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Optimal strategy for domestic electric water heaters based on virtual energy storage characteristics

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ABSTRACT

Characteristic of virtual energy storage can be found by controlling electric water heaters, which play a role similar to a battery in the grid. Virtual energy storage model is built by discretization and linearization of classic equivalent thermal parameter model. Virtual state of charge queue strategy is proposed to achieve unified control of different electric water heater types and users' needs at the same time. Compared with traditional temperature state queue strategy, this strategy proposed solved load fluctuations caused by adjusting setting. The simulation verifies feasibility and effectiveness of strategy proposed, and it can be found that the cost of maintaining load diversity is sacrificing response speed and amplitude control.

Keywords: Electric water heater; Demand response; Virtual energy storage; Virtual state of charge

1. Introduction

Nowadays, the demand for electricity load has grown sustainably, and there is a local and periodical tension between domestic power supply and demand [1,2]. The proportion of new load with "source" and "load" bidirectional characteristics, such as electric vehicles, electric water heaters and central air-conditionings, is increasing. Some consumers can adjust their own electricity demand according to incentive electricity price, which provides a theoretical basis for the demand response [3]. The rapid development of bidirectional communication technology and advanced metering infrastructure provides technical support for monitoring and controlling user load [4,5].

Demand response (DR) can be defined as the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time [6]. The DR technology is currently used for residential load and small commercial load, especially air-conditioning, electric water heaters and so on, which have thermal storage capacity [7–9]. Users who participate in DR generally receive economical compensation by cost subsidies from control transfer or price discounts.

The working principle of the electric water heater is Joule's Law. The temperature of the box is maintained in a specific temperature range through the way of heating the resistance wire. The control mode of the electric water heater is more flexible, and the participation methods are various. At the same time, they have a high degree of controllable margin and no impact power [10]. It can form a virtual energy storage (VES) characteristic by dispatching control of large-scale electric water heaters in the community. The electric water heaters are closed to "discharge" to meet vacancy of the power grid and opened to "charge" to stabilize the power fluctuation.

The concept of VES is defined recurrently. Reference puts forward the concept of VES of air-conditioners and partly relevant characteristics, however, it cannot be applied in quantitative assessment [11]. In reference, air-conditioner load curve can be adjusted to establish a "virtual storage"

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effort and a strategy is built to suppress power fluctuation in tie lines in micro-grid based on continuous state constraint-based optimal control [12]. Reference proposes an optimal scheduling method for a combined cooling, heating and power building micro-gird considering virtual storage system [13]. China Electric Power Research Institute, Tianjin University and North China Electric Power University have carried out extensive research on VES [11,14,15].

In the modeling and controlling field of DR, reference takes full consideration of specific characteristics of residential roads and established the load model based on user behavior [16]. According to the behavior characteristics of electric water heaters, reference presents a high accuracy model reflecting different conditions of them, but it is not suitable for cluster scheduling due to the large amount of computation in the grid [17]. Reference proposes a load model suitable for terminal voltage control of electric water heaters to reduce peak load on the premise of ensuring the comfort of the users [18]. Reference proposes an operational planning framework, consisting of a day-ahead scheduling stage and a real-time operation stage, for large-scale thermostatically controlled load dispatch [19]. The bi-level optimal dispatch and control model for air-conditioning load based on direct load is proposed to deal with the problem in reference [20]. Reference use the adjustment of temperature setting value to control aggregated load, which can reduce the switching frequency and physical loss significantly compared with the traditional control [21–23]. However, a small adjustment of temperature setting value will cause the loss of load diversity and huge load fluctuation by above method for high degree of concentration of load. At present, the dispatch scheduling is confined to electric water heaters with similar parameters and the same demands, and their potent cannot be excavated.

This paper takes the electric water heaters as the research objects, analyzes its VES characteristics, deals classical equivalent thermal parameter (ETP) model with discretization and linearization, establishes mathematical model of VES and proposes control scheduling based on virtual state of charge. This control strategy can help different types and demands electric water heaters take part in DR, and solve the load fluctuation caused by adjustment of setting value in the traditional methods. Finally, the effectiveness and feasibility of the control strategy are verified.

2. ETPs model of electric water heaters

The key to achieve precise control is to establish a model for energy conversion of electric water heaters. In this paper, an equivalent thermal parameters model (ETP model) is used to characterize the heat exchange process of electric water heaters. The main idea of the ETP model is that the internal environment, the external environment and conversion of electric energy are equivalent to components of circuits such as resistors, capacitors and sources, so as to use circuit knowledge to analyze the relationship between temperature and energy.

2.1. Simplification of ETP model

The classical three-order ETP model takes into account of heat impedance difference between indoor solid and gas, temperature difference between inner and exterior wall, and analyze comprehensively the energy transfer process of environment and box. The two-order ETP model, shown as Fig. 1, can be widely applied in consideration of practical application and calculation speed [24].

A state space equation of ETP model is as follows:

$$\begin{aligned}
&\dot{x} = Ax + Bu \qquad \dot{y} = Cy + Du \\
&\dot{x} = \begin{bmatrix} \dot{T}_{\text{in}_g} \\ \dot{T}_{\text{in}_m} \end{bmatrix} \quad \dot{y} = \begin{bmatrix} T_{\text{in}_g} \\ T_{\text{in}_m} \end{bmatrix} \quad u = 1 \\
&A = \begin{bmatrix} -\left(\dfrac{1}{R_2 C_a} + \dfrac{1}{R_1 C_a}\right) & \dfrac{1}{R_2 C_a} \\ \dfrac{1}{R_2 C_m} & -\dfrac{1}{R_2 C_m} \end{bmatrix} \\
&B = \begin{bmatrix} \dfrac{T_o}{R_1 C_a} + \dfrac{Q}{C_a} \\ 0 \end{bmatrix} \\
&C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad D = 0
\end{aligned} \tag{1}$$

In practice, gas could be neglected in the electric water heater boxes. It is considered that there is no difference in temperature as water is fully touched with the inner wall of the box. Assuming $T_{\text{in}\_g} = T_{\text{in}\_m} = T_{\text{in}}$, the two-order ETP model can be simplified to one-order ETP model, shown as Fig. 2.

Where C_e represents equivalent heat capacity in the box, T_{in} represents temperature in the box. The simplified state space description of the one-order model is:

$$\frac{T_{\text{in}} - T_o}{R_1} + C_e \frac{dT_{\text{in}}}{dt} = Q \tag{2}$$

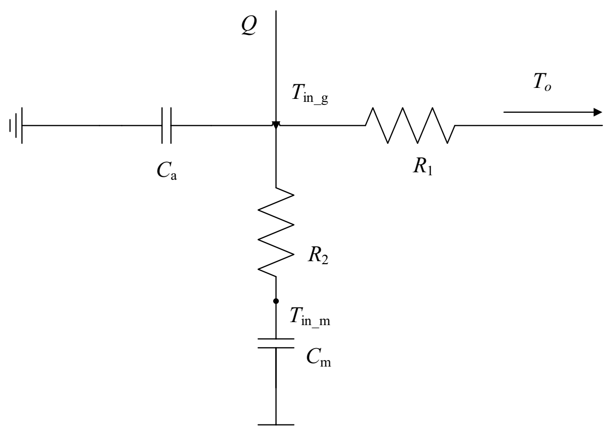

Fig. 1. Two-order ETP model of electric water heaters. Q – heat rate for electric water heaters (kW), $Q = \eta P$; η – energy efficiency ratio; P – electric power in heating (kW); T_{in_g} – air temperature inside the box (°C); T_{in_m} – mass temperature inside the box (°C); T_o – temperature outside the box (°C); C_a – air heat capacity (J/°C); C_m – mass heat capacity (J/°C); R_1 – heat transfer resistance between box and external environment (°C/W); R_2 – heat transfer resistance between air and mass in the box (°C/W).

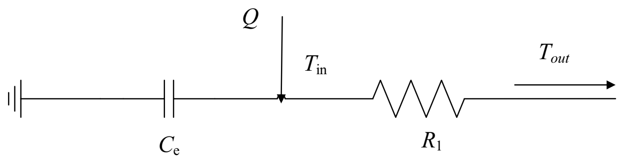

Fig. 2. One-order ETP model of electric water heaters.

It is described by $(T_{in}-T_o)/R_1$ that the loss of thermal power rate due to difference in temperature between box and external environment. $C_e dT_{in}/dt$ expresses thermal power rate to heat the box.

2.2. Discretization of ETP model

Assuming $T_{in}(t_0) = C$, Eq. (3) is solved by Eq. (2):

$$T_{in}(t) = T_o(t) + R_1 Q - \left(T_o(t) + R_1 Q - C\right) e^{-\frac{t}{R_1 C_e}} \quad (3)$$

Q should be a discrete variable in the time domain, because electric water heaters are controlled by switch on or off. Assuming time interval is Δt, the recurrence equation of temperature (4) is obtained by discretization of (3):

$$\begin{cases} T_{in}^{t+1} = T_o^{t+1} - \left(T_o^{t+1} - T_{in}^{t}\right) e^{-\frac{\Delta t}{R_1 C_e}} & S = 0 \\ T_{in}^{t+1} = T_o^{t+1} + R_1 Q - \left(T_o^{t+1} + R_1 Q - T_{in}^{t}\right) e^{-\frac{\Delta t}{R_1 C_e}} & S = 1 \end{cases} \quad (4)$$

T_{in}^{t} temperature of box at time t (°C);
T_{in}^{t+1} temperature of box at time $t+1$ (°C);
T_o^{t} temperature of external environment at time t (°C);
T_o^{t+1} temperature of external environment at time $t+1$ (°C);
S switching function, which 1 expresses there is input electric power, and 0 expresses there is no power.

Taking electric water heaters as an example, electric power of electric water heaters has effort on temperature in the box, as shown in Fig. 3.

2.3. Linearization of ETP model

The external environment does not change during participation in DR, that is $T_o^t = T_o^{t+1}$. Assuming the range of temperature in the box is $[T_{min}, T_{max}]$, control cycle of Q is t_p, turn-on time is t_{on} and turn-off time is t_{off}. Eq. (5) is obtained by iterative computation of taking T_{min} and T_{max} into Eq. (4):

$$\begin{aligned} T_{max} &= \left(T_o + R_1 Q\right)\left(1 - e^{-\frac{t_{on}\Delta t}{R_1 C_e}}\right) + T_{min} e^{-\frac{t_{on}\Delta t}{R_1 C_e}} \\ T_{min} &= T_o\left(1 - e^{-\frac{t_{off}\Delta t}{R_1 C_e}}\right) + T_{max} e^{-\frac{t_{off}\Delta t}{R_1 C_e}} \\ t_p &= t_{on} + t_{off} \end{aligned} \quad (5)$$

And turn-on t_{on} and turn-off t_{off} is described by Eq. (6) as follows:

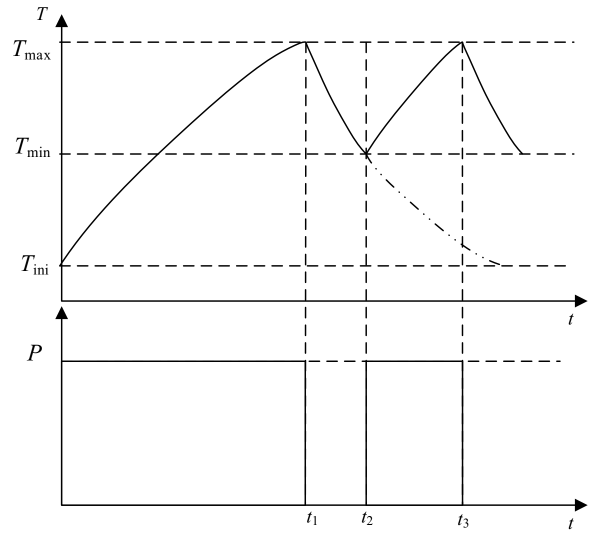

Fig. 3. Power and temperature curve of electric water heaters.

$$t_{on(off)} = \frac{R_1 C_e}{\Delta t} \ln\left(\frac{T_{min} - T_o - S R_1 Q}{T_{max} - T_o - S R_1 Q}\right) \quad (6)$$

Variable T_o, R_1, C is constant, and $\Delta t/t_{on}$ (off) is equal to constant value because its range of change is very small when temperature change is little. The linearization of ETP model is realized through fixed proportion of time interval Δt accounting for turn-on time t_{on} or turn-off time t_{off} describe temperature variation.

$$\begin{cases} T_{in}^{t+1} = T_{in}^{t} + \dfrac{\Delta t}{t_{on}}\left(T_{max} - T_{min}\right) & s = 1 \\ T_{in}^{t+1} = T_{in}^{t} - \dfrac{\Delta t}{t_{off}}\left(T_{max} - T_{min}\right) & s = 0 \end{cases} \quad (7)$$

Calculation parameters refer to reference and simulation is on the MATLAB platform. Linearized ETP model is compared with one-order ETP model, as shown in Fig. 4 [24,25].

The correlation coefficient R of the two curves is calculated by Eq. (8), and $R = 0.99869$ between linearized ETP model and one-order ETP model. It can be considered that linearization would have little effort on relevant results:

$$R(X,Y) = \frac{\mathrm{Cov}(X,Y)}{\sqrt{D(X) \times D(Y)}} \quad (8)$$

where $R(X,Y)$ expresses correlation coefficient of X and Y, Cov(X,Y) expresses covariance and $D(X)$ expresses standard deviation.

3. VES model

In practice, different types of electric water heaters and residential different habits make it difficult to unify the range value T_{min} and T_{max}. A VES is presented based on energy

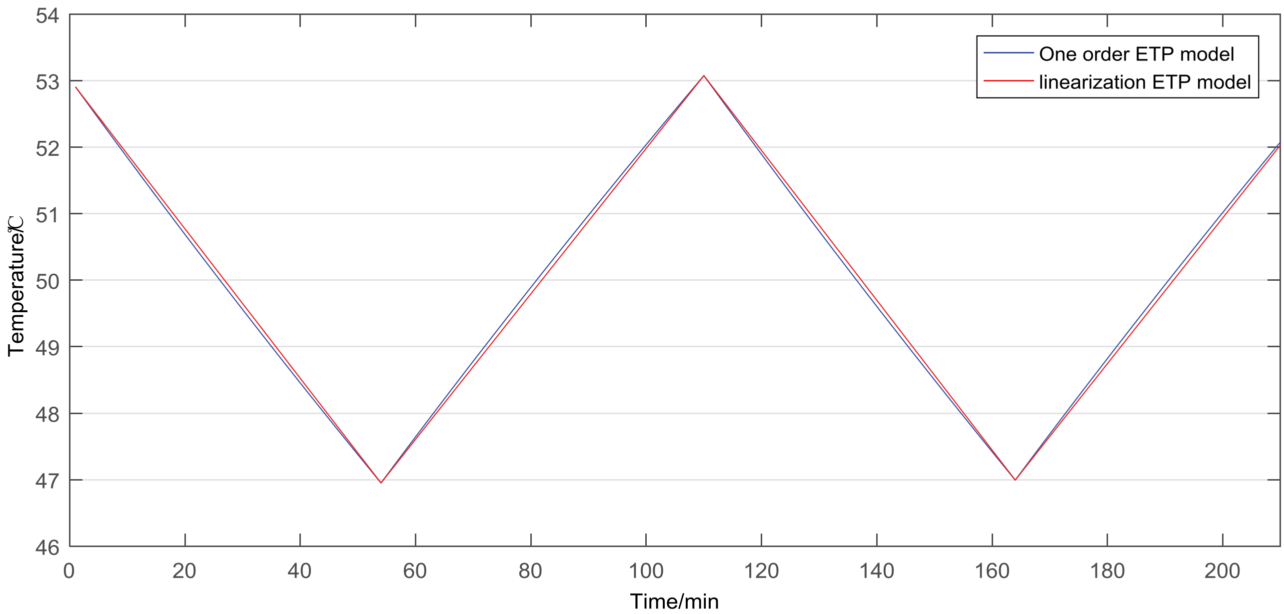

Fig. 4. Comparison between linearized ETP model and one-order ETP model.

storage characteristics. Discharge corresponds to action from opening to closing, while charge corresponds to action from closing to opening. The unified control of different types and needs can be realized by taking virtual state of charge (VSOC) as the benchmark.

The charge and discharge power of VES should be the rated power of electric water heater, as described by Eq. (9):

$$P^j_{\text{disc/char}} = \text{SP}^j_{\text{rated}} \tag{9}$$

where subscript disc expresses discharge of VES, while subscript char expresses charge of that. Superscript j expresses number of VES. P^j rated expresses rated power of number j of electric water heaters.

It is in agreement that range of control temperature is $[T_{\min}, T_{\max}]$, and temperature of electric water heater is $T_{\text{in}}(t)$ at time t. Taking $T_{\min}$ as the zero of equivalent storage capacity, the equivalent storage capacity of electric water heater is described by Eq. (10) at time t:

$$Q_s(t) = C_e\left(T_{\text{in}}(t) - T_{\min}\right) \tag{10}$$

According to the definition of the state of charge, the virtual state of charge is described by Eq. (11) as follows:

$$\text{VSOC}(t) = \frac{Q_s(t)}{Q_{\text{capacity}}} = \frac{T_{\text{in}}(t) - T_{\min}}{T_{\max} - T_{\min}} \tag{11}$$

The VES model will be used to control strategy of electric water heater next.

4. Control strategy

This section proposes VSOC queue control strategy to achieve unified control of different types and needs, and solve the problem of load fluctuation caused by adjusting temperature setting in the traditional strategy. VSOC queue strategy is proposed referring to the commonly used state queue strategy [6]. Fig. 5 shows running operation of an electric water heater. Suppose that each control cycle includes 12 changing VSOC, state 1–4 show charging state of VES (shaded blocks in Fig. 5); state 5–12 show discharging state of VES (blank blocks in Fig. 5). Normally, VES would rotate among state 1–12 in order to ensure that the state is in the range of (0,1).

Set the following assumptions so that VSOC queue strategy is more practical.

Assumption 1: the data refreshing time is 3 min, that is, each state lasts 3 min.

Assumption 2: the initial load has high diversity and the average distribution is in each state.

Assumption 3: the external environment of the electric water heater remains still during the DR.

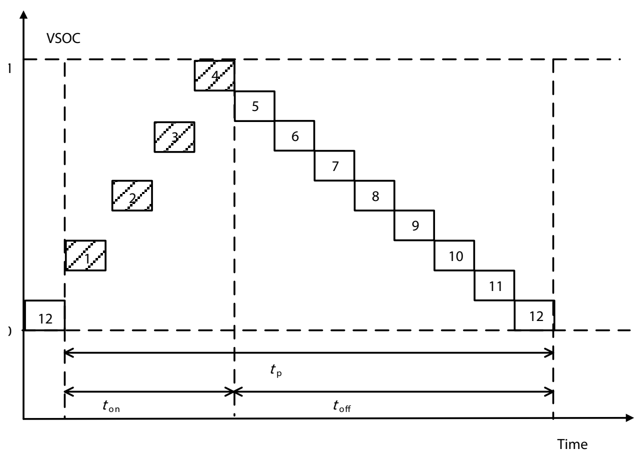

Fig. 5. VSOC queue of an electric water heater.

N VES evenly distributed in the above 12 states, each state contains VES *N*/12 which is called state group. As time goes on, the original state group moves forward according to Fig. 4. Original state group 1 becomes state group 2, while original group 2 becomes state group 3 and so on. Original state group 12 becomes new state group 1 and starts a new cycle.

Table 1 describes the above process in detail, where row number is the number of VES and column number expresses runtime.

The total power of VES operation can be obtained by Eq. (12):

$$P_{\text{sum}} = \frac{n_{\text{on}}}{n_p}\text{NP}_{\text{disc/char}} = \frac{t_{\text{on}}}{t_p}\text{NP}_{\text{disc/char}} \quad (12)$$

where n_1 expresses the number of turn-on state in a cycle; n_p expresses the total number of state; *N* expresses the total number of VES.

Taking discharge as an example, the specific control is illustrated based on Fig. 6. Different from traditional state queue strategy, transition period is added for solving load fluctuation. The added transition period could guide the VES restore stable operation after load cutting. The general course of transition period is amplifying limited range temporarily to maintain diversity of VES, and lead into a new stable range.

When temperature range rises ΔT, the VSOC of VES uniformly distributed in (0,1) becomes within temperature range $[\Delta T/(T_{\max}–T_{\min}), 1 + \Delta T/(T_{\max}–T_{\min})]$, as shown in Fig. 6a temperature setting rising leads to range of VSOC rise, and portion exceeds the limits.

The VESs discharging operate in the range of $(0, 1 + \Delta T/(T_{\max}–T_{\min}))$, control range will become (0,1) successively when VSOC = 0. While the VESs charging operate in range of $(\Delta T/(T_{\max}–T_{\min}), 1 + \Delta T/(T_{\max}–T_{\min}))$, control range will become $(0, 1 + \Delta T/(T_{\max}–T_{\min}))$ successively when VSOC = $1 + \Delta T/(T_{\max}–T_{\min})$. Until VSOC = 0 the control range will come back to (0,1). The above transition state achieves VES discharging and maintains stable operation for a long time. The specific process is shown in Fig. 6b, the original state 5–12 are transferred to the new state 5′–12′, original state 1–4 are transferred from turn-on state to the location where original state 5–8 was, that is, new state 1′–4′. State is transferred to stable state, as shown in Fig. 6c, under the premise of maintaining diversity. The principle of VES discharging is that the VES opening is closed in this strategy, and in transition state limited range of former closed VES widens to reduce the number of opening state, leading opening time is later than schedule.

Table 1
VSOC distribution during a time cycle

	1	2	3	4	5	6	7	8	9	10	11	12
3	**1**	**2**	**3**	**4**	5	6	7	8	9	10	11	12
6	**2**	**3**	**4**	5	6	7	8	9	10	11	12	**1**
9	**3**	**4**	5	6	7	8	9	10	11	12	**1**	**2**
12	**4**	5	6	7	8	9	10	11	12	**1**	**2**	**3**
15	5	6	7	8	9	10	11	12	**1**	**2**	**3**	**4**
18	6	7	8	9	10	11	12	**1**	**2**	**3**	**4**	5
21	7	8	9	10	11	12	**1**	**2**	**3**	**4**	5	6
24	8	9	10	11	12	**1**	**2**	**3**	**4**	5	6	7
27	9	10	11	12	**1**	**2**	**3**	**4**	5	6	7	8
30	10	11	12	**1**	**2**	**3**	**4**	5	6	7	8	9
33	11	12	**1**	**2**	**3**	**4**	5	6	7	8	9	10
36	12	**1**	**2**	**3**	**4**	5	6	7	8	9	10	11

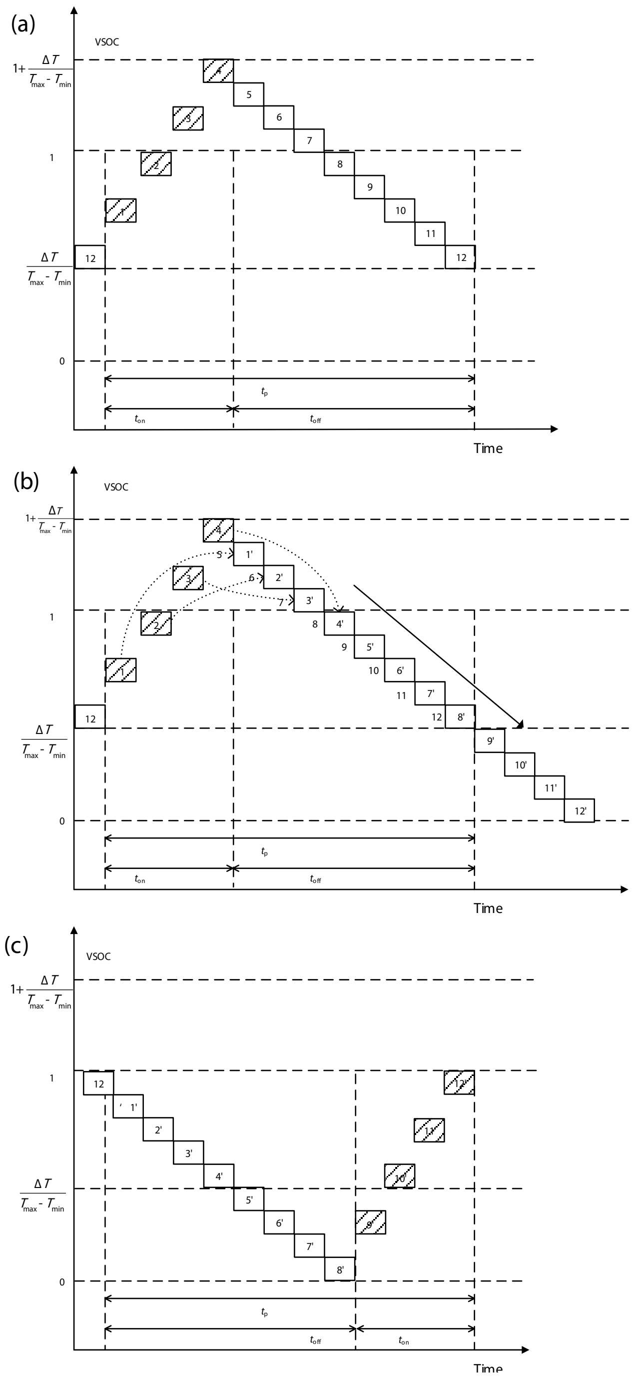

Fig. 6. VSOC queue strategy diagram (a) initial state, (b) transition period, and stable state.

The max discharging power of VES is obtained by Eq. (13):

$$\begin{cases} P_{\text{disc\_max}} = \left(1 - \dfrac{\Delta T}{T_{\max} - T_{\min}} \times \dfrac{t_{\text{off}}}{t_{\text{on}}}\right) P_{\text{sum}} & \dfrac{\Delta T}{T_{\max} - T_{\min}} \le \dfrac{t_{\text{on}}}{t_{\text{off}}} \\ P_{\text{disc\_max}} = P_{\text{sum}} & \dfrac{\Delta T}{T_{\max} - T_{\min}} > \dfrac{t_{\text{on}}}{t_{\text{off}}} \end{cases} \quad (13)$$

Charging is similar to the above strategy, and giving details is unnecessary.

5. Example simulation

VSOC queue strategy proposed is compared with traditional temperature state queue strategy which refers to the study by Ran [23]. There are 600 electric water heaters and

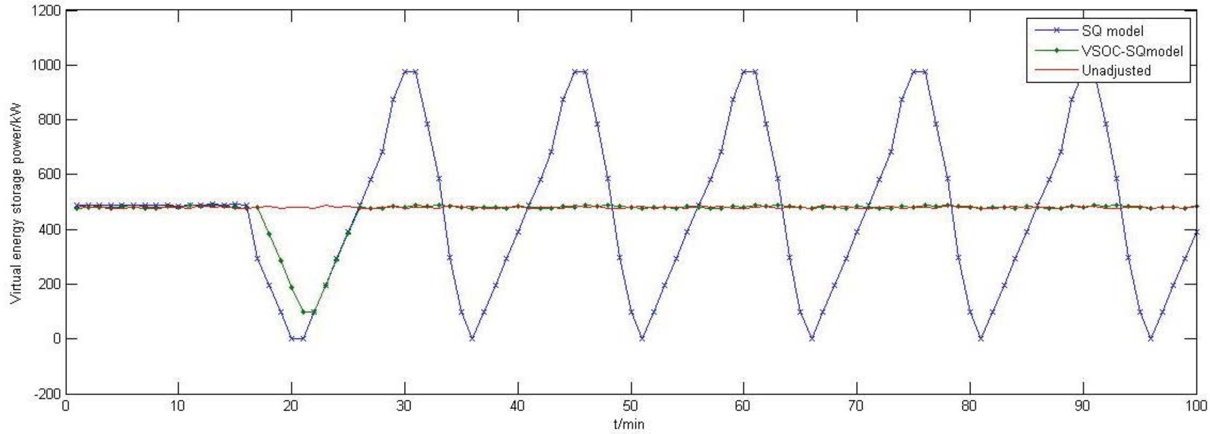

Fig. 7. Comparison of different control strategy (temperature setting falls by 4°C).

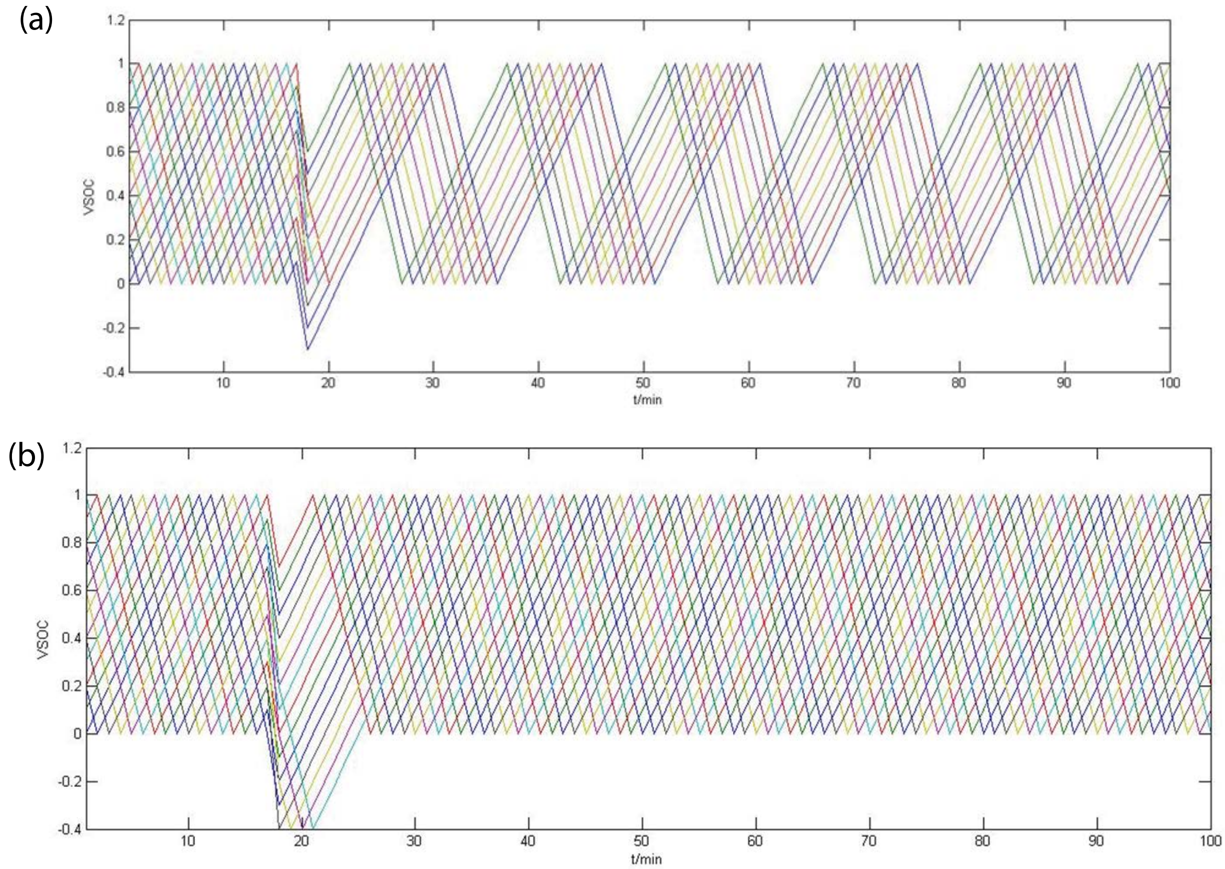

Fig. 8. VSOC curves of different control strategy (temperature setting falls by 4°C) (a) VSOC of SQ model and (b) VSOC of VSOC-SQ model.

time interval is 3 min. The initial VSOC is a random number 0–1 uniformly distributed. Rated power is a random number 2.3–2.5 kW uniformly distributed. Protocol minimum temperature of each electric water heater is a random number 45°C–55°C uniformly distributed. Protocol maximum temperature of each electric water heater is a random number 55°C–65°C uniformly distributed. Equivalent heat capacity of each electric water heater is a random number 0.05–0.07 kWh/°C uniformly distributed [26–30]. Equivalent heat resistance of each electric water heater is a random number 40°C–42°C/kW uniformly distributed. Energy efficiency ratio of each electric water heater is a random number

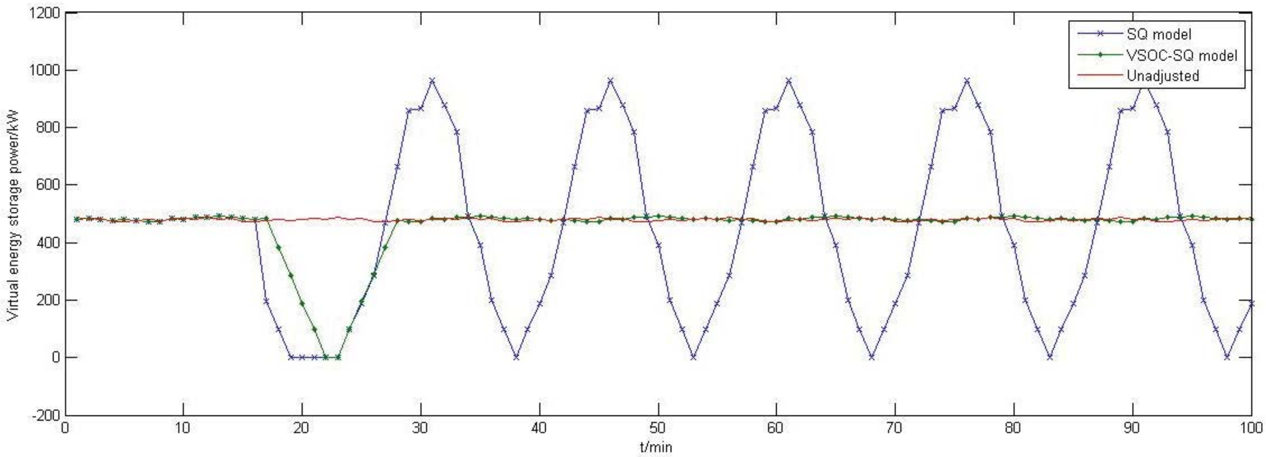

Fig. 9. Comparison of different control strategy (temperature setting falls by 6°C).

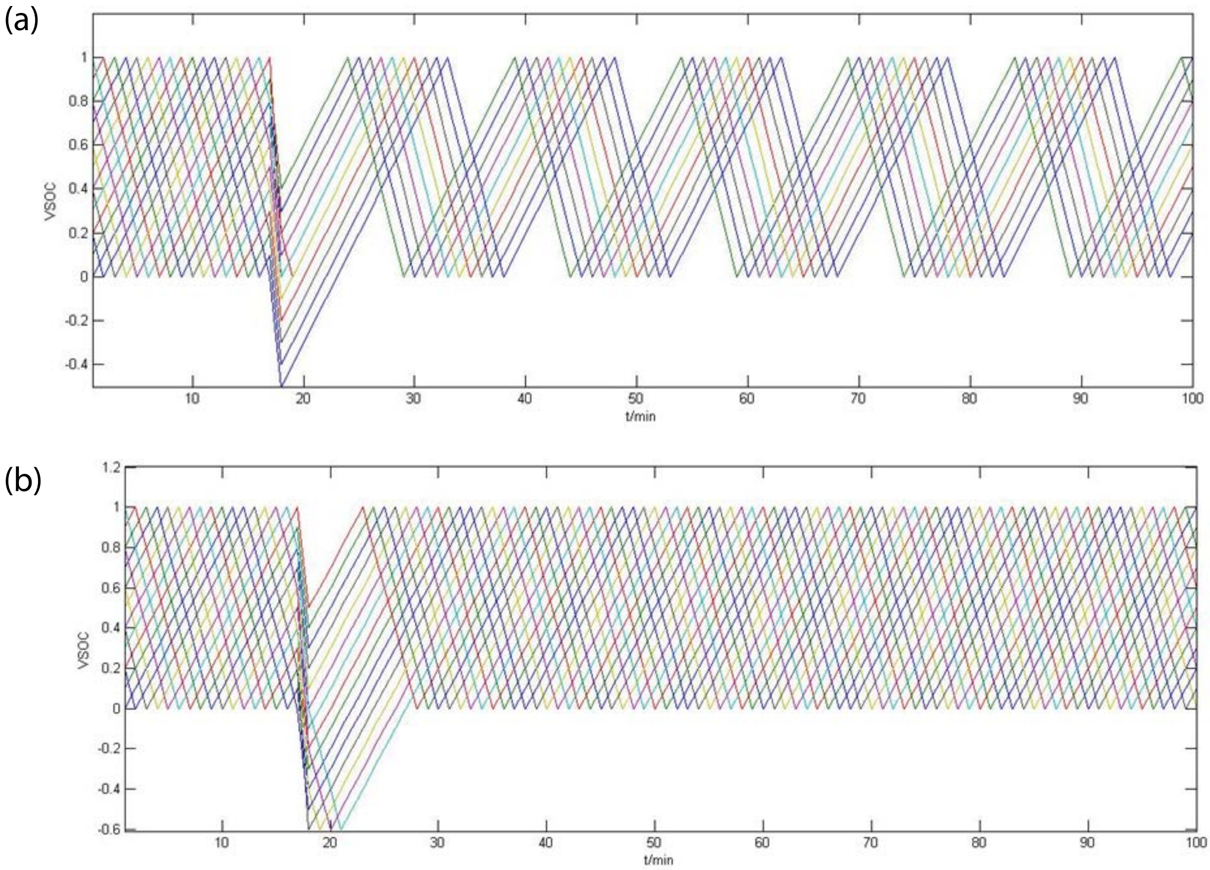

Fig. 10. VSOC curves of different control strategy (temperature setting falls by 4°C) (a) VSOC of SQ model and (b) VSOC of VSOC-SQ model.

2.6–3.4 uniformly distributed. Taking discharging of VES as an example, it is analyzed that setting range is reduced by 4°C and 6°C, respectively.

For the convenience of comparison, the temperature state in traditional strategy (SQ model) is transferred into VSOC by Eq. (11). Fig. 7 shows discharging power of different control strategy and Fig. 8 shows VSOC curves when temperature setting falls by 4°C. In theory, it is found that maximum discharging power with VSOC queue strategy (VSOC-SQ model) should be four-fifths of the original power represented by Eq. (13) when temperature setting falls by 4°C, and in simulation this is the fact that amplitude of green line with spot is about four-fifths of that of blue line with cross [31–36]. Compared with traditional strategy, VSOC queue strategy maintains load diversity obviously, as shown in Fig. 8, but decreasing amplitude is larger and response speed is slower. It can be seen that the VSOC queue strategy sacrifices response speed and amplitude control for diversity.

Figs. 9 and 10 show comparison of power and VSOC, respectively, when setting temperature falls by 6°C. The comparison results verify the above conclusions, the change of temperature setting is bigger, and the sacrifices of response speed and amplitude control are bigger.

6. Conclusion

This paper proposes virtual energy shortage model on the basis of ETP model and VSOC queue strategy to achieve unified control of different types and needs by users at the same time. The response potent of electric water heaters is fully excavated, and load fluctuations caused by adjusting temperature setting in traditional strategy are solved effectively. Finally, the feasibility and effectiveness of control strategy proposed are verified by simulation, which provides a support for more thermostatically controlled loads participating in DR.

At the same time, it is found that load diversity plays an important role in restraining load fluctuation. However, maintaining load diversity costs slower response speed and larger amplitude. For different needs, it will be the focus in the future that how to coordinate load diversity with corresponding speed and vibration amplitude.

Acknowledgments

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