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Improved particle filter based soft sensing of room cooling load

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ABSTRACT

Accurate value of room cooling load is the basis data for energy conservation and demand response in the air conditioning operating process. Unfortunately, traditional calculation methods for room cooling load are too complex and time-consuming to meet the demand of real-time control. Soft sensing is an attractive technology, however the room cooling load cannot be measured directly, so the parameter identification for soft sensing model cannot be realized based on the sample data. Aiming at the bottleneck problem in room cooling load soft sensing, an improved particle filter based method is presented in this article. Firstly, a model for room cooling load soft sensing is built with analysis of room energy balance equation. Then frequency domain decomposition is employed for rough measurement, and deep learning is employed for prediction. Finally, the improved particle filter is employed to realize the real-time state estimation of room cooling load. In the process of particle filter, the artificial fish swarm algorithm is introduced to overcome the sample impoverishment problem of traditional Re-sample method. The simulation experiments and real-test experiments show that the proposed method can realize the soft sensing of room cooling load quickly and efficiently, which method also provide references for the soft sensing of other un-measurable variables.

1. Introduction

Carbon emission from energy consumption is one of the reasons for environmental pollution and climate change. The residential building energy consumption is responsible for more than 20% of social total energy consumption, whereas the Heating Ventilation Air Conditioning (HVAC) systems account for more than 45% of residential building energy consumption, which is also one of hot fields in building energy conservation [1]. For energy conservation in building heating and cooling load, scholars in different areas put forward different schemes at the view of their major [2], such as structural forms selection [3], materials selection [4] and renovation [5] in building design stage, improving air conditioning efficiency [6], and ice storage [7,8], water storage [9,10], district heating [11,12] in HVAC systems operation process.

Demand Response (DR) is an intelligent energy control technology developed from Demand Side Management [13], which plays an important role for the realization of dynamic optimization of supply-demand balance and enhance the power resource allocation. It is an effectively method for peak cut and clean energy consumption [14]. The Direct Load Control (DLC) in Demand Response has the characteristics of fast response, which can be used for supply-demand balance and save the construction cost of energy storage equipment, combined with loads with energy storage characteristics. Then the room cooling load becomes the common research object used in Direct Load Control for its own characteristics [15]. To meet the need of energy conservation and demand response, some scholars put forward control strategies directly on room cooling load with the utilization of building thermal inertial [16], such as air temperature set-point control [17], building thermal energy storage [18], intermittent operation in refrigerated warehouses [19], and so on. These strategies realize the energy conservation with utilization of room air temperature control mode.

Accurate value of real-time room cooling load is the basis data for real-time control and on-demand supply in the air conditioning operating process [20]. Estimating the heating or cooling load means to find out what is the power needed by the building in order to maintain the indoor temperature at a desired value when the heat gains and losses vary [21]. There are two main methods for cooling load calculation: mechanism analysis method and data learning method [22]. Accurate parameters determination and complex calculation procedures are needed in mechanism analysis methods, which are always off-line methods for building design and HVAC system installation [23]. The data learning based methods always do not distinguish the cooling load and heat extraction, which is ideal condition and suit for energy supply side control [24,25]. Neither of the methods can be used for the room cooling

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load calculation under room air temperature control mode, which is also not suit for Direct Load Control in the air conditioning operating process.

With the measurable variables as auxiliary variables, based on the mathematical model between auxiliary variables and dominant variables, the soft sensing technology can realize the online real-time estimation of un-measurable variables [26]. As an important method to calculate some key variables, the soft sensing technology gets more and more attention, and is applied from chemical industry to many other industrial fields [20].

Since the Bootstrap Filter proposed in 1993 [27], the particle filter has quickly been one of the most important nonlinear recursive Bayesian filter method. Compared with Kalman filter and H infinity filter, particle filter needs a more loose system constraint, neither linear system model, nor Gaussian noise distribution, which has better expansibility and universality [28]. Particle filter has been widely used in fields such as target tracking [29]. Considering that the cooling load is nonlinear, non-stationary and modeling error distribution unknown, the particle filter is an optional method.

Aiming at real-time calculation of room cooling load, it is first time to successfully realize the room cooling load soft sensing based on room temperature response under temperature control mode, from the perspective of incentives-response in control systems, with the improved particle filter technology. Firstly, a model for room cooling load soft sensing is built with analysis of room energy balance equation. Then frequency domain decomposition is employed for rough measurement, and deep learning is employed for prediction. Finally, the improved particle filter is employed to realize the real-time state estimation of room cooling load. In the process of particle filter, the artificial fish swarm algorithm is introduced to overcome the sample impoverishment problem of traditional Re-sample method. The simulation experiments and real-test experiments show that the proposed method can realize the soft sensing of room cooling load quickly and efficiently.

2. Modeling

2.1. Soft sensing framework

Room cooling loads are the rates of energy input or removal required to maintain an indoor environment at a desired temperature condition [23]. Under the conditions that the room air temperature changes with time, in a room with HVAC systems, there is an energy balance equation as follows [20]:

$$cl(n) = he(n) - hs(n) \tag{1}$$

where $cl(n)$ is hourly room cooling load at current hour under a constant reference room air temperature, $he(n)$ is hourly heat extraction by HVAC systems at current hour. The heat extraction is used to offset the room cooling load, and the deviation part is hourly heat storage at current hour $he(n)$.

The heat extraction can be obtained through calculating the enthalpy between outlet and inlet, as follows

$$he(n) = G(n) * (h_{out}(n) - h_{in}(n)) h_{out}(n) = c_g t_{out}(n) + (2500 + c_q t_{out}(n)) d_{out} h_{in}(n) = c_g t_{in}(n) + (2500 + c_q t_{in}(n)) d_{in} \tag{2}$$

where $G(n)$ is the air mass flow at current hour; $h_{out}(n)$ is the enthalpy of outlet air, $h_{in}(n)$ is the enthalpy of inlet air, c_g is the dry air specific heat at constant pressure, c_q is the water vapor specific heat at constant pressure, d_{out} is water vapor mass contained in unit mass of dry outlet air, $d_{in}(n)$ is water vapor mass contained in unit mass of dry inlet air, $t_{out}(n)$ is the outlet air temperature, and $t_{in}(n)$ is the inlet air temperature.

The heat storage is defined as the energy deviation between room cooling load and heat extraction, storied in building envelope and indoor furniture. The relationship between heat storage and room air temperature is as follows [20]

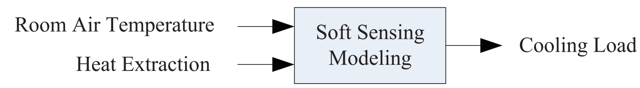

Fig. 1. Soft Sensing Framework.

$$hs(n) = \sum_{i=0}^{\infty} k_i * \Delta t(n-i) \tag{3}$$

where $\Delta t(n-i)$ is the deviation of room air temperature i hours ago from the reference value, $i = 0$ is the current hour, and k_i is the corresponding heat storage coefficient, which reflect the numerical relationship between heat storage and temperature deviation.

At this point, the soft sensing framework is clear, as in Fig. 1.

2.2. Rough measurement

The room cooling load is un-measurable, but the heat extraction can be measure. To calculate the heat storage, the corresponding heat storage coefficient in Eq. (3) should be identified.

It is an ideal condition to maintain the room air temperature at a reference value, which is not realistic for real-test. The frequency domain decomposition is introduced to implement the coefficient identification in Eq. (3), which is used for room cooling load soft sensing [20].

With the Fourier Transfer, the room energy balance equation can be rewrite as follows

$$cl(\omega) = he(\omega) - \sum_{i=1}^{\infty} k_i dt(\omega) e^{-j\omega i} \tag{4}$$

where $cl(\omega)$ is Fourier Transfer of room cooling load, $he(\omega)$ is Fourier Transfer of heat extraction, $dt(\omega)$ is Fourier Transfer of temperature deviation.

The energy is focused on the frequency of points cycling for 24 h (1 day) and its secondary/ three harmonic. It means the room energy balance equation can be rewrite as follows

$$cl(\omega) = he(\omega) - \sum_{i=1}^{K} k_i dt(\omega) e^{-j\omega i} \quad \omega = \omega_1, \omega_2, \omega_3 0 = he(\omega) - \sum_{i=1}^{K} k_i dt(\omega) e^{-j\omega i} \quad \omega \neq \omega_1, \omega_2, \omega_3 \tag{5}$$

where K is truncation order of heat storage.

The frequency domain decomposition method can be used for coefficients identification effectively. With the corresponding heat storage coefficients k_i, the heat storage can be calculated. The soft sensing value of room cooling load was further obtained with Eq. (1) [20], in which method the measurement error, system truncation error and identification error is all attributed to the soft sensing results. It is regarded as rough measurement for particle filter in this article.

2.3. Prediction

The Neural Networks gain extensive attention and widely application for its strong nonlinear fitting and generalization ability [30]. Since a fast training method was put forward in 2006 by Geoffrey Hinton [31], the deep learning has become a new hot area in machine learning research [32]. By exploring deep architectures, deep learning approaches are able to discover the hidden structures and features at different levels of abstraction from data