

Based on the regulating capacity evaluation model of individual TCL, the regulating capacity provided by aggregated TCLs is analysed here. The aggregated TCLs contain multi-TCL, whose set temperature, duration time and the corresponding costs can be different. Hence, for a given time period from 1 to *T*, the regulating capacity of aggregated TCLs AC_{TCL} could be determined by the aggregation of each individual TCL, as shown in Figure 3. It should be noted that, the regulating capacity provided individual TCL at time t is related to the length of duration time. When the time t is in the duration time, the regulating capacity is P_{TCL} and otherwise is zero. Hence, for a time period *T*, the regulating capacity of aggregated TLCs can be represented as:

$$\begin{aligned} AC_{ATCL} &= \sum_{t=1}^{T}\sum_{m=1}^{M} P_{m,TCL} \cdot \mathrm{I}(t < DT_{m,TCL}) \\ &= \sum_{t=1}^{T}\sum_{m=1}^{M} \frac{R(T_{m,set}^{k+1} - T_{m,set}^{k})}{EER} \cdot \mathrm{I}(t < DT_{m,TCL}) \end{aligned} \tag{3}$$

where $\mathrm{I(True)} \equiv 1$ and $\mathrm{I(False)} \equiv 0$, $P_{m,TCL}$ represents the regulating capacity provided by TCL m at time t, $DT_{m,TCL}$ is the duration time of TCL m to provide regulating reserve, and M is the number of TCLs.

Likewise, the costs paid for the aggregated TCLs for the regulation of set temperatures can also be obtained by the aggregation of each individual TCL. Hence, the costs paid for the aggregated TCLs can be represented as:

$$C_{ATCL} = \sum_{t=1}^{T}\sum_{m=1}^{M} C_{m,TCL} \tag{4}$$

where $C_{m,TCL}$ is the costs paid for the TCL m to provide regulating capacity $P_{m,TCL}$.

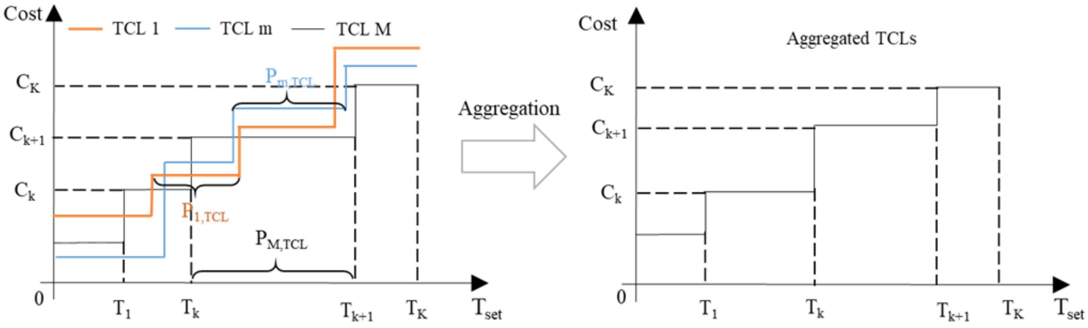

Figure 3. The regulating capacity provided by aggregated TCLs.

2.3. *Operation dispatch integrated with aggregated TCLs*

Based on the regulating capacity evaluation of aggregated TCLs, the aggregated TCLs could provide system operator with an approach to regulate the power consumption in real-time operation for a given time period T. Considering the random failures of power grid, the operation dispatch is developed according to optimal power flow model, where the generation and aggregated TCLs are dispatched [5, 13]. Therefore, when system state transits from normal state to contingency state l, the generation output and the reduction of power consumption of aggregated TCLs could be determined by solving the following optimization problem.

The objective is to minimize the total system cost including generation cost and the regulation cost for aggregated TCLs for a given time period T.

$$Min\ TC = \sum_{i=1}^{N}\sum_{g=1}^{ng_i} C_{ig}^l(P_{ig}^l) + \sum_{i=1}^{N} C_{i,ATCL}^l(LC_i^l) \tag{5}$$

where C_{ig}^l and P_{ig}^l are the cost function and the power output of generator g at node i, respectively. ng_i represents the number of generators at node i and N is the number of nodes in system. LC_i^l and $C_{i,ATCL}^l$ are the reduction of power consumption and the corresponding cost of aggregated TCLs at node i, respectively.

Equation is subject to the following constraints:

Power balance constraints:

$$(\mathbf{B}^l \cdot \boldsymbol{\theta}^l)_i = \sum_{g=1}^{n_{gi}} P_{ig}^l - P_{iD}^l + LC_i^l \tag{6}$$

Generation limits:

$$\underline{P_{ig}^l} \le P_{ig}^l \le \overline{P_{ig}^l} \tag{7}$$

Regulating capacity limits of aggregated TCLs:

$$0 \le LC_i^l \le AC_{i,ATCL}^l \tag{8}$$

Line flow limits:

$$\left|\frac{1}{x_{ij}}\left(\theta_i - \theta_j\right)\right| \le F_{ij}^{\max} \tag{9}$$

In the optimization problem, $\mathbf{B}^l$ and $\boldsymbol{\theta}^l$ represent the admittance matrix of transmission network and phase angle vector of the node voltages, respectively. $\underline{P_{ig}^l}$ and $\overline{P_{ig}^l}$ are the upper limit and lower limit of power generation g at node i, respectively. $AC_{i,TCL}^l$ represents the regulating capacity of aggregated TCLs. x_{ij} and $F_{ij}^{\max}$ denote the reactance and maximum power flow of the transmission line between node i and j. θ_i and P_{iD}^{l} are the phase angle of voltage and the load at node i.

3. Case study

The modified IEEE 30-bus system is restructured to demonstrate the proposed models and techniques, as shown in Figure 4. The power system consists of 6 generating nodes, 27 load nodes, 41 transmission lines and 9 generating units. It is assumed that aggregated TCLs located at each load nodes. The physical parameters (such as equivalent thermal conductance and energy efficiency ratio) used to calculate the regulating capacity of TCLs can be found in [6]. Besides, the cost paid for the aggregated TCLs to regulate the set temperature is set according to the consumer satisfaction quantization in [6].

Considering the random failures of power grid, *N-K* principle is introduced in this paper to simulate the contingency states of system [13]. The simulation results are compared with the results without considering the integration of aggregated TCLs during contingencies. Among several contingencies, two contingency states are selected to evaluate the effects of aggregated TCLs on the operation of power system. The simulation results in Figure 4 correspond to the failures of two generators at node 2 and one generator at node 11 and the simulation results in Figure 5 correspond to the failures of three generators at node 2.

It can be noted in Figure 5 and Figure 6 that with the integration of aggregated TCLs, the power output of generators at node 8 and 11 are smaller than that without considering aggregated TCLs. This is mainly because that the aggregated TCLs reduce the power consumption by regulating set temperature. Under this circumstance, the generating capacity is relatively sufficient and the reliability of power grid is improved. It can be seen from Figure 5 that aggregated TCLs provide about 72.4MWh regulating capacity by reducing their power consumption at contingency state 1.

Besides, the integration of aggregated TCLs can also lower the operation cost of power grid, which can be shown in Figure 7 and Figure 8. According to the simulation results, the nodal price at most nodes is only 43.6 \$/MWh at normal state and 77.9 \$/MWh at contingency state 1. When integrated with aggregated TCLs, the nodal price decreases to 57.1 \$/MWh at contingency state 1. Moreover, the total system cost considering aggregated TCLs at contingency state 1 are 16462.02 \$/MWh, which is much smaller than 17661.86 \$/MWh without considering aggregated TCLs. Therefore, regulating the power consumption of aggregated TCLs could be of great benefits to the safety and economy operation of power system.

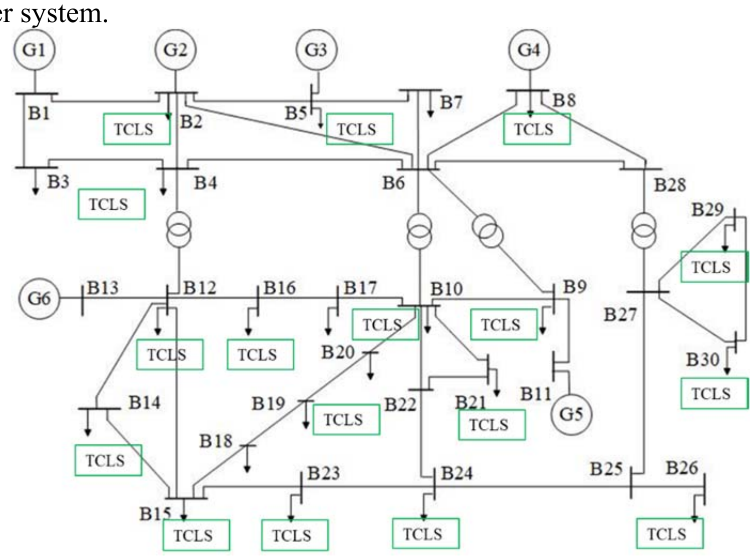

Figure 4. The modified IEEE 30-bus system.

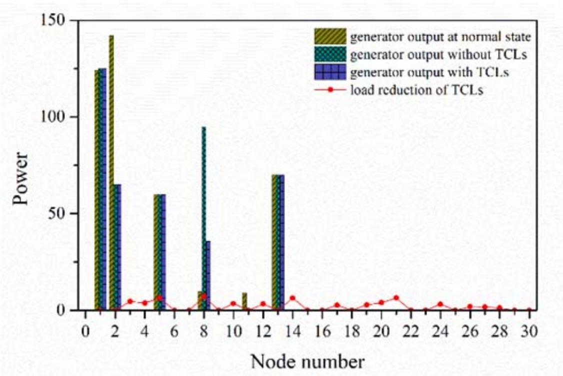

Figure 5. The comparison between the operation dispatch considering and without considering TCLs at contingency state 1.

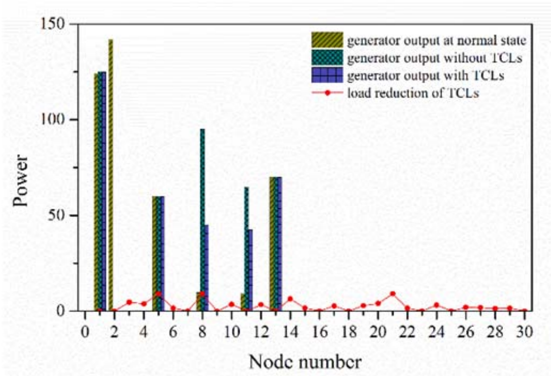

Figure 6. The comparison between the operation dispatch considering and without considering TCLs at contingency state 2.

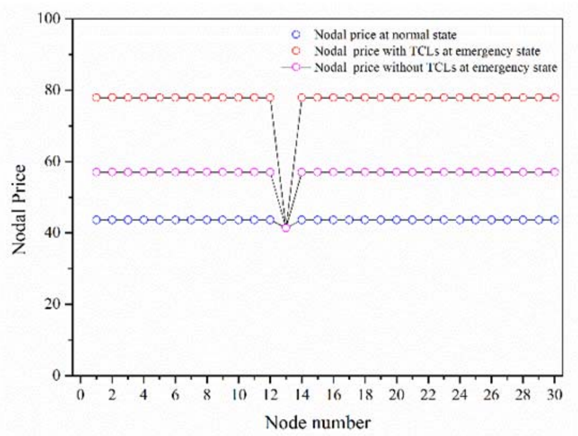

Figure 7. The comparison between the operation dispatch considering and without considering TCLs at contingency state 1.

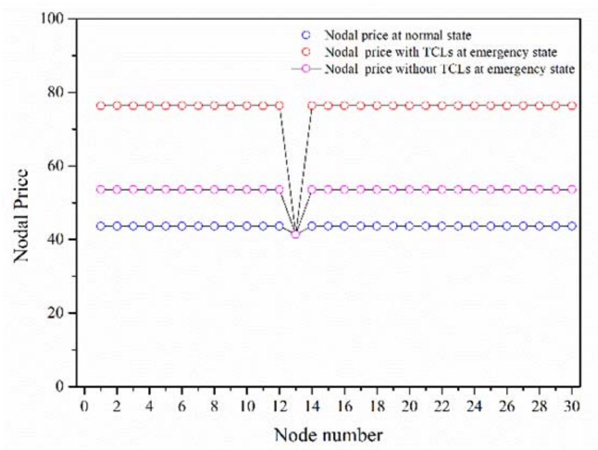

Figure 8. The comparison between the operation dispatch considering and without considering TCLs at contingency state 2.

4. Conclusions

The deregulation of power grid in China will provide the system operator with an approach to regulate TCLs to maintain the power balance between supply and demand during contingencies. This paper presents an optimization model for integrating aggregated TCLs with conventional generators to guarantee the reliable operation of power system during contingencies. Firstly, the regulating capacity of aggregated TCLs is evaluated by the aggregation of individual TCL considering the customer behavior and electric-thermal characteristics. What's more, the optimal power flow model considering the total cost of generators and aggregated TCLs is proposed to determine the operation dispatch of power system. The simulation results show that the integration of aggregated TCLs could improve the reliability of power grid by regulating the power consumption. Besides, it is also an effective method to lower the total operation cost of power grid. However, when applied to the real operation of power system, the installation costs of smart devices can be relatively high.

Acknowledgement

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