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A Review of Air Conditioning Load Aggregation in Distribution Networks

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In the context of global energy transformation, it is particularly important to tap the potential of flexible load on the distribution network side to participate in grid operation. As an important flexible adjustable load in the distribution network, air conditioning loads have typical characteristics of thermal energy storage, rapid response, and flexible scheduling, which is an ideal load resource. Effective and reliable load aggregation technologies for air conditioning load participation are the basis for operation in a power grid. To better understand the current research status of air conditioning load aggregation technologies and make full use of the existing research results to carry out further research, this paper comprehensively reviews the various aggregation technologies being used in distribution networks, including the modeling strategy for air conditioning load aggregation, control strategy, control method, and application analysis. Moreover, future research directions are summarized as a guide to improving the technology of air conditioning load aggregation.

Keywords: air conditioning load, aggregate modeling, control method, response strategy, application analysis, literature review

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1 INTRODUCTION

At present, the large-scale development and utilization of new energy has become a common choice for all countries in the world to promote energy transition and ensure energy security (Suo et al., 2021). New energy is mainly used by the grid in two ways: large-scale centralized grid connection; or hierarchical distributed grid connection. Large-scale centralized grid-connected new energy units, such as traditional fire, water, and nuclear power units, present difficulties in terms of conducting centralized management and control. The power grid needs to reserve sufficient capacity to cope with its high levels of randomness and volatility (Naik et al., 2018; Gil et al., 2020). However, the hierarchical and distributed new energy grid connection makes the capacity and availability factor of each region in the grid different at each moment. This will increase uncertainty in the power flow of the power grid, increase the risk of branch circuits, cross-section active heavy loads, or overruns, increase difficulties related to frequency and peak regulation, and endanger the security of the power grid (Jiang et al., 2011; Luo et al., 2019). Dealing with these problems and improving the grid's new energy consumption capacity and stable operation is generally achieved by increasing the reserve of the power system, but this method will lead to an increase in grid investment and the waste of resources. In recent years, generally speaking, starting from tapping the demand response load resources on the distribution network side, increasing the potential of the demand response load resources on the distribution network side to participate in grid regulation has been favored by researchers (Mohammadi et al., 2011; Madzharov et al., 2014; Wang et al., 2017).

Compared with the power generation side, the demand response load resources on the distribution network side have lower control costs and faster response speed. Among the various demand response load resources on the distribution network side, the air conditioning load accounts for a large proportion. In many countries, buildings account for a large proportion of the total energy consumption, and almost half of the energy consumption is caused by the heating, ventilation, and air conditioning (HVAC) systems (Zhao et al., 2021). For example, available data and market surveys conducted in Ghana have shown that 60–80% of electricity consumed in the offices of public and commercial buildings was used to run air conditioners to provide indoor thermal comfort for productive office work (Opoku et al., 2019). A large amount of air conditioning load entails huge response potential. At the same time, air conditioning load as a typical temperature control load has cold and hot storage capacity and can effectively respond to energy demand without affecting human comfort. Compared with other distribution network loads, it has broader application prospects. However, the power of a single air conditioner is small, and the power is easy to jump. Through effective control methods and reasonable control modes, a combined polymerization that combines multiple air conditioners has great potential. Further, it is easy to control. On the one hand, it can provide a variety of auxiliary services for the power grid and can be used as an important distribution network demand response load resource for in-depth exploration. On the other hand, it has good economic and environmental benefits.

Technically, the air conditioning load in the power grid is widely used, characterized by its large amount, wide distribution, small capacity, and different characteristics. Stable and advanced two-way communication (Viel et al., 2020) and advanced measurement techniques (Zhang et al., 2020) can be applied to the grid. The continuous development of active distribution networks (Martins and Borges, 2011) and virtual power plant (VPP) technology (Pudjianto et al., 2007) provides an opportunity and a solid technical foundation for centralized air conditioning loads to participate in grid operation.

Air conditioning load aggregates participate in different power system application fields, and different modeling methods are also required. When air conditioning load aggregates are included in power system stability calculations, it is necessary to appropriately simplify the air conditioning load model from the perspective of the power grid (Waseem et al., 2021). The air conditioning model is equivalent to the relevant constant impedance model, constant current model, constant power load model, etc., which meet the grid stability calculation (Waseem et al., 2021). For example, if the application field is power system transient calculation, the air conditioning model needs to be equivalent to a corresponding model that conforms to transient calculations, such as an air conditioner compressor single phase induction motor (SPIM) model for use in electromagnetic transients (EMTs) (Liu et al., 2013), while a thermal model of a room and the electrical model of an inverter AC is required for providing FRS (Hui et al., 2019), etc. These modeling methods are of great significance for the macroscopic participation of air conditioning load in the stability analysis and power flow calculation of the power system, but they ignore the unique properties of the air conditioning itself and the environment in which the air conditioning is located, and at the same time, it is impossible to consider the user experience in a refined manner. Therefore, this is not suitable for modeling air conditioning in demand response. Relatively speaking, the air conditioning load has the advantages of rapid response and easy control, so the demand response of participating in the power grid after aggregation has been the focus of researchers. The load model of demand response in the distribution network needs to be based on the characteristic relationship between room temperature and air conditioning load, and the model should be refined considering the response to the customer's feelings; for example, the thermal characteristics of buildings, multiple comfort requirements of users, and dynamic ambient temperature were comprehensively considered by Hui et al.(2022). On this basis, a multi-stage bidding strategy of a high-voltage air conditioning system based on an inverter was proposed to reduce energy costs and alleviate distribution network congestion. In order to solve the problems caused by standardizing the centralized control scheme of inverter air conditioners (IACs), Hong et al. (2022) developed a distributed consensus algorithm with a nonlinear protocol for IACs to achieve the regulation objective of guaranteeing customers' comfort requirements. A smart grid interactive building controller was developed by Zhang et al.(2022), which can optimize building operation during demand response events. This article mainly summarizes the air conditioning load aggregation model for demand response in the distribution network.

Examining the demand response and regulation of power systems through the precise aggregation of air conditioning load in the distribution network is of great significance in breaking the boundary between the physical generation side and the user side of traditional power systems, promoting distributed energy access, fine grid management, and intelligent decision-making. Researchers both in China and abroad have also undertaken much useful research regarding air conditioning load aggregation technology. Based on the summary of the work of Chinese and foreign researchers, this article analyzes the aggregation modeling, control strategy, regulation method, and application of air conditioning load in the distribution network. The research status of demand response aggregation of air conditioning load in a distribution network is summarized using four dimensions. These four dimensions are complementary and organically unified. An accurate air conditioning aggregation model was used as the basis for the air conditioning load in the distribution network to participate in the grid demand response. An effective control strategy was used as a prerequisite for the distribution network load aggregates to participate in the grid response. An intelligent control method was used as the guarantee for the air conditioning load aggregate to participate in the grid operation. A demand response application analysis was used to analyze the effect of the air conditioning load aggregate in the power grid; this is an example verification of the previous three dimensions. Finally, this article examines the development trend of demand response air conditioning load aggregation technology in future distribution networks.

2 AIR CONDITIONING SYSTEM MODEL

An accurate single unit air conditioning system model is the basis of the effective aggregation of air conditioning. Early researchers mostly focused on single unit air conditioning systems and ignored the complex environment of air conditioning. For example, Mortensen and Haggerty (1990) established five state equations for an air conditioning system operation by studying the transient state of recovery in the start-up process of cooling and heating load. Malhame and Chong (1985), considering the dynamic characteristics of the air conditioning system, modeled the switching dynamics of a single device and proposed a stochastic mixed-state model for the air conditioning system. Based on research on the relationship between the temperature and the power of the air conditioning system in the building, the complicated environment of the air conditioning system has been increasingly taken into account, and a more mature model of the air conditioning system has been developed. The model can divided into two parts. The first part is the building's thermodynamic model (Sonderegger, 1978; Bruning, 2004; Kämpf and Robinson, 2007; Lu, 2012; Zhang et al., 2012; Zhang et al., 2013; Peppanen et al., 2014; Hao et al., 2015; Zhang et al., 2021), which describes the time-varying relationship between the indoor temperature of the building where the air conditioner is located and the refrigeration (heat) quantity of the air conditioner. The second part is the electrothermal conversion model, which describes the quantitative relationship between air conditioning power and refrigeration (heat) quantity (Lu and Chassin, 2004; Lu, 2012; Kim et al., 2015; Yan et al., 2015; Kim et al., 2016; Peng et al., 2020). The first part is used to describe the relationship between the air conditioning refrigeration capacity and the surrounding environment, while the second part describes the relationship between the air conditioning motor and air conditioning refrigeration capacity.

2.1 Thermodynamic Model for Air Conditioning

The study of the thermodynamic model of the building in which the air conditioner is located began some time ago, and the current models are more mature, mainly comprising the equivalent thermal parameter (ETP) model (Sonderegger, 1978; Bruning, 2004; Kämpf and Robinson, 2007; Lu, 2012; Zhang et al., 2013; Peppanen et al., 2014) and the air conditioning load modeling method based on the cold (hot) load calculation (Bruning, 2004; Peppanen et al., 2014). The ETP model introduces the concepts of power supply, resistance, and capacitance into thermodynamics, adopts the circuit parameter model of power supply, resistance, and capacitance, and describes the indoor and outdoor environment characteristics (indoor and outdoor environment temperature, indoor and outdoor heat production, and indoor and outdoor heat exchange) and other thermodynamic behavior (Malhame and Chong, 1985). A classical thermodynamic model of the third-order state space was proposed by Zhang et al. (2013), which takes into account the air temperature change process in the building, the temperature difference between indoors and outdoors, and other thermodynamic scenarios in detail. This model has high accuracy. Lu (2012) and Zhang et al. (2012) ignored the temperature difference between indoors and outdoors, and the model was reduced to a second-order model. To simplify the calculation, the model was equivalent to the first-order model (Hao et al., 2015; Zhang et al., 2021), which only considered the process of indoor temperature change. Although the high-order model had high accuracy and provided a detailed description of the thermodynamic process under air conditioning, the computational process was complicated, and generally speaking, the first-order model has been favored by the majority of researchers. The ETP first-order equivalent thermodynamic parameter model is shown in **Figure 1**.

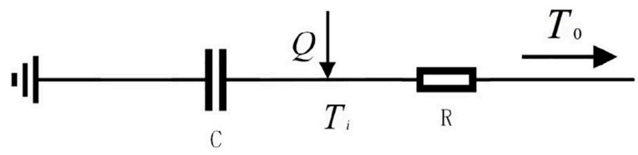

FIGURE 1 | ETP first-order equivalent thermal parameter model diagram.

The first-order differential equation for the ETP model shown in **Figure 1** can be obtained as follows:

$$C\frac{dT_i(t)}{dt} = \frac{1}{R}[T_0(t) - T_i(t)] - Q(t) \tag{1}$$

where: C is the equivalent heat capacity of the room (F); $T_i(t)$ is the indoor temperature at time t (°C); $T_0(t)$ is the outdoor temperature at time t (°C); R is the equivalent thermal resistance of the room (Ω); and $Q(t)$ is the cooling capacity of air conditioning at time t (kW).

Assuming that the outdoor temperature does not change in the step time t, the relationship between the room temperature and the cooling capacity of the air conditioner can be obtained by discretizing the above differential equation as follows:

$$T_i(t+1) = T_0(t+1) - Q(t)\cdot R - [T_0(t) - Q(t)\cdot R - T_i(t)]\cdot e^{-\frac{\Delta t}{RC}} \tag{2}$$

The ETP model effectively describes the time-varying process of the room temperature in a building, which lays a theoretical foundation for the large-scale aggregation of the air conditioning load. Considering the influence of indoor and outdoor environmental factors on the model parameters, it is necessary to dynamically identify the parameters of the ETP model (Che et al., 2019). Commonly used dynamic model parameter identification methods include the Hilbert transform (Shi et al., 2009), wavelet transforms (Tsatsanis and Giannakis, 1993), the adaptive method, the state estimation method, etc. However, a scenario suitable for Hilbert transform needs to meet

TABLE 1 | Features of two thermodynamic models.

Model	Advantages	Shortcoming
ETP model	1. The high-order model can accurately describe the dynamic process of heat transfer with high accuracy.	1. It is necessary to identify the parameters of the model. 2. The solution of the high-order model is difficult and the amount of calculation is large.
	2. The modeling method is flexible, and the high-order or low-order models can be selected according to the needs.	3. The accuracy of the low-order model is limited.
Cold (hot) load calculation model	1. The principle of modeling is simple.	1. The dynamic interaction of indoor and outdoor factors is not considered, which affects the accuracy of the model.
	2. No need for parameter identification.	2. In the process of calculation, most of the processes need approximation, which reduces the accuracy of the model.

the mathematical conditions of Hilbert transform. Wavelet transform needs a reasonable selection of wavelet basis functions. The adaptive method can achieve better identification results when the parameters change, and the Kalman filtering method (Guo, 1990) and particle filtering (Ristic et al., 2003) in the state estimation method can better solve the problem of model parameters. Cheng et al. (2017) used the variable window particle filter method to effectively identify the parameters of the ETP model. In short, the model parameters need to be chosen based on a reasonable parameter identification method according to the actual needs.

The model based on the cooling (heating) load calculation is based on the law of the conservation of energy. The energy change of the building where the air conditioner is located per unit time is equal to the difference between the cooling (heating) quantity of the air conditioner and the cooling load of the building. The cooling load includes outdoor cooling load (solar radiation, heat entering other rooms, etc.), indoor cooling load (human body fever, heat dissipation of other household equipment, etc.), and fresh air cooling load, etc. (Tiptipakorn and Lee, 2007; Khammayom et al., 2020). Through the energy identity of the building, the time-varying equation of indoor temperature can be derived:

$$\frac{dT_i(t)}{dt} = \alpha[T_0(t) - T_i(t)] + \beta - \gamma Q(t) \tag{3}$$

where α, β, and γ are constant coefficients.

The modeling method for cooling (heating) load calculation does not need to identify the thermodynamic parameters, but it is more sensitive to the composition of the cooling load in the room. The emphasis of the two thermodynamic models is different. The ETP model focuses on describing the dynamic heat transfer between indoors and outdoors, while the modeling method based on cooling (heating) load calculation focuses on the accurate static calculation of cooling and heating load. However, the essence of the two methods is the same, which is based on the principle of conservation in the process of energy exchange. The performance comparison between the two models is shown in **Table 1**.

The process of air conditioning load aggregation is affected by many factors, and various factors will change with time, so it is necessary to select the air conditioning system model according to the needs of load aggregation modeling.

2.2 Electromechanical Conversion Model for Air Conditioning

The electromechanical conversion model for the air conditioning system is mainly used to describe the relationship between air conditioning refrigeration (heat) and air conditioning power, and the type of air conditioning is related to the type of air conditioner. If it is a split fixed frequency air conditioner, the conversion mode is simple, and the electric power can be multiplied by the energy efficiency ratio of the air conditioner (Lu and Chassin, 2004; Lu, 2012; Yan et al., 2015; Zhang et al., 2021). The relationship between electric power and refrigeration (heat) of split frequency conversion air conditioners has been described by Kim et al. (2015) and Kim et al. (2016). The energy efficiency ratio is not constant, and its value is related to the frequency of the compressor: the lower the frequency, the higher the energy efficiency. On the other hand, the transformation relationship of central air conditioning is more complex, and there are more factors between its power and refrigeration (heat) capacity (energy efficiency ratio). In addition to the compressor, it also involves many modules, such as a fresh air system, cold storage (ice) system during refrigeration, cooling (frozen) water circulation system during heat release, etc. (Peng et al., 2020), which is difficult to model. At present, there is no perfect model for central air conditioning.

Although researchers in China and abroad have undertaken much research on the electric cooling (heat) conversion models of various air conditioning systems, most have focused on split fixed frequency air conditioners, and research on the participation of split frequency conversion air conditioners in the power grid model is lacking. In particular, the electromechanical conversion model of variable frequency air conditioners needs further research. At the same time, because the central air conditioning involves so many modules, and the relationship between each module is complex and changeable, researchers need to further explore this aspect.

3 MODELING OF AIR CONDITIONING LOAD AGGREGATION

There are many kinds of air conditioners in the distribution network, and the load characteristics of different air conditioners vary. Therefore, it is necessary to cluster the air conditioners first

TABLE 2 | Comparison of four Classical clustering methods.

Clustering Method	Advantages	Shortcoming
K-means	Strong adaptability, fast operation, and simple operation.	It is greatly affected by the initial value, and the clustering result is affected when noise data appears.
Mean shift clustering	There is no need to determine the number of categories in advance; when the initial number of central points is sufficient, it will spontaneously converge to the areas with the highest density.	The convergence effect is poor when applied to uniformly distributed data.
Hierarchical clustering	There is no need to know in advance the number of clusters that need to be synthesized or segmented, and a variety of distance calculation methods can be used to calculate the distance between clusters.	The amount of calculation is large and the efficiency is low.
DBSCAN algorithm	It is suitable for dense data, is not sensitive to the noise in the data, and the clustering results are relatively less disturbed by other factors.	If the sample density is uneven, it will lead to low clustering quality.

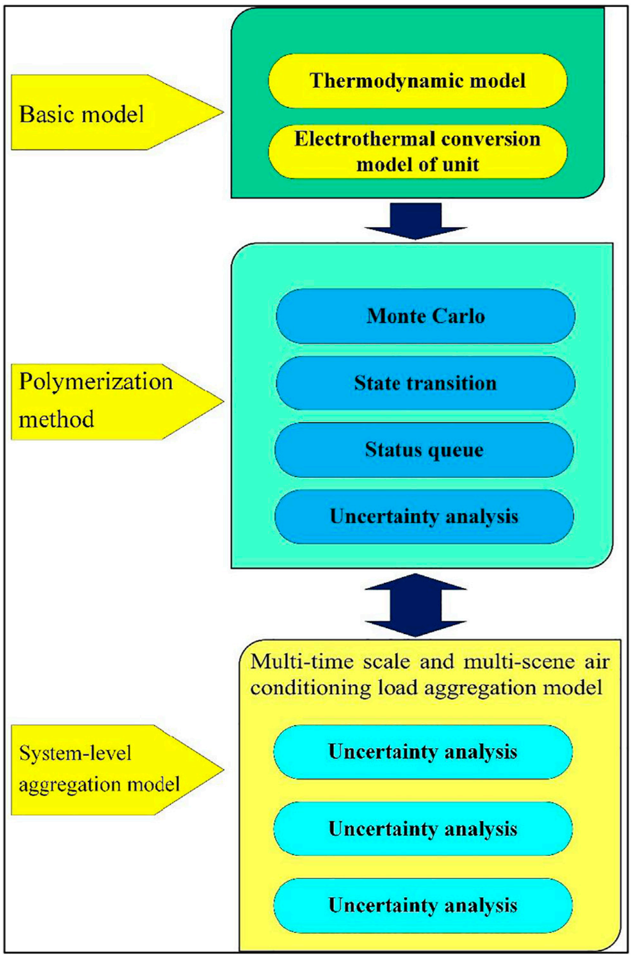

FIGURE 2 | The framework of air conditioning load aggregation.

and then aggregate them. Clustering technology refers to the combination of similar data in the same cluster, which can be used to cluster a large number of air conditioning loads. By clustering the air conditioning loads with similar regulation potential and operable space into a group, the demand response regulation ability of the user side can be brought into full play (An et al., 2018; Patteeuw et al., 2019; Li et al., 2020; Luo 2020; Chen et al., 2022). Clustering algorithms include traditional algorithms such as K-means clustering, hierarchical clustering, fuzzy clustering, etc. Several common clustering algorithms are shown in **Table 2**.

The so-called aggregation refers to the air conditioning load group as an organic whole. In the context of the in-depth study of the air conditioning load model, researchers have found that, as far as the single air conditioning load is concerned, the power is small and easy to increase (Ucak and Caglar, 1998; Molina et al., 2004; Molina-García et al., 2011; Zhang et al., 2015; Song et al., 2017). In contrast, air conditioning load aggregates have the advantage of great potential and flexible response, so the aggregation model of air conditioning load groups has received increasing attention. **Figure 2** shows the framework for air conditioning load aggregation. The aggregation strategy is formulated based on the basic model, and the aggregation model at the application level of the system is obtained; subsequently, the model needed at the application level of the system, in turn, affects the formulation of the aggregation strategy.

3.1 Polymerization Method

According to researchers' different focus, the aggregation methods can be divided into the following categories: Monte Carlo method, state transition and state queue, stochastic model, etc. (as shown in **Table 3**). The Monte Carlo method, which focuses on expanding the spatial thermal model of a single air conditioning system, is the most direct aggregation method (Ucak and Caglar, 1998; Lin et al., 2012; Zhang et al., 2015; Song et al., 2017; Zhou et al., 2019). Lin et al. (2012) and Zhou et al. (2019) used the Monte Carlo statistical survey method to simulate the overall characteristics of air conditioning load aggregates. Molina et al. (2003) sampled the relevant parameters of the load physical model based on the Monte Carlo method, and a load aggregation model was established. The Monte Carlo principle is simple, and a more accurate aggregation model can be established for air conditioning loads with similar parameter characteristics. However, when the heterogeneity of air conditioning load parameters is obvious, it is difficult to use the Monte Carlo model to describe it, and the accuracy is reduced.

TABLE 3 | Advantages and disadvantages of various aggregation methods.

Polymerization method	Typical method	Advantages	Disadvantages
Thermal space expansion	Monte Carlo	The modeling method is simple and the calculation is convenient.	1. The requirement of parameter unity of air conditioning load is high. 2. The dynamic evolution process of air conditioning load polymerization cannot be described accurately.
Load state evolution	State transitions and status queues	1. It is beneficial to control modeling. 2. Describes the diversity of the running state of air conditioning polymerization very well.	The amount of calculation is large.
Random model	Fokker Planck	The random characteristics affecting the operation of air conditioning are simulated.	It is difficult to build a fine-grained model.

However, it is inevitable that, in the process of practical application, the air conditioning load varies due to its situation (equipment type) and external environment (building structure, climate, etc.). Theoretically, the K-means method can be used to cluster and group the air conditioning parameters. Kalsi et al. (2012) and Zhang et al. (2013) first grouped the air conditioning parameters by similarity (K-means method). They then established a second-order ETP model with high accuracy for the same group of air conditioners, subsequently adding to each group of air conditioners according to different weights. Thus, the aggregation model of air conditioning load can be established. The neural network is another clustering method that can be used to deal with different properties of air conditioning load parameters. A novel control strategy for the aggregation model of air conditioners based on the thermal model of the room was proposed by Hui et al. (2017). By resetting the temperature of each air conditioner, the operation state can be adjusted temporarily without affecting customers' satisfaction. The operation characteristics both of individual air conditioners and the aggregation model of air conditioners has also been analyzed. Zhao et al. (2017) used a stochastic battery model to solve the problem of the heterogeneity of load parameters, considering the air conditioning load polymerization as a virtual battery, and then fitting the parameters of the virtual battery. Hao et al. (2015) used the Minkowski sum to approximate the parameters of the loaded polymerization. Zhou et al. (2019) focused on air conditioning loads as an example of thermostatically controlled loads (TCLs) and proposed a simple and transferable aggregate model by establishing a virtual house model, which accurately captured the aggregate flexibility. Lin et al. (2012), Mai and Chung (2015), and Mahdavi et al. (2017) established second- and third-order heat storage models of air conditioning systems considering related factors such as air temperature differences and solar radiation in different geographical locations and aggregated the air conditioning load based on the actual scenario of multi-area buildings. On the whole, expanding the spatial thermal model of a single air conditioning system in this way can clearly describe the working process and thermodynamics of the air conditioning system and meet the application requirements in many working conditions. However, this method cannot accurately describe the dynamic evolution process of air conditioning load aggregates, as is not conducive to the control of air conditioning load aggregates. To better describe the dynamic evolution process of air conditioning load aggregates, researchers use state transition to describe air conditioning load aggregation.

Typical methods, such as state transition and state queue, are used to describe the dynamic evolution model of air conditioning load aggregation. A state queue model was proposed to simulate air conditioning load aggregation by Lu and Chassin (2004). Lee et al. (2011) presented a novel load management technique for the air conditioner loads in large apartment complexes using systematic aggregations and load factor controls of the air conditioner loads based on a queuing system model and the Markov birth and death process. Koch et al. (2011) and Mathieu et al. (2013) used a Markov chain to describe the state evolution model of air conditioning load aggregates, and used the Kalman filter method to estimate the state matrix. However, this method requires a large amount of calculation and may fall into the possibility of non-convergence with the increase of the state of air conditioning load aggregates. Song et al. (2019b) proposed an improved aggregate TCL state-space model and a TCL aggregation control model to track the collective TCL performance considering the compressor delay when applying the control signal. State transition and state queue models describe well the dynamic evolution process of air conditioning load aggregation. However, in most cases, to facilitate the solution of the model, it is necessary to simplify the model and study the randomness of load aggregation.

Randomness is also one of the difficulties in modeling the aggregation model. To solve the randomness of the air conditioning load aggregation model, Cheng et al. (2018) adopted the electric power change and heat transfer process in the process of the load operation. The load aggregation model was derived by using the Fokker–Planck equation. This method is suitable for the study of randomly distributed load aggregation power demand. Wu et al. (2018) used the ETP model to analyze the principle of the aggregate load fluctuation of air conditioners with similar or the same parameters caused by traditional temperature regulation methods, and an effective improvement method was put forward. A new distributed aggregation control method was proposed by Wang et al. (2019) for multiple grid-interactive smart buildings in one frequency control area (e.g. a residential community) to provide fast frequency support. The proposed method was based on the distributed sliding mode

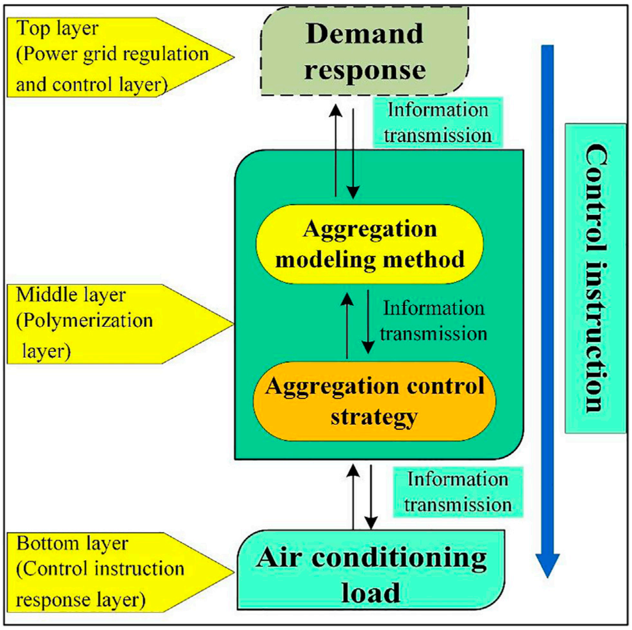

FIGURE 3 | Air conditioning load aggregation layered control architecture.

control via a leader–follower communication scheme. Liu and Jiang (2021) established an energy consumption prediction model for HVAC systems by using the back-propagation neural network (BPNN) and adaptive boost (AdaBoost) algorithms. The random model simulated the random characteristics of air conditioning load aggregation. However, generally speaking, the random model was affected by model samples, equipment data, and social meteorological factors, so the model was relatively rough. A refined stochastic model requires further research.

3.2 System-Application-Level Aggregation Model

The final form of air conditioning load aggregation is based on system application. According to the response needs of the system, air conditioning load aggregation can participate in the scheduling and operation of the system or provide auxiliary services of various time scales for the system. At the application level of system response, different time-scale aggregation models mainly include the virtual unit model, virtual battery model, power pulse model, etc. Wang G et al. (2021) proposed an enhanced sufficient battery model (ESBM) as well as a binary search algorithm for an improved inner approximation of the aggregate flexibility of TCL arrays. The air conditioning load was aggregated into a peak shaving unit to participate in the demand response of the power grid by Lee et al. (2011). The model parameters of the virtual battery model were fitted by Hao et al. (2015). The multi-time-scale air conditioning load aggregation model for fixed frequency air conditioning was established by Song et al. (2019a), including the second virtual battery model, minute pulse power model, and hour virtual unit model. According to the inherent heat storage capacity of the air conditioning load, the air conditioning load was modeled as a virtual energy storage device by Ji et al. (2020). Song et al. (2018) established virtual battery and virtual unit models with different time scales according to the characteristics of air conditioning load groups at different time scales. Virtual units or batteries and conventional units or batteries also present different characteristics. The basic model and aggregation method provides an aggregation model for the system application level, and the system application level provides modeling guidance for aggregation.

4 AIR CONDITIONING LOAD AGGREGATION CONTROL MODE

An effective control mode is the means to ensure that the load body of the power system normally participates in the demand response of the power grid. The participation of air conditioning load aggregates in the power grid regulation and control process is a typical hierarchical control (Ju et al., 2019; Xia et al., 2019). The hierarchical control framework is presented in **Figure 3**, in which the top (control) layer is the power grid regulation. It is necessary to issue response instructions to the middle layer (aggregation layer) according to the needs of the power grid, while the middle layer formulates the aggregation modeling method and aggregation control strategy of load aggregates that meet the needs of the power grid according to the instructions of the power grid. Finally, the middle layer sends the control instructions to the bottom layer (response layer). In some cases, the control layer will send control instructions directly to the response layer. This control method is also referred to as centralized control (Zhang and Lu, 2013; Vanouni and Lu, 2015; Gong et al., 2021). Bashash and Fathy (2013) used a new framework of partial differential equations to model these loads, and developed a bilinear partial differential equation model and a sliding mode controller for real-time load management of constant temperature air conditioning. The phenomenon of aggregate load fluctuation was effectively overcome using a temperature control load polymerization by Wu et al. (2018). This control mode has high requirements for the communication system, so it is necessary to set up special communication lines between each layer, which increases the control cost. However, this control mode is more predictable, and it is a system-friendly control mode.

Another control method is to directly add relevant intelligent response devices at the bottom (response layer) to judge whether to participate in the control according to the situation measured by the intelligent response installation. This kind of control is also called decentralized control. Peppanen et al. (2014) proposed a multi-agent distributed cooperative control model based on master–slave consistency to coordinate the control of the middle layer. The autonomous control model for large-scale air conditioning load was established by Lee et al. (2011). This model can enable large-scale air conditioning aggregate load to be calculated and adjusted flexibility and to respond to relevant

TABLE 4 | Three control methods of DLC.

Specific response mode	Decision variable	Advantages	Disadvantages
Adjust temperature	Set temperature	High user satisfaction and less damage to air conditioning.	Limited response capacity.
Switch	Switching state	The response speed is fast, and the response capacity is easy to control.	Customer satisfaction needs to be guaranteed, and it greatly damages to air conditioning equipment.
Periodic pause	Duty cycle	The regulation period is long, and the response speed is fast.	The compensation mechanism for users is complicated.

control signals. Guo et al. (2016) proposed a game-theoretic approach to develop a decentralized aggregated control algorithm. The convergence of the proposed algorithm was shown by employing potential game theory. An event-based distributed control strategy was proposed by Wan et al. (2021). This strategy exchanged the adjacent temperature control load information only when the dynamic event trigger condition was satisfied, in order to intelligently determine the necessary transmission frequency to save communication resources.

5 DEMAND RESPONSE AND ECONOMIC OPERATION OF AIR CONDITIONING LOAD AGGREGATES

In the process of air conditioning load aggregation participating in power grid demand response, the control method and demand response strategy complement each other. According to the different response modes of air conditioning load (Callaway, 2009), there are mainly two ways for air conditioning users to participate in demand response: incentive-based demand response (Yao et al., 2005; Lee et al., 2008; Escrivá-Escrivá et al., 2010; Hui and Yang, 2012; Sinitsyn et al., 2013); and price-based demand response (Li et al., 2016a; Li et al., 2016b).

5.1 Demand Response Based on Incentive

Incentive-based demand response is the attention response mode of air conditioning load aggregation, in which the direct load control (DLC) response is the most common and effective incentive-based demand response (Chu and Jong, 2008; Erdinc et al., 2019). The main control mode of DLC is the centralized control described Section 3 of this paper. The response process is that the power grid layer formulates the response strategy according to the power grid demand or electricity price information, and then directly controls the air conditioner through specific hardware. Generally speaking, the response strategies of DLC air conditioners can be divided into the following categories: temperature control response (Sinitsyn et al., 2013; Wu et al., 2018); switch control response (Yao et al., 2005; Lee et al., 2008); and periodic pause control response (Escrivá-Escrivá et al., 2010; Hui and Yang, 2012). The advantages and disadvantages of the three response strategies are shown in **Table 4**, in which the temperature control response mode takes the temperature control as the response decision variable, which is a relatively mild response measure, mainly based on the indoor and outdoor temperature changes and electricity price information where the air conditioner is located. This regulation mode provides a certain energy response on the premise affecting the user's comfort as little as possible. However, its adjustable capacity is difficult to calculate, and its regulation capacity is limited. Wu et al. (2018) used 30,000 air conditioners with a power of 2.5 kW to simulate temperature regulation control. When the scheduling target accounted for 3.3% of the total air conditioning aggregate power, the scheduling result was not ideal.

Relatively speaking, the regulation potential of switch control response is greater. Switch control takes the air conditioning switch state as the decision variable, which generally means that when the power grid needs the air conditioning load to participate in the demand response, the switch instruction is issued to the air conditioner in advance. The air conditioning load is controlled according to the instruction. Switch control response is beneficial to the control of the regulation capacity of the upper power grid. Yao et al. (2005), to minimize the error between the actual value and the predicted value of the polymerization, used the iterative deepening genetic algorithm to solve the optimal switch combination state. Chu and Jong (2008) established an air conditioning load aggregation DLC model for outdoor temperature effect, user thermal comfort level, and air conditioning load recovery phenomenon. As a result, an air conditioning switch control response mode with a good peak cutting effect was established.

The periodic suspension control response takes the "duty cycle" of the air conditioner as the control decision variable, and the so-called "duty cycle" is the proportion of the running time of the air conditioner in a cycle on the premise of ensuring the user's comfort to define the temperature control range. However, this frequent suspension operation of split air conditioners is not only difficult to respond to in time but also causes damage to the air conditioning load, which is mainly used in the field of central air conditioning (Hui and Yang, 2012). Hui and Yang (2012) analyzed the feasibility and practicability of the periodic pause control response of central air conditioning from the perspectives of system design and practical application. Taking into account the human comfort constraints and taking the maximum power saving as the objective function, an optimization model for the periodic pause control response of central air conditioning was established by Escrivá-Escrivá et al. (2010).

The aggregate response mode of air conditioning load based on excitation response is of great significance to the power grid, but there will inevitably be various working state transitions, such as on and off states. The transition of this state will create short-term power fluctuations in the air conditioning load, which will adversely affect the power grid. At present, there are relatively few studies on the quantification of the power fluctuation of the air conditioning polymerization and its impact on the power grid. The aspect needs to be further studied.

5.2 Demand Response Based on Price

The most typical method of price response is demand-side bidding (DSB). Price response leads to demand-side resources no longer being simple price receivers; they participate in the electricity market competition by changing users' power consumption mode and obtaining certain economic benefits, which improves the degree of participation of demand-side resources and is of great significance for improving the two-way interaction between the network side and the demand side (Yan et al., 2015; Li et al., 2016). Li et al. (2016) considered the characteristics of the air conditioning load involved in the response in the process of designing the bidding strategy of the electricity market. Although forms of DSB regulation have been deeply studied outside of China (Li et al., 2016) and have become one of the main demand-side response methods, in China, this is still in its initial stage, and we need to formulate targeted DSB regulation methods according to the actual situation of our power grid.

On the whole, the demand response based on incentive is mostly used in the response mode of general air conditioners. Although the demand response based on price is random, its development prospects are broad. At present, when discussing air conditioning load aggregation, most of the regulation methods in the literature have only focused on one regulation method, and research on the integration and combination of multiple regulation modes is still relatively scarce.

5.3 Optimizing Economic Operation

The rapid growth of distributed energy resources (DERs) brings more fluctuating output power to the distribution network, and the output power of DERs is seriously affected by the environment, which has great uncertainty. The main power grid needs to reserve more flexible regulation resources to maintain the balance of the system, which reduces the economic benefits of the system (Hui et al., 2022). Air conditioning load has great regulation potential as a flexible load, and most modern commercial buildings are equipped with advanced building management system (BMS), which can reduce the cost of using commercial HVAC load to benefit the power system (Wang et al., 2021). Han et al.(2019) used the actual operation data to carry out simulation tests, which proved that air conditioning load control can improve the optimal allocation of resources and improve energy efficiency, not only improving the comfort of users, but also reducing the cost of power purchase by participating in demand-side management. Bhattacharya et al.(2019) proposed an algorithm based on low-complexity dynamic programming to control the switching on/off of HVAC units and minimize the cooling cost. An optimal dispatching method for intelligent buildings integrating an active distribution network considering the aggregate load rate of intelligent buildings was proposed by Jiang et al.(2018).

6 AIR CONDITIONING LOAD'S PARTICIPATION IN THE DEMAND RESPONSE OF THE POWER GRID

The increasing integration of intermittent renewable energy brings challenges to the stable operation of the power grid. The intermittence and volatility of renewable energy increase the uncertainty of the system, which makes it more difficult to achieve the balance between supply and demand (Ji and Xu, 2020). For example, the rapid fluctuation of photovoltaic power generation may potentially affect the power balance and quality; the integration of wind power into the power system will lead to low or zero inertia, threatening its frequency stability (Mahdavi et al., 2017; Zhao et al., 2019; Jin et al., 2022). On the other hand, due to the complex load model and the complexity of human behavior, the comprehensive control of power load in large buildings has always been a challenge. The uncoordinated energy management of a large number of buildings in the distribution network feeder may make the distribution system enter a state of emergency in which the operational constraints are not fully satisfied. In addition, an increasing number of energy-saving frequency conversion air conditioners may produce a large number of harmonics in the power grid. The next peak load with insufficient reactive power may cause voltage collapse (Liu et al., 2018; Mirakhorli and Dong, 2018; Zhu et al., 2020).

Air conditioning load aggregates play an important role in stabilizing the fluctuation of new energy output, peak regulation, frequency regulation, and increasing system reserve in the power grid. It is of great significance to the reliable and stable operation of the power grid and the improvement of renewable energy consumption capacity.

6.1 Stabilizing the Fluctuation in New Energy Output

The volatility of renewable energy is an important issue that affects its consumption. The traditional way to limit the volatility of renewable energy is to improve the reserve of the system, which increases the operating cost of the system. Scholars in China and abroad have found that, through the aggregation of air conditioning load in the distribution network, it can be combined with the output of renewable energy, limit the volatility of renewable energy to a certain extent, and improve the consumption capacity of renewable energy in the power grid. Short et al. (2007) showed that air conditioning polymerization could effectively limit the power grid frequency fluctuation caused by the wind power grid connection. Peng et al. (2020), based on the analysis of the regulation characteristics of central air conditioning, established an air conditioning polymerization considering user comfort and air conditioning aggregation economy to stabilize the fluctuation in wind power output.

However, at present, research on the use of air conditioning load aggregation for new energy consumption is mainly aimed at the potential and the effect of new energy consumption, as well as the comfort of users, while research on the economy of air conditioning consumption using new energy is scarce. In the future, the problem of multi-objective absorption taking into account user comfort, economic benefits, and consumption potential should be considered.

6.2 Peak Shaving

The thermal inertia of temperature control load in distribution network load and the energy storage characteristics of energy storage load make it possible for flexible load aggregates to respond to power grid dispatching and participate in power grid peak regulation. The economy of heat storage load participating in power grid peak regulation was studied by Kämpf and Robinson (2007). A hierarchical control architecture for air conditioning load aggregates participating in power grid peak regulation was constructed by Ju et al. (2019). Lu (2012) considered the difference in air conditioning in the modeling of air conditioning aggregation, assuming air conditioning polymerization as the peak shaving unit of the power grid to participate in peak regulation.

At present, most research on air conditioning load participation in peak regulation focuses on the peak–trough difference and related economic problems reduced after air conditioning aggregation and peak regulation. The analysis of the impact of power uncertainty caused by the aggregation of air conditioning load on power grid operation (voltage, frequency, etc.) and the impact of air conditioning load aggregates on power grid operation after participating in power grid peak regulation is not yet deep enough and requires further study.

6.3 Frequency Modulation

The flexible load polymerization of the distribution network participates in the frequency stability control of the distribution network because of its advantages, such as high economic benefit and rapid response. Che et al. (2019) proposed a control method to track the secondary frequency modulation signal of the power grid by controlling the temperature of the air conditioner polymerization. Kim et al. (2015), Zhang et al. (2015), and Kim et al. (2016) also examined the primary or secondary frequency modulation of the power grid after effectively aggregating the air conditioning load.

Air conditioning load aggregation participates in the problem of power grid frequency modulation, which mainly focuses on the economic research regarding response control and frequency modulation. The admittance mechanism and management system of air conditioning load participating in frequency modulation are worthy of further exploration in the future.

6.4 Providing a System Backup

Air conditioning load aggregation in distribution networks can also provide support in increasing the system reserve and reducing system operating costs. Che et al. (2019) effectively analyzed the situation of providing a reserve for the power grid after air conditioning load aggregation. Cheng et al. (2017) considered that the temperature control load of residents (air conditioners, water heaters, etc.) could be used for system backup by aggregation. The economy of air conditioning load aggregates as a power grid rotating reserve was calculated by Khammayom et al. (2020). Tiptipakorn and Lee (2007) regarded the aggregate of air conditioning load as the reserve of the power system, and it was incorporated into the dynamic economic dispatching model of the power system. Based on the specific scenario of high power shortage of power system, the effectiveness of air conditioning load aggregation as the reserve can be explored.

As a system backup, air conditioning load has certain advantages, such as large capacity, economic and environmental protection, etc. However, the impact of air conditioning load aggregates on power grid demand response has been mainly addressed in economic research and reserve capacity research. The air conditioners involved in polymerization inevitably have the characteristics of dispersion, so it is necessary to consider the impact of communication architecture to study and design an economical and reasonable communication architecture while taking into account the reliability of communication. At the same time, the types of flexible loads (such as electric vehicles, energy storage, etc.) should be expanded to participate in the system reserve, and a multi-scale and multi-scenario power grid reserve model with multiple flexible loads should be studied to provide support for the safe and stable operation of the power grid and the deep absorption of new energy.

6.5 Air Conditioning Load in Virtual Power Plants (VPPs)

With the development of the smart grid and the improvement of communication technology, it is possible for flexible load to participate in power system regulation (Xu et al., 2020). As a typical constant TCL, air conditioning has the characteristics of inherent operation flexibility and schedulable load, which can be centrally managed by a VPP and gathered together to join the power market. A VPP optimizes resource allocation reasonably through control, measurement, and communication technology, which is a comprehensive technology and operation mode for air conditioning load to participate in power system operation and to facilitate the application of low-carbon renewable energy (Gong et al., 2021). Guo et al.(2021) quantified the potential of central air conditioning through a thermodynamic model, transforming central air conditioning into virtual unit model, and proposing a two-stage operation strategy of a VPP. A quadratic function model of trigger temperature and frequency variation of air conditioning compressor was established by Wan et al.(2017); the primary frequency modulation method and secondary frequency modulation method of energy storage system were combined to optimize the frequency of microgrid. A sequential demand response scheme as part of a VPP control was proposed by Gong et al.(2022) to reduce both ramping rate and peak power at the aggregated level.

7 RESEARCH PROSPECTS

Although researchers in China and abroad have undertaken a lot of useful research on air conditioning load aggregation in the distribution network, there are still some directions that researchers need to pay attention to and explore more deeply:

1) Uncertainty quantification of air conditioning load aggregation modeling is required. There are too many random factors in the modeling process of air conditioning load aggregation, which will inevitably lead to uncertainty in the aggregation model. Future research needs to establish a fine-grained flexible load model based on in-depth analysis and quantification of the uncertainty of the air conditioning load in order to lay a foundation for the precise regulation and control of the flexible load in the power grid in the future.
2) Regarding the multi-time-scale fine modeling technology of frequency conversion and central air conditioning, most of the current literature is based on split fixed frequency air conditioning, but there are few studies on split frequency conversion air conditioning and central air conditioning. However, the proportion of frequency conversion air conditioners in the distribution network is increasing, and central air conditioning has high power consumption and great response potential, so it is a good response resource. To make variable frequency air conditioners and central air conditioners better participate in the regulation and control of the power grid, it is necessary to dig more deeply into the characteristics of variable frequency air conditioners and central air conditioners and establish a fine-grained model under multi-time scales.
3) Communication architecture design based on future communication technology is necessary. Communication is the soul of the aggregate regulation and control of the air conditioning load. The fragmentation and decentralization of air conditioning load in the distribution network will inevitably increase the cost of regulation and control communication and reduce the reliability of communication. If we want to carry out the in-depth application of air conditioning load aggregates in the power grid in the future, it is particularly important to design a new communication architecture for future communication technology with low delay, low power consumption, low cost, large capacity, and high reliability.
4) Our national conditions regarding air conditioning load aggregation must be considered in relation to participating in the power system demand response business model. There is a general trend for air conditioning load to participate in the demand response of power systems intelligently and automatically. It is necessary to formulate a strategy for air conditioning load aggregation through the development of laws for China's power market in advance, on the premise of taking into account the interests of all parties. The formulation of this strategy is inseparable from the analysis of the potential of, and prospects for, air conditioning load participating in power grid operation, based on effectively evaluating the economy of air conditioning load participating in the actual operation of the power grid through technical means such as the power market and formulating the air conditioning load aggregation strategy in line with the development of laws for China's power market.
5) Affected by the season, short-term but peak electricity demand will increase the cost of upgrading the power infrastructure. Applying the regulation ability of flexible load and improving the capacity of sustainable energy consumption is an effective way to alleviate the shortage of power resources. Exploring the control strategy of air conditioning polymerization that can comprehensively consider the duration of regulation and user comfort is key to unlocking the potential of air conditioning load in peak regulation and stable power fluctuation. This can be achieved through the centralized management of VPPs and access to the power market, in order to achieve the purpose of alleviating the fluctuation of renewable energy generation power output, improve the local utilization rate of low-carbon renewable energy, and alleviate power congestion in the distribution network.
6) It is necessary to formulate technical standards related to air conditioning load aggregation. The air conditioning load itself has unique characteristics. To make better use of load-side resources, it is necessary to develop relevant technical standards, such as load aggregation access standards, communication standards, etc.

8 CONCLUSION

Effective and reliable air conditioning load aggregation technology in the distribution network is of great significance for the power grid to provide new energy consumption capacity and ensure safe and stable operation. This paper has summarized the technical achievements of researchers in China and abroad, and has systematically discussed and summarized the problem of air conditioning load aggregation on the demand side of the distribution network. Further, this paper has summarized and analyzed the research content pertaining to the four dimensions of air conditioning load aggregation model, control methods, response strategies, and application, and future research directions have been proposed. It is hoped that this paper can provide some ideas and references for researchers regarding air conditioning load aggregation in the distribution network.

AUTHOR CONTRIBUTIONS

HW completed the writing of the manuscript. HC and YL wrote sections of the manuscript. All authors contributed to manuscript revision and have read and approved the submitted version.

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REFERENCES

An, J., Yan, D., and Hong, T. (2018). Clustering and Statistical Analyses of Air-Conditioning Intensity and Use Patterns in Residential Buildings. *Energy Build.* 174, 214–227. doi:10.1016/j.enbuild.2018.06.035

Bashash, S., and Fathy, H. K. (2013). Modeling and Control of Aggregate Air Conditioning Loads for Robust Renewable Power Management. *IEEE Trans. Contr. Syst. Technol.* 21, 1318–1327. doi:10.1109/TCST.2012.2204261

Bhattacharya, S., Kar, K., and Chow, J. H. (2019). Economic Operation of Thermostatic Loads under Time Varying Prices: An Optimal Control Approach. *IEEE Trans. Sustain. Energy* 10 (4), 1960–1970. doi:10.1109/TSTE.2018.2876797

Bruning, S. F. (2004). A New Way to Calculate Cooling Loads. Ashrae J. 46, 20–24. Retrieved from https://www.proquest.com/scholarly-journals/new-way-calculate-cooling-loads/docview/220458643/se-2?accountid=42626.

Callaway, D. S. (2009). Tapping the Energy Storage Potential in Electric Loads to Deliver Load Following and Regulation, with Application to Wind Energy. *Energy Convers. Manag.* 50, 1389–1400. doi:10.1016/j.enconman.2008.12.012

Che, Y., Yang, J., Zhao, Y., and Xue, S. (2019). Control Strategy for Inverter Air Conditioners under Demand Response. *Processes* 7, 407. doi:10.3390/pr7070407

Chen, S., Wang, L., Li, J., Zhou, G., and Zhou, X. (2022). A Training Pattern Recognition Algorithm Based on Weight Clustering for Improving Cooling Load Prediction Accuracy of HVAC System. *J. Build. Eng.* 52, 104445. doi:10.1016/j.jobe.2022.104445

Cheng, D., Zhang, W., and Liu, J. (2017). Window-Varying Particle Filter for Parameter Identification of Space Thermal Model. *IEEE Trans. Instrum. Meas.* 66, 165–176. doi:10.1109/TIM.2016.2619986

Cheng, D., Zhang, W., and Liu, Y. (2018). Aggregate Modeling and Analysis of Air Conditioning Load Using Coupled Fokker-Planck Equations. *J. Mod. Power Syst. Clean. Energy* 6, 1277–1290. doi:10.1007/s40565-018-0396-2

Chu, C. M., and Jong, T. L. (2008). A Novel Direct Air-Conditioning Load Control Method. *IEEE Trans. Power Syst.* 23, 1356–1363. doi:10.1109/TPWRS.2008.926432

Erdinc, O., Tascikaraoglu, A., Paterakis, N. G., and Catalao, J. P. S. (2019). Novel Incentive Mechanism for End-Users Enrolled in DLC-Based Demand Response Programs within Stochastic Planning Context. *IEEE Trans. Ind. Electron.* 66, 1476–1487. doi:10.1109/TIE.2018.2811403

Escrivá-Escrivá, G., Segura-Heras, I., and Alcázar-Ortega, M. (2010). Application of an Energy Management and Control System to Assess the Potential of Different Control Strategies in HVAC Systems. *Energy Build.* 42, 2258–2267. doi:10.1016/j.enbuild.2010.07.023

Gil, G. M. V., Cunha, R. B. A., Di Santo, S. G., Monaro, R. M., Costa, F. F., and Sguarezi, A. J. (2020). Photovoltaic Energy in South America: Current State and Grid Regulation for Large-Scale and Distributed Photovoltaic Systems. *Renew. Energy* 162, 1307–1320. doi:10.1016/j.renene.2020.08.022

Gong, H., Jones, E., Alden, R., Frye, A., Colliver, D., and Ionel, D. (2022). Virtual Power Plant Control for Large Residential Communities Using HVAC Systems for Energy Storage. *IEEE Trans. Ind. Appl.* 58 (1), 622–633. doi:10.1109/TIA.2021.3120971

Gong, X., Castillo-Guerra, E., Cardenas-Barrera, J. L., Cao, B., Saleh, S. A., and Chang, L. (2021). Robust Hierarchical Control Mechanism for Aggregated Thermostatically Controlled Loads. *IEEE Trans. Smart Grid* 12, 453–467. doi:10.1109/TSG.2020.3009989

Guo, D., Zheng, R., Lin, Z., and Yan, G. (2016). A Game-Theoretic Approach to Decentralized Control of Heterogeneous Load Population. *Electr. Power Syst. Res.* 140, 552–559. doi:10.1016/j.epsr.2016.05.019

Guo, L. (1990). Estimating Time-Varying Parameters by the Kalman Filter Based Algorithm: Stability and Convergence. *IEEE Trans. Autom. Contr.* 35, 141–147. doi:10.1109/9.45169

Guo, M., Guo, X., Yang, J., Gao, C., and Chen, T. (2021). Operation Strategy of Central Air Conditioning Virtual Power Plant Based on Risk Measurement Method. *Front. Energy Res.* 9, 773149. doi:10.3389/fenrg.2021.773149

Han, X., Wang, F., and Chen, M. (2019). Economic Evaluation of Micro-grid System in Commercial Parks Based on Echelon Utilization Batteries. *IEEE Access* 7, 65624–65634. doi:10.1109/ACCESS.2019.2916181

Hao, H., Sanandaji, B. M., Poolla, K., and Vincent, T. L. (2015). Aggregate Flexibility of Thermostatically Controlled Loads. *IEEE Trans. Power Syst.* 30, 189–198. doi:10.1109/TPWRS.2014.2328865

Hong, J., Hui, H., Zhang, H., Dai, N., and Song, Y. (2022). Distributed Control of Large-Scale Inverter Air Conditioners for Providing Operating Reserve Based on Consensus with Nonlinear Protocol. *IEEE Internet Things J.*, 1. doi:10.1109/JIOT.2022.3151817

Hui, H., Ding, Y., Liu, W., Lin, Y., and Song, Y. (2017). Operating Reserve Evaluation of Aggregated Air Conditioners. *Appl. Energy* 196, 218–228. doi:10.1016/j.apenergy.2016.12.004

Hui, H., Ding, Y., and Zheng, M. (2019). Equivalent Modeling of Inverter Air Conditioners for Providing Frequency Regulation Service. *IEEE Trans. Ind. Electron.* 66, 1413–1423. doi:10.1109/TIE.2018.2831192

Hui, H., Siano, P., Ding, Y., Yu, P., Song, Y., Zhang, H., et al. (2022). A Transactive Energy Framework for Inverter-Based HVAC Loads in a Real-Time Local Electricity Market Considering Distributed Energy Resources. *IEEE Trans. Ind. Inf. (Early Access)*, 1. doi:10.1109/TII.2022.3149941

Hui, X., and Yang, G. (2012). "Central Air-Conditioning Terminal Intelligent Control System," in 2012 Second International Conference on Instrumentation, Measurement, Computer, Communication and Control, Harbin, China, 08-10 December 2012, 1029–1032. doi:10.1109/IMCCC.2012.243

Ji, Y., and Xu, Q. (2020). Frequency Regulation Support from Aggregation of Air Conditioners Based on the Trigger Value Local Update Strategy. *IET Gener. Transm. & Distrib.* 14 (16), 3150–3160. doi:10.1049/iet-gtd.2019.0718

Ji, Y., Xu, Q., Luan, K., and Yang, B. (2020). Virtual Energy Storage Model of Air Conditioning Loads for Providing Regulation Service. *Energy Rep.* 6, 627–632. doi:10.1016/j.egyr.2019.11.130

Jiang, T., Li, Z., Jin, X., Chen, H., Li, X., and Mu, Y. (2018). Flexible Operation of Active Distribution Network Using Integrated Smart Buildings with Heating, Ventilation and Air-Conditioning Systems. *Appl. Energy* 226, 181–196. doi:10.1016/j.apenergy.2018.05.091

Jiang, W., Yan, Z., and Hu, Z. (2011). A Novel Improved Particle Swarm Optimization Approach for Dynamic Economic Dispatch Incorporating Wind Power. *Electr. Power Components Syst.* 39, 461–477. doi:10.1080/15325008.2010.528536

Jin, L., He, Y., Zhang, C.-K., Shangguan, X.-C., Jiang, L., and Wu, M. (2022). Equivalent Input Disturbance-Based Load Frequency Control for Smart Grid with Air Conditioning Loads. *Sci. China Inf. Sci.* 65 (2), 122205. doi:10.1007/s11432-020-3120-0

Ju, P., Jiang, T., Li, H., Wang, C., and Liu, J. (2019). Hierarchical Control of Air-Conditioning Loads for Flexible Demand Response in the Short Term. *IEEE Access* 7, 184611–184621. doi:10.1109/ACCESS.2019.2960054

Kalsi, K., Elizondo, M., Fuller, J., Lu, S., and Chassin, D. (2012). "Development and Validation of Aggregated Models for Thermostatic Controlled Loads with Demand Response," in 2012 45th Hawaii International Conference on System Sciences, Maui, HI, USA, 04-07 January 2012, 1959–1966. doi:10.1109/HICSS.2012.212

Kämpf, J. H., and Robinson, D. (2007). A Simplified Thermal Model to Support Analysis of Urban Resource Flows. *Energy Build.* 39, 445–453. doi:10.1016/j.enbuild.2006.09.002

Khammayom, N., Maruyama, N., and Chaichana, C. (2020). Simplified Model of Cooling/heating Load Prediction for Various Air-Conditioned Room Types. *Energy Rep.* 6, 344–351. doi:10.1016/j.egyr.2019.11.086

Kim, Y.-J., Fuentes, E., and Norford, L. K. (2016). Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump. *IEEE Trans. Power Syst.* 31, 3090–3099. doi:10.1109/TPWRS.2015.2472497

Kim, Y.-J., Norford, L. K., and Kirtley, J. L. (2015). Modeling and Analysis of a Variable Speed Heat Pump for Frequency Regulation through Direct Load Control. *IEEE Trans. Power Syst.* 30, 397–408. doi:10.1109/TPWRS.2014.2319310

Koch, S., Mathieu, J. L., and Callaway, D. S. (2011). Modeling and Control of Aggregated Heterogeneous Thermostatically Controlled Loads for Ancillary Services, in Proc. PSCC, Stockholm, Sweden, 1–7.

Lee, S. C., Kim, S. J., and Kim, S. H. (2011). Demand Side Management with Air Conditioner Loads Based on the Queuing System Model. *IEEE Trans. Power Syst.* 26, 661–668. doi:10.1109/TPWRS.2010.2066583

Lee, T. F., Cho, M. Y., Hsiao, Y. C., Chao, P. J., and Fang, F. M. (2008). Optimization and Implementation of a Load Control Scheduler Using Relaxed Dynamic Programming for Large Air Conditioner Loads. *IEEE Trans. Power Syst.* 23, 691–702. doi:10.1109/TPWRS.2008.919311

Li, S., Zhang, W., Lian, J., and Kalsi, K. (2016a). Market-Based Coordination of Thermostatically Controlled Loads-Part I: A Mechanism Design Formulation. *IEEE Trans. Power Syst.* 31, 1170–1178. doi:10.1109/TPWRS.2015.2432057

Li, S., Zhang, W., Lian, J., and Kalsi, K. (2016b). Market-Based Coordination of Thermostatically Controlled Loads-Part II: Unknown Parameters and Case Studies. *IEEE Trans. Power Syst.* 31, 1179–1187. doi:10.1109/TPWRS.2015.2432060

Li, Z., Lin, B., Zheng, S., Liu, Y., Wang, Z., and Dai, J. (2020). A Review of Operational Energy Consumption Calculation Method for Urban Buildings. *Build. Simul.* 13 (4), 739–751. doi:10.1007/s12273-020-0619-0

Lin, Y., Middelkoop, T., and Barooah, P. (2012). "Issues in Identification of Control-Oriented Thermal Models of Zones in Multi-Zone Buildings," in 2012 IEEE 51st IEEE Conference on Decision and Control (CDC), Maui, HI, USA, 10-13 December 2012, 6932–6937. doi:10.1109/CDC.2012.6425958

Liu, Y., Vittal, V., Undrill, J., and Eto, J. H. (2013). Transient Model of Air-Conditioner Compressor Single Phase Induction Motor. *IEEE Trans. Power Syst.* 28, 4528–4536. doi:10.1109/TPWRS.2013.2275256

Liu, Y., Yu, N., Wang, W., Guan, X., Xu, Z., Dong, B., et al. (2018). Coordinating the Operations of Smart Buildings in Smart Grids. *Appl. Energy* 228, 2510–2525. doi:10.1016/j.apenergy.2018.07.089

Liu, Z., and Jiang, G. (2021). Optimization of Intelligent Heating Ventilation Air Conditioning System in Urban Building Based on BIM and Artificial Intelligence Technology. *Comsis J.* 18, 1379–1394. doi:10.2298/CSIS200901027L

Lu, N. (2012). An Evaluation of the HVAC Load Potential for Providing Load Balancing Service. *IEEE Trans. Smart Grid* 3, 1263–1270. doi:10.1109/TSG.2012.2183649

Lu, N., and Chassin, D. P. (2004). A State-Queueing Model of Thermostatically Controlled Appliances. *IEEE Trans. Power Syst.* 19, 1666–1673. doi:10.1109/TPWRS.2004.831700

Luo, G., Zhang, X., Liu, S., Dan, E., and Guo, Y. (2019). Demand for Flexibility Improvement of Thermal Power Units and Accommodation of Wind Power under the Situation of High-Proportion Renewable Integration-Taking North Hebei as an Example. *Environ. Sci. Pollut. Res.* 26, 7033–7047. doi:10.1007/s11356-019-04177-3

Luo, X. J. (2020). A Novel Clustering-Enhanced Adaptive Artificial Neural Network Model for Predicting Day-Ahead Building Cooling Demand. *J. Build. Eng.* 32, 101504. doi:10.1016/j.jobe.2020.101504

Madzharov, D., Delarue, E., and D'haeseleer, W. (2014). Integrating Electric Vehicles as Flexible Load in Unit Commitment Modeling. *Energy* 65, 285–294. doi:10.1016/j.energy.2013.12.009

Mahdavi, N., Braslavsky, J. H., Seron, M. M., and West, S. R. (2017). Model Predictive Control of Distributed Air-Conditioning Loads to Compensate Fluctuations in Solar Power. *IEEE Trans. Smart Grid* 8, 3055–3065. doi:10.1109/TSG.2017.2717447

Mai, W., and Chung, C. Y. (2015). Economic MPC of Aggregating Commercial Buildings for Providing Flexible Power Reserve. *IEEE Trans. Power Syst.* 30, 2685–2694. doi:10.1109/TPWRS.2014.2365615

Malhame, R., and Chee-Yee Chong, C. Y. (1985). Electric Load Model Synthesis by Diffusion Approximation of a High-Order Hybrid-State Stochastic System. *IEEE Trans. Autom. Contr.* 30, 854–860. doi:10.1109/TAC.1985.1104071

Martins, V. F., and Borges, C. L. T. (2011). Active Distribution Network Integrated Planning Incorporating Distributed Generation and Load Response Uncertainties. *IEEE Trans. Power Syst.* 26, 2164–2172. doi:10.1109/TPWRS.2011.2122347

Mathieu, J. L., Koch, S., and Callaway, D. S. (2013). State Estimation and Control of Electric Loads to Manage Real-Time Energy Imbalance. *IEEE Trans. Power Syst.* 28, 430–440. doi:10.1109/TPWRS.2012.2204074

Mirakhorli, A., and Dong, B. (2018). Model Predictive Control for Building Loads Connected with a Residential Distribution Grid. *Appl. Energy* 230, 627–642. doi:10.1016/j.apenergy.2018.08.051

Mohammadi, J., Rahimi-Kian, A., and Ghazizadeh, M.-S. (2011). Aggregated Wind Power and Flexible Load Offering Strategy. *IET Renew. Power Gener.* 5, 439–447. doi:10.1049/iet-rpg.2011.0066

Molina, A., Gabaldon, A., Fuentes, J. A., and Alvarez, C. (2003). Implementation and Assessment of Physically Based Electrical Load Models: Application to Direct Load Control Residential Programmes. *IEE Proc. Gener. Transm. Distrib.* 150, 61–66. doi:10.1049/ip-gtd:20020750

Molina, A., Gabaldón, A., Kessler, M., Fuentes, J. A., and Gómez, E. (2004). "Application of Smoothing Techniques to Solve the Cooling and Heating Residential Load Aggregation Problem," in *Compel the International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, 23, 48–64. PMAPS 2002. PMAPS 2002, Naples, Italy: Yorkshire: Emerald Group Publishing LTD. doi:10.1108/03321640410507545

Molina-Garcia, A., Kessler, M., Fuentes, J. A., and Gomez-Lazaro, E. (2011). Probabilistic Characterization of Thermostatically Controlled Loads to Model the Impact of Demand Response Programs. *IEEE Trans. Power Syst.* 26, 241–251. doi:10.1109/TPWRS.2010.2047659

Mortensen, R. E., and Haggerty, K. P. (1990). Dynamics of Heating and Cooling Loads: Models, Simulation, and Actual Utility Data. *IEEE Trans. Power Syst.* 5, 243–249. doi:10.1109/59.49112

Naik, J., Satapathy, P., and Dash, P. K. (2018). Short-term Wind Speed and Wind Power Prediction Using Hybrid Empirical Mode Decomposition and Kernel Ridge Regression. *Appl. Soft Comput.* 70, 1167–1188. doi:10.1016/j.asoc.2017.12.010

Opoku, R., Edwin, I. A., and Agyarko, K. A. (2019). Energy Efficiency and Cost Saving Opportunities in Public and Commercial Buildings in Developing Countries - the Case of Air-Conditioners in Ghana. *J. Clean. Prod.* 230, 937–944. doi:10.1016/j.jclepro.2019.05.067

Patteeuw, D., Henze, G. P., Arteconi, A., Corbin, C. D., and Helsen, L. (2019). Clustering a Building Stock towards Representative Buildings in the Context of Air-Conditioning Electricity Demand Flexibility. *J. Build. Perform. Simul.* 12 (1), 56–67. doi:10.1080/19401493.2018.1470202

Peng, B., Zou, H.-M., Bai, P.-F., and Feng, Y.-Y. (2020). Building Energy Consumption Prediction and Energy Control of Large-Scale Shopping Malls Based on a Noncentralized Self-Adaptive Energy Management Control System. *Energy Explor. Exploitation* 39, 1381–1393. doi:10.1177/0144598720920731

Peppanen, J., Reno, M. J., and Grijalva, S. (2014). "Thermal Energy Storage for Air Conditioning as an Enabler of Residential Demand Response," in 2014 North American Power Symposium (NAPS), Pullman, WA, USA, 07-09 September 2014, 1–6. doi:10.1109/NAPS.2014.6965476

Pudjianto, D., Ramsay, C., and Strbac, G. (2007). Virtual Power Plant and System Integration of Distributed Energy Resources. *IET Renew. Power Gener.* 1, 10–16. doi:10.1049/iet-rpg:20060023

Ristic, B., Arulampalam, S., and Gordon, N. (2003). *Beyond the Kalman Filter: Particle Filters for Tracking Applications*. Boston, London: Artech house.

Shi, Z. Y., Law, S. S., and Xu, X. (2009). Identification of Linear Time-Varying Mdof Dynamic Systems from Forced Excitation Using Hilbert Transform and EMD Method. *J. Sound Vib.* 321, 572–589. doi:10.1016/j.jsv.2008.10.005

Short, J. A., Infield, D. G., and Freris, L. L. (2007). Stabilization of Grid Frequency through Dynamic Demand Control. *IEEE Trans. Power Syst.* 22, 1284–1293. doi:10.1109/TPWRS.2007.901489

Sinitsyn, N. A., Kundu, S., and Backhaus, S. (2013). Safe Protocols for Generating Power Pulses with Heterogeneous Populations of Thermostatically Controlled Loads. *Energy Convers. Manag.* 67, 297–308. doi:10.1016/j.enconman.2012.11.021

Sonderegger, R. C. (1978). *Dynamic Models of House Heating Based on Equivalent Thermal Parameters* (Princeton, NJ, USA: Princeton University). PhD, dissertation.

Song, M., Ciwei, G., Yang, J., Liu, Y., and Cui, G. (2017). Novel Aggregate Control Model of Air Conditioning Loads for Fast Regulation Service. *IET Gener. Transm. & Distrib.* 11, 4391–4401. doi:10.1049/iet-gtd.2017.0496

Song, M., Gao, C., Shahidehpour, M., Li, Z., Lu, S., and Lin, G. (2019a). Multi-Time-Scale Modeling and Parameter Estimation of TCLs for Smoothing Out Wind Power Generation Variability. *IEEE Trans. Sustain. Energy* 10, 105–118. doi:10.1109/TSTE.2018.2826540

Song, M., Gao, C., Shahidehpour, M., Li, Z., Yang, J., and Yan, H. (2019b). State Space Modeling and Control of Aggregated TCLs for Regulation Services in Power Grids. *IEEE Trans. Smart Grid* 10, 4095–4106. doi:10.1109/TSG.2018.2849321

Song, M., Gao, C., Yan, H., and Yang, J. (2018). Thermal Battery Modeling of Inverter Air Conditioning for Demand Response. *IEEE Trans. Smart Grid* 9, 5522–5534. doi:10.1109/TSG.2017.2689820

Suo, X., Zhao, S., Ma, Y., and Dong, L. (2021). New Energy Wide Area Complementary Planning Method for Multi-Energy Power System. *IEEE Access* 9, 157295–157305. doi:10.1109/ACCESS.2021.3130577

Tiptipakorn, S., and Lee, W.-J. (2007). A Residential Consumer-Centered Load Control Strategy in Real-Time Electricity Pricing Environment. *North Am. Power Symposium*, 505–510. doi:10.1109/NAPS.2007.4402357

Tsatsanis, M. K., and Giannakis, G. B. (1993). Time-varying System Identification and Model Validation Using Wavelets. *IEEE Trans. Signal Process.* 41, 3512–3523. doi:10.1109/78.258089

Ucak, C., and Caglar, R. (1998). The Effects of Load Parameter Dispersion and Direct Load Control Actions on Aggregated Load. *Int. Conf. Power Syst. Technol. IEEE.* 1, 280–284. doi:10.1109/ICPST.1998.728970

Vanouni, M., and Lu, N. (2015). Improving the Centralized Control of Thermostatically Controlled Appliances by Obtaining the Right Information. *IEEE Trans. Smart Grid* 6, 946–948. doi:10.1109/TSG.2014.2357211

Viel, F., Cunha, R., Di Santo, S. G., Monaro, R. M., Celeste Ghizoni Teive, R., and Albenes Zeferino, C. (2020). An Efficient Interface for the Integration of IoT Devices with Smart Grids. *Sensors* 20, 2849. doi:10.3390/s20102849

Wan, Q., Bian, Y., and Chen, Y. (2017). Research on a Micro-grid Frequency Modulation Strategy Based on Optimal Utilization of Air Conditioners. *Energies* 9 (12), 1085. doi:10.3390/en9121085

Wan, Y., Long, C., Deng, R., Wen, G., Yu, X., and Huang, T. (2021). Distributed Event-Based Control for Thermostatically Controlled Loads under Hybrid Cyber Attacks. *IEEE Trans. Cybern.* 51, 5314–5327. doi:10.1109/TCYB.2020.2978274

Wang, G., Li, Z., and Wang, F. (2021). Enhanced Sufficient Battery Model for Aggregate Flexibility of Thermostatically Controlled Loads Considering Coupling Constraints. *IEEE Trans. Sustain. Energy* 12, 2493–2496. doi:10.1109/TSTE.2021.3099314

Wang, J., Huang, S., Wu, D., and Lu, N. (2021). Operating a Commercial Building HVAC Load as a Virtual Battery through Airflow Control. *IEEE Trans. Sustain. Energy* 12 (1), 158–168. doi:10.1109/TSTE.2020.2988513

Wang, Y., Liu, D., and Sun, C. (2017). A Cyber Physical Model Based on a Hybrid System for Flexible Load Control in an Active Distribution Network. *Energies* 10, 267. doi:10.3390/en10030267

Wang, Y., Xu, Y., and Tang, Y. (2019). Distributed Aggregation Control of Grid-Interactive Smart Buildings for Power System Frequency Support. *Appl. Energy* 251, 113371. doi:10.1016/j.apenergy.2019.113371

Waseem, M., Lin, Z., Ding, Y., Wen, F., Liu, S., and Palu, I. (2021). Technologies and Practical Implementations of Air-Conditioner Based Demand Response. *J. Mod. Power Syst. Clean Energy* 9, 1395–1413. doi:10.35833/MPCE.2019.000449

Zhang, W., Kalsi, K., Fuller, J., Elizondo, M., and Chassin, D. (2012). Aggregate Model for Heterogeneous Thermostatically Controlled Loads with Demand Response. *IEEE Power Energy Soc. General Meet.*, 1–8. doi:10.1109/PESGM.2012.6345351

Wu, X., Liang, K., and Han, X. (2018). Renewable Energy Output Tracking Control Algorithm Based on the Temperature Control Load State-Queuing Model. *Appl. Sci.* 8, 1099. doi:10.3390/app8071099

Xia, M., Song, Y., and Chen, Q. (2019). Hierarchical Control of Thermostatically Controlled Loads Oriented Smart Buildings. *Appl. Energy* 254, 113493. doi:10.1016/j.apenergy.2019.113493

Xu, H., Cheng, L., Qi, N., and Zhou, X. (2020). Peak Shaving Potential Analysis of Distributed Load Virtual Power Plants. *Energy Rep.* 6, 515–525. doi:10.1016/j.egyr.2020.11.204

Yan, C., Xue, X., Wang, S., and Cui, B. (2015). A Novel Air-Conditioning System for Proactive Power Demand Response to Smart Grid. *Energy Convers. Manag.* 102, 239–246. doi:10.1016/j.enconman.2014.09.072

Yao, L., Chang, W.-C., and Yen, R.-L. (2005). An Iterative Deepening Genetic Algorithm for Scheduling of Direct Load Control. *IEEE Trans. Power Syst.* 20, 1414–1421. doi:10.1109/TPWRS.2005.852151

Zhang, Y., and Lu, N. (2013). Parameter Selection for a Centralized Thermostatically Controlled Appliances Load Controller Used for Intra-hour Load Balancing. *IEEE Trans. Smart Grid* 4, 2100–2108. doi:10.1109/TSG.2013.2258950

Zhang, J., Wang, Y., Weng, Y., and Zhang, N. (2020). Topology Identification and Line Parameter Estimation for Non-PMU Distribution Network: A Numerical Method. *IEEE Trans. Smart Grid* 11, 4440–4453. doi:10.1109/TSG.2020.2979368

Zhang, R., Chu, X., Zhang, W., and Liu, Y. (2015). Active Participation of Air Conditioners in Power System Frequency Control Considering Users' Thermal Comfort. *Energies* 8, 10818–10841. doi:10.3390/en81010818

Zhang, W., Lian, J., Chang, C.-Y., and Kalsi, K. (2013). Aggregated Modeling and Control of Air Conditioning Loads for Demand Response. *IEEE Trans. Power Syst.* 28, 4655–4664. doi:10.1109/TPWRS.2013.2266121

Zhang, X., Chen, Y., Bernstein, A., Chintala, R., Graf, P., Jin, X., et al. (2022). Two-Stage Reinforcement Learning Policy Search for Grid-Interactive Building Control. *IEEE Trans. Smart Grid* 13 (3), 1976–1987. doi:10.1109/TSG.2022.3141625

Zhang, Y., Lu, J., Jiang, X., Shen, S., and Wang, X. (2021). A Study on Heat Transfer Load in Large Space Buildings with Stratified Air-Conditioning Systems Based on Building Energy Modeling: Model Validation and Load Analysis. *Sci. Prog.* 104, 003685042110361. doi:10.1177/00368504211036133

Zhao, B. Y., Zhao, Z. G., Li, Y., Wang, R. Z., and Taylor, R. A. (2019). An Adaptive PID Control Method to Improve the Power Tracking Performance of Solar Photovoltaic Air-Conditioning Systems. *Renew. Sustain. Energy Rev.* 113, 109250. doi:10.1016/j.rser.2019.109250

Zhao, H., Zhao, J., Shu, T., and Pan, Z. (2021). Hybrid-Model-Based Deep Reinforcement Learning for Heating, Ventilation, and Air-Conditioning Control. *Front. Energy Res.* 8, 610518. doi:10.3389/fenrg.2020.610518

Zhao, L., Zhang, W., Hao, H., and Kalsi, K. (2017). A Geometric Approach to Aggregate Flexibility Modeling of Thermostatically Controlled Loads. *IEEE Trans. Power Syst.* 32, 4721–4731. doi:10.1109/TPWRS.2017.2674699

Zhou, X., Shi, J., Tang, Y., Li, Y., Li, S., and Gong, K. (2019). Aggregate Control Strategy for Thermostatically Controlled Loads with Demand Response. *Energies* 12, 683. doi:10.3390/en12040683

Zhu, J.-h., Gu, J., and Wu, M. (2020). Grid-Friendly Active Demand Strategy on Air Conditioning Class Load. *Appl. Sci.* 10 (18), 6464. doi:10.3390/app10186464

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