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The extended 2-dimensional state-queuing model for the thermostatically controlled loads

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ABSTRACT

The thermostatically controlled loads (TCLs) are one of the best candidates to participate in the demand response (DR) programs such as direct load control (DLC). The dynamics of large amounts of TCLs are characterized by the state-queuing (SQ) in many recent research works. However, the traditional SQ model is not accurate enough due to the limited information conveyed in the state vector. By analyzing the limitations of the traditional SQ modelling approach, this paper proposes a 2D SQ modelling approach for the TCLs that extends the state vector to a 2-dimensional state matrix. The first dimension represents the on/off states and the TCLs' temperature intervals, whereas the second dimension reflects the temperature-varying-rate (TVR) information. And the transition of the states is established by the operation of the sub-matrixes. By introducing the additional TVR information, the accuracy of the modelling is improved. Numerous testing results verify the effectiveness of the proposed method.

1. Introduction

Regarding the trend of fossil energy exhaustion and the requirement of environmental protection, the renewable energy resources such as wind, solar, etc. become increasingly important [1]. However, their intermittence and fluctuation bring disturbances to the power system [2]. Demand response (DR) is one of the methods to deal with this problem [3]. Recently, with the development of advanced smart metering technologies, the direct load control (DLC), which is a strategy for DR, has gained increasing interest. DLC is widely adopted in peak load reduction, load shifting and improvement of stability for a power grid [4,5].

The thermostatically controlled loads (TCLs), e.g. refrigerators, freezers, and water heaters, have shown great potential to be engaged in power system services under the DLC strategy. With the characteristic of thermal energy storage, TCLs become one of the most suitable appliances to participate in the DLC, because temporarily shutting down these loads will cause little inconvenience to residents [6].

So far there are numbers of methods proposed to characterize the dynamics of the TCLs. And it is of importance for the TCL control strategies to accurately characterize the dynamics of the TCLs. For individual TCL, the equivalent thermal parameter (ETP) model is often used to characterize its dynamics. For a large number of TCLs, the simplest way to characterize their aggregated dynamics is to simply aggregate the individual TCLs' models of component TCLs based on the ETP model [7,8]. In spite that this method is easy to implement, it is difficult to calculate especially when the number of TCLs increases. Another easy method is the reduced-order linear time-invariant (LTI) model [9–11], which models the aggregate TCLs with a transfer function. This method has an advantage over simplifying the TCL model and decreasing the computation. However this way can only reflect the aggregate power of TCLs according to some specific control signals such as the temperature set point.

For universality and extensiveness, the state-queuing (SQ) method [12–16] is adopted in many existing research works. The TCLs with homogeneous parameters [12] or heterogeneous parameters [13–16] can be characterized by the SQ method. Focusing on improving the precision of the SQ model, [17] further puts forward a modified SQ model with an optimized modification matrix so that it can more accurately characterize the aggregate TCLs.

Notwithstanding the goodness of the SQ model, nearly all the existing SQ modelling approaches [12–17] model the TCLs by a state vector that fails to consider the temperature-varying-rate (TVR) information, which reflects how fast one state can transit to another. TVR information contains important information of the TCLs' dynamics that may affect the accuracy of the modelling. Though the TVR information can be partly reflected by the state transition process, the traditional SQ model is not enough to characterize the full dynamics of the aggregate

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Nomenclature

T_i	internal temperature
T_o	ambient temperature
Δt	time step size
R	equivalent thermal resistance
C	equivalent heat capacity
Q	equivalent heat rate ($Q > 0$ for cooling mode and $Q < 0$ for heating mode)
s	on/off states of the TCL (0/1 for off /on)
T_{min}/T_{max}	lower/upper limits of TCL's internal temperature
T_{set}	temperature setting
ΔT	temperature dead-band
N	the total number of states in the first dimension
N_{off}	the number of power-off states
N_{on}	the number of power-on states
$\mathbf{X}(k)$	state vector at time step k
$x_i(k)$	the number of TCLs in the state i at time step k
$\mathbf{P}$	$N \times N$ transition matrix which describes the transition probabilities from $\mathbf{X}(k)$ to $\mathbf{X}(k+1)$
$\mathbf{P}'$	the modified transition matrix of $\mathbf{P}$
$\mathbf{M}$	modification matrix
a, b	the parameters of $\mathbf{M}$
$\mathbf{X}^{2D}$	2-dimensional state matrix
i,v	the indexes of the first and second dimension of $\mathbf{X}^{2D}$, respectively
$x_{i,v}$	the number of TCLs in the i_{th} on/off and temperature interval, and the v_{th} temperature varying rate interval
V	the number of intervals in the second dimension
$\mathbf{X}_i^S$,$\mathbf{X}_i^P$	two sub-matrixes of $\mathbf{X}^{2D}$
$\mathbf{P}_i^{SP}$	transition probability matrix from $\mathbf{X}_i^P(k)$ to $\mathbf{X}_i^S(k+1)$
$p_{l,k}$	the transition probability from $x_{i\text{-}b,l}$ to $x_{i,k}$
$\mathbf{X}_j^S$	another state matrix distinguished from $\mathbf{X}_i^S$
$\mathbf{P}_i^{SW}$	transition probability matrix from $\mathbf{X}_i^S$ to $\mathbf{X}_j^S$
η	coefficient of performance of TCLs
P_{Agg_SQ}	the aggregate power of the TCLs simulated by the SQ modelling methods
P_{Agg_I}	the aggregate power of the TCLs simulated by the individual TCLs model
[0 T]	time range for integration
t_{Pros}	the processing time of simulation

TCLs.

To fill this gap, this paper proposes a 2D SQ modelling approach for TCLs that extends the state vector to two dimensions by introducing additional TVR information, by which the accuracy can be effectively improved. Note that the proposed method is totally different from [18] since the information considered in the second dimension is TVR instead of mass temperature.

The remaining of this paper is organized as follows: In Section 2, several existing SQ modelling approaches are briefly introduced. In Section 3, the problems of the conventional SQ modelling methods are posed and the extended 2D SQ modelling approach is developed. Testing results are analysed in Section 4. Finally, conclusions are summarized in Section 5.

2. Related work

This section gives some brief introduction to the TCLs modelling approaches in recent research works. Three modelling approaches are reviewed: the ETP model of the individual TCLs, SQ modelling approach, and the modified SQ modelling approach [17].

2.1. Modelling of the individual TCL

The dynamics of an individual TCL can be modeled by the ETP model [7–9,14–16], of which discrete-time form can be described by:

$$T_i(t+1) = T_i(t)\cdot e^{-\Delta t/RC} + (1-e^{-\Delta t/RC})\cdot(T_o(t) - s(t)\cdot QR) \tag{1}$$

The on/off state s changes when the TCL's internal temperature reaches T_{min} and T_{max}, which is determined by T_{set} and ΔT (e.g. $T_{min} = T_{set} - 0.5\Delta T$ and $T_{max} = T_{set} + 0.5\Delta T$). The time domain curve of T_i for an individual TCL is shown in Fig. 1.

The aggregate dynamics of numerous TCLs can be represented by simply simulating the ETP model of individual TCLs simultaneously. It is time-consuming but most accurate way to model the aggregate TCLs and can be used to test the accuracy of other modelling models.

2.2. SQ modelling approach

The SQ modelling approach provides an efficient way to simulate the aggregate TCLs. The SQ modelling approach models the aggregate TCLs by dividing the normalized temperature dead-band for the on/off states into N different intervals, resulting in N_{off} power-off states and N_{on} power-on states, as shown in Fig. 2. And the aggregate TCLs are described by a state vector $\mathbf{X}(k) = [x_1(k), x_2(k), \ldots, x_N(k)]$. The $N \times N$ transition matrix $\mathbf{P}$ describes transition probabilities from $\mathbf{X}(k)$ to $\mathbf{X}(k+1)$:

$$\mathbf{X}(k+1) = \mathbf{X}(k)\cdot\mathbf{P} \tag{2}$$

Equation (2) gives full dynamics of the TCLs.

The SQ modelling approach is initially proposed by Lu et al. in [12,13,16]. Mathieu et al. propose a similar Markov-chain modelling approach in [14,15]. The only difference is that the method in [14,15] convert into a standard state space form (e.g. $\mathbf{X}^T(k+1) = \mathbf{A}\cdot\mathbf{X}^T(k)$), and define $N_{on} = N_{off}$. The following of this paper develops the SQ model in the form of (2) according to [12,13,16], and define $N_{on} = N_{off}$ for simplicity.

2.3. The modified SQ modelling approach

To further improve the accuracy of the SQ modelling approach, a modified SQ modelling approach is proposed in [17], in which the transition matrix is modified by:

$$\mathbf{P}' = \mathbf{P}\cdot\mathbf{M} \tag{3}$$

where $\mathbf{P}$ is the initially obtained transition matrix and $\mathbf{M}$ is structured as following:

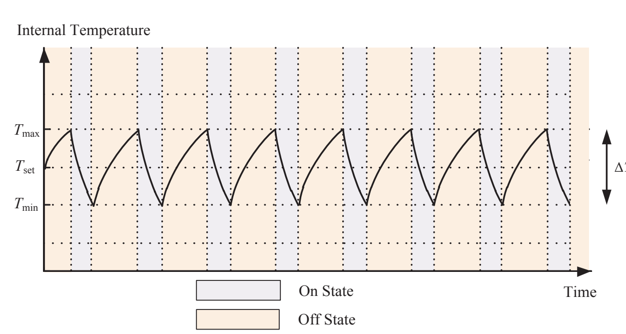

Fig. 1. Time domain curve of T_i for an individual TCL (in the cooling mode).