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Regulation techniques and applications of distributed load resources in urban power grids based on internet of things

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The power consumption of urban power systems is increasing rapidly with two typical trends: the first one is that the daily peak-valley difference of loads is more significant, and the power supply is tight during peak hours, which threatens the system's safe and stable operation; the second one is that the load energy efficiency in urban power systems is not high, which is the primary source of carbon emission in the power industry. Therefore, reducing the peak power and improving the system's energy efficiency are urgent tasks for enhancing the system's security and achieving the carbon emission goals. The rapid development of the Internet of Things (IoTs) ushers new opportunities for regulating demand-side loads. By analyzing the technical characteristics of load control based on IoTs, this paper investigates the modeling methods of load resources. On this basis, different control and optimization methods of load resources are analyzed and compared thoroughly. Besides, considering that load control is not only related to technical methods but also impacted by incentive strategies, the load control mechanisms under the mature and immature market environments are analyzed. Finally, the research gap and prospect of load regulation are proposed.

KEYWORDS

internet of things, urban power grids, load resources, demand response, regulation techniques

1 Introduction

The rapid increase in electricity consumption in urban power grids has presented two significant trends: firstly, the continuous widening gap between peak and off-peak periods, leading to a tight supply-demand balance during peak hours, which threatens the safe and stable operation of the power grid (Zhou Xiaoxin et al., 2018); secondly, the increasing proportion of new energy sources, which poses higher challenges for the real-time supply-demand balance due to their intermittent output (Sun et al., 2007). Therefore, reducing peak loads in urban power grids and enhancing system flexibility are essential pathways to achieve the power grid's safe, stable, and economically efficient operation (Song et al., 2016). The rapid development of the Internet of Things (IoTs) has enabled broader device connectivity, faster and more reliable data transmission, and enhanced privacy protection for the power system (Hui et al., 2020, Song Y. et al., 2017). It allows for regulating large-scale load resources in the power system to achieve peak shaving, valley filling, and new energy integration at lower costs and higher efficiency (Zhang et al., 2008). The essence of load regulation is to reduce or shift demand-side power consumption, providing services such as standby, peak shaving, and frequency regulation to the power system (Xue et al., 2007). To ensure a satisfactory user experience and minimize impacts on production and life, load regulation mainly targets load types with energy storage characteristics or transferable characteristics, such as energy storage batteries, electric vehicles, and temperature control loads (Wang Ke et al., 2014). For example, implementing orderly charging based on dynamic time-of-use electricity prices for electric vehicles can assist in peak shaving and valley filling in the power system (Zhiwei et al., 2014). Optimized control strategies for temperature control load clusters can achieve smooth tracking of load aggregation power to set targets, utilizing load resources to achieve system supply-demand balance (Wang et al., 2012).

Based on extensive theoretical research, load regulation technology is also transitioning from pilot verification to large-scale application. For example, the ERCOT electricity market in Texas, USA, has incorporated load regulation resources into the ancillary services market, providing services such as spinning reserves, fast response, and emergency regulation to the system (Yi et al., 2017). Japan has established a megawatt market, allowing demand-side users to participate in load regulation, reducing peak demand for thermal power generation, and increasing the utilization of new energy (Yang, 2015). The European Union has launched the Smart Grid project, using real-time electricity prices to influence end-users' electricity consumption behaviors, assisting in integrating new energy into the power system (Ding et al., 2013). China has also conducted a series of demonstration projects in the field of load regulation, such as constructing a friendly interaction system between urban users and the power grid in Jiangsu Province, tapping into the coordinated regulation capabilities of load resources and generation resources (Hui et al., 2018a). Besides, the commercial buildings are constructed as virtual power plants in Shanghai to participate in peak shaving and valley filling in the power system (Shengchun et al., 2020). Flexible grids in Zhejiang Province are aggregated to promote the local integration of distributed photovoltaics (Zou et al., 2019).

Based on the above literature review, previous research gaps can be summarized as three points. i) Load modeling technology: traditional models only focus on power consumption while failing to comprehensively reflect real-time production processes, dynamic equipment parameters, and product quality, among other factors. ii) Load regulation technology: current load control mainly focuses on electricity, making it challenging to control multi-dimensional load resources such as heat, cold, and natural gas, leading to challenges in coordinating loads in integrated energy systems. iii) Load control for improving system resilience: current research mainly focuses on resilience assessment, unit planning, mobile energy storage resource scheduling, etc., with limited attention to load resources with significant control potential.

This paper discusses the technical characteristics of load resource regulation under the Internet of Things (View on 5G architecture, 2019; G network architecture, 2016; Embrace 5G new world, 2019; Telecom and GridHuawei, 2018; Yilmaz, 2016), including diversification of types (Yi Wang. et al., 2019; Knud, 2014; Hui et al., 2019; Siano, 2014; Shi et al., 2018), refinement of control (Hui et al., 2020), and data privacy protection (Zhou Z. et al., 2018; Leligou et al., 2018; Commercial feasibility analysis of smart, 2019). Besides, this paper investigates the modeling methods of load resources (JU and Ma, 2008; TANG et al., 2007; Yong, 2012; Ju et al., 2020; Yi Ding. et al., 2019; Yayuan et al., 2019; Ahmad et al., 2020; Das et al., 2020; Morello et al., 2018), especially including temperature-controlled loads (Sonderegger, 1978; Lu, 2012; Sun et al., 2016; Wang et al., 2016; Wang Dan et al., 2014; Mathieu and Callaway, 2012; Kirschen et al., 2000; Zhenfang, 2004; Liu et al., 2008; Technology information; Bachao, 2017; Song M. et al., 2017; Shao et al., 2004; Park et al., 2001; Zhang Q. et al., 2016; Hui et al., 2018b) and (Song et al., 2011; Xiang et al., 2015; Luo et al., 2011; Zhang Hongcai et al., 2014; Wang et al., 2019; Zhiwei et al., 2012; Junhua et al., 2010; Jinghong et al., 2012; Hongmei et al., 2015; Liu et al., 2016; Nosair and Bouffard, 2015; Wang et al., 2005; Yaping et al., 2017; Zhang Fang et al., 2014). On this basis, different control and optimization methods of load resources are analyzed and compared thoroughly (Hui et al., 2017; Dong et al., 2015; Bhattacharyya and Crow, 1996; Chu et al., 1993; Laurent et al., 1995; Meng, 2015; Qi et al., 2017; Zhang et al., 2015; Samarakoon et al., 2012; Vrettos et al., 2018; Babahajiani et al., 2018; Singh et al., 2017; Ledva et al., 2018; Li et al., 2020; Jia et al., 2013; Su et al., 2018; Shi et al., 2019; Cai et al., 2019; Zhang et al., 2017; Measurement of electrical and magnetic quantities. C37.118.1-2011, 2011; Douglass et al., 2013; Kaiqiao et al., 2016; Wenting et al., 2016; Bao et al., 2015; Weckx et al., 2014; Yao et al., 2018). Next, considering that load control is not only related to technical methods but also impacted by incentive strategies, the load control mechanisms under the mature (Albadi and El-Saadany, 2008; Xie et al., 2018; Hongtu et al., 2010; Ruan et al., 2013; Nyeng and Ostergaard, 2011; Siano and Sarno, 2016; Ding et al., 2013; Kai et al., 2020; Zhang Ning et al., 2016; Chen et al., 2018; Jian et al., 2017; Wang et al., 2020; Bin et al., 2018; Tai et al., 2016) and immature market environments are analyzed (Zeng et al., 2016; Zeng et al., 2013; Zeng et al., 2015; Zhong et al., 2013; Chen et al., 2017; Hui et al., 2022; Yi Ding et al., 2019). Finally, this paper summarizes the shortcomings of load regulation technology and provides prospects for future research (Rui, 2018; Antiy Institute, 2019; Ju et al., 2019; Qiu et al., 2020; Zhaohong et al., 2020; Bo et al., 2020; Zhang et al., 2019; Pierre, 1987; Chen et al., 2020; Yin et al., 2019).

2 Methodological approach

2.1 Characteristics of load regulation technologies based on IoTs

Information and communication technologies represented by 5G have facilitated the rapid development of the IoT (View on 5G architecture, 2019). First, massive machine communication technology enables large-scale access to load devices in the IoT, with up to 1 million devices per square kilometer (G network architecture, 2016). Secondly, enhanced mobile broadband technology enables fast data exchange between control centers and load devices in the IoT, with transmission speeds of up to 20 Gbps (Embrace 5G new world, 2019). Furthermore, ultra-reliable, low-latency communication technology allows for high-reliability data transmission and instantaneous load control in the IoT, with a data transmission failure rate as low as 10^{-9} fully meeting the 99.999% reliability requirements for load control in power grids (Telecom and GridHuawei, 2018). The data transmission latency

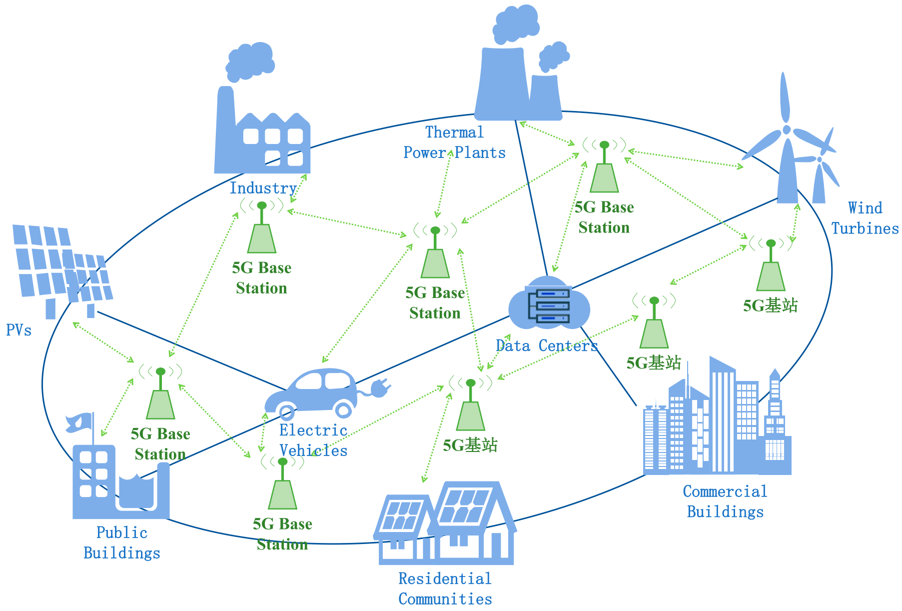

FIGURE 1
Internet of Things-based pluralistic load control.

can be reduced to as low as 1 ms, meeting the millisecond-level precise load control requirements (Yilmaz, 2016). Therefore, the IoT supported by next-generation communication technologies has promoted the rapid development of load control technology. This section discusses the technical characteristics of load control in the IoT from three aspects: diversification of control types, refinement of control, and data privacy protection.

2.1.1 Diversification of load regulation types

Diversification of regulation types has two layers of meaning. The first layer refers to diversifying user types participating in load control. Traditional load control, limited by communication methods and the number of control terminals, mainly targets large-capacity users, such as using fiber optic communication for load control in industrial enterprises and commercial buildings. However, the development of the IoT has led to the widespread deployment of smart meters and remote-control terminals for small and medium-sized users, such as smart sockets, which are rapidly increasing (Yi Wang. et al., 2019). Load control now covers many small and medium-sized users, leading to a more diverse range of user types, as shown in Figure 1 (Knud, 2014).

The second layer of meaning refers to the diversification of services provided to the power system. Traditional load control involves sending instructions from the dispatch department to end users, resulting in inevitable communication delays (Hui et al., 2019). Therefore, load control primarily provides auxiliary services with extended time scales to the power system, such as reserves and peak shaving (Siano, 2014). With the IoT based on next-generation communication technologies, data transmission speeds are fast, especially with 5G's ultra-reliable low-latency communication technology, which can reduce communication latency to the millisecond level. This enables load control to provide a more diverse range of services to the power system, such as frequency regulation and emergency backup (Shi et al., 2018).

2.1.2 Refinement of load regulation

The development of load control refinement can be divided into three stages (Hui et al., 2020). In the first stage, power reduction or transfer is achieved through the interconnection lines between control area grids and the primary grid, and direct disconnection occurs during power shortages. This regional control method cannot consider individual power demands and reduction losses. In the second stage, Home Energy Management Systems enables control over individual electricity users, allowing users to autonomously choose the method, capacity, and period for participating in load control. In the third stage, load control based on the IoT gives users more choices. Users can decide whether each load device participates in control and how it participates. For example, air conditioning loads can be set within a comfortable temperature range, allowing for independent and refined management of loads. This ensures a better electricity consumption experience for users under control.

2.1.3 Data privacy protection

The characteristics of diversification of control types and refinement of control can bring better economic benefits or electricity comfort to a broader range of users. However, a significant obstacle to the large-scale application of load control is the issue of user data security and privacy. The Internet of Things protects the transmission of load data, including software-defined networking technology (Zhou Z. et al., 2018), network function virtualization technology (Leligou et al., 2018), and network slicing technology (Commercial feasibility analysis of smart, 2019). For example, network slicing technology allows operators to construct multiple virtual networks based on a single network physical layer for different application scenarios, achieving communication isolation between specific business data and enabling customized services and domain slicing management for "dedicated networks." Specifically, through massive machine communication slicing, fine-grained collection of energy usage information for many users can be achieved; through ultra-reliable low-latency communication slicing, real-time control of loads can be achieved (Telecom and GridHuawei, 2018).

2.2 Modeling methods of distributed load resources

The primary issue in load control is establishing accurate and applicable load models and quantifying different loads' adjustability. Traditional load models mainly include static models such as constant impedance-current-power, classical, and comprehensive load models, with model parameters determined through measurement, fault simulation, and statistics (Ju and Ma, 2008; Tang et al., 2007; Yong, 2012). However, these traditional load models primarily describe the electrical characteristics of loads, established for power scheduling and electrical characteristics to support simulation calculations and operational control of power systems without considering the comfort and experience of electricity users. Literature (Ju et al., 2020) defines loads whose electricity consumption can vary within specified ranges or be shifted in different periods as "demand response." Demand response requires considering the electrical characteristics of the load itself and its interactivity, controllability, and comfort of electricity use. Currently, the research objects of load control include water heaters, air conditioners, heat pumps, refrigerators, washing machines, energy storage batteries, electric vehicles, etc. Due to space limitations, this paper mainly introduces two typical load modeling methods: temperature-controlled loads represented by air conditioners and energy storage loads represented by electric vehicles. Air conditioners account for a high proportion of total loads, with significant adjustment potential, and have minimal impact on user electricity comfort during adjustments (Yi Ding. et al., 2019). Electric vehicles are increasing, and their charging and discharging can provide colossal energy storage resources to the power system.

On the one hand, the fast-charging technologies bring more fluctuations to the power systems (Yayuan et al., 2019). On the other hand, battery swapping technologies bring more opportunities to provide long-term charging battery storage for power systems (Ahmad et al., 2020). Besides, electric vehicles have different standards and charging voltage requirements (Das et al., 2020), which bring more regulation potentials on power systems to provide multi-type regulation services (Morello et al., 2018). Therefore, air conditioners represent the load type with the most development potential currently, while electric vehicles represent the load type with the most adjustment capacity in the future.

2.2.1 The first typical load: Temperature-controlled loads

Modeling temperature-controlled loads requires considering the electrical model of the interaction between the load and the power system and the thermodynamic model of the load and its spatial location. Equivalent thermodynamic parameters are the most representative modeling method (Sonderegger, 1978), equivalently representing temperature-controlled loads as equivalent circuits composed of capacitors and resistors, as shown in Figure 2 (Wang et al., 2012).

Where Q is the equivalent thermodynamic power of air conditioning load considers the cooling or heating states; the switch status represents the operating state of the air conditioner; $T_i T_o$ and T_m represents indoor temperature, outdoor ambient temperature, and temperature of indoor objects, respectively, which are all equivalent to different node voltage values; R_1 and R_2 represent the equivalent thermal resistances between the building and outdoor environment, and between objects inside the building, respectively; C_1 and C_2 represent the specific heat capacities of the indoor air and objects, respectively, which are equivalent to capacitance values (Lu, 2012). Based on Kirchhoff's current law, the relationship between current, voltage, resistance, and capacitance in the equivalent thermodynamic parameter model can be expressed as Equations 1, 2:

$$\frac{dT_i}{dt} = \frac{Q}{C_1} - \frac{T_i - T_o}{C_1 R_1} - \frac{T_i - T_m}{C_1 R_2} \tag{1}$$

$$\frac{dT_m}{dt} = \frac{T_i - T_m}{C_2 R_2} \tag{2}$$

where parameter Q is the cooling capacity from the air conditioning system. It is generally calculated by the operating power P and the Coefficient of Performance (COP), which can be expressed as $Q(t) = P(t) * COP$.

In addition to the equivalent thermodynamic parameter model for temperature-controlled loads, literature (Sun et al., 2016) proposes an exponential model describing the dynamic characteristics of a typical water heater, achieving peak shaving and valley filling in the power system through aggregated control of water heater demand response. Literature (Wang et al., 2016) presents an economically driven ice storage load model, participating in demand response in the medium to long-term electricity market environment. Literature (Wang Dan et al., 2014) establishes a temperature-controlled load model that considers user comfort constraints, aggregates temperature-controlled loads into energy-efficient power plants to participate in dynamic power system regulation and achieves the same objectives as conventional power plants. Literature (Mathieu and Callaway, 2012) uses a Markov chain model to describe the state change process of aggregated temperature-controlled loads and uses Kalman filtering technology for joint estimation of parameters and states, accurately tracking the operating power of the temperature-controlled load model. Literature (Kirschen et al., 2000; Zhenfang, 2004; Liu et al., 2008) establishes an elasticity matrix describing user electricity behavior based on the price elasticity coefficient in economics. The self-elasticity and cross-elasticity coefficients describe the amount of electricity adjustment for the user in the current and other periods, respectively, and the elasticity matrix can represent the mutual influence of electricity loads at different times.

Furthermore, with the advancement of power electronics technology, the market share of variable-frequency air conditioners equipped with rectifier-inverter devices is rapidly expanding, surpassing conventional fixed-frequency air conditioners in sales in China (Technology information). The

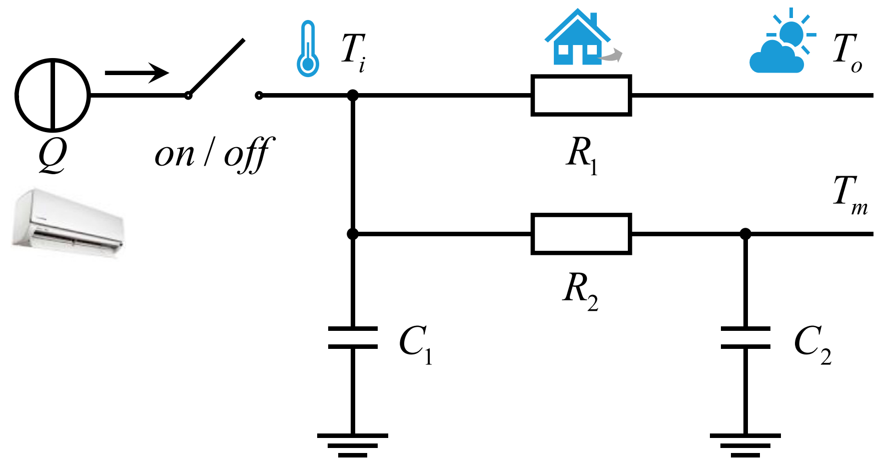

FIGURE 2
Model of thermostatically controlled loads.

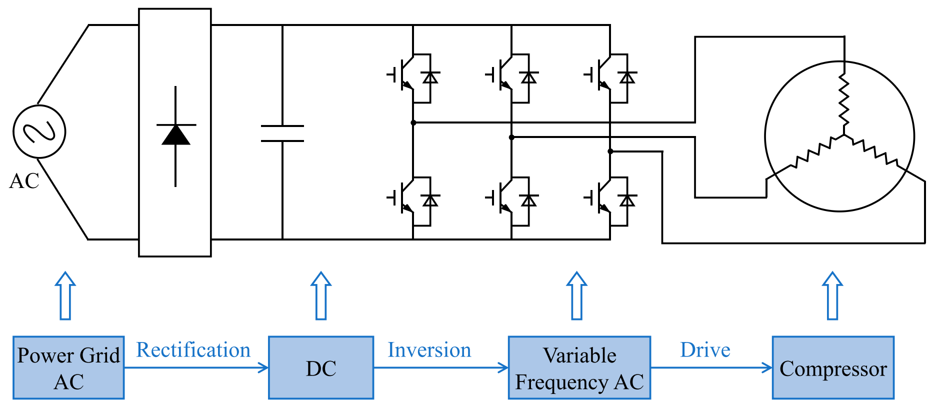

FIGURE 3
The operating principle of variable frequency air conditioners.

main difference between variable-frequency air conditioners and fixed-frequency air conditioners lies in the compressor's control mode, as shown in Figure 3 (Bachao, 2017).

The compressor of a fixed-frequency air conditioner has only two operating modes, on/off, with the operating power switching approximately between rated power and zero power, maintaining the indoor temperature within a specific range. In contrast, the compressor speed of a variable frequency air conditioner can be continuously adjusted through a frequency converter, making it more suitable for participating in dynamic responses of the power system. Literature (Song M. et al., 2017) and (Shao et al., 2004) establish variable frequency air conditioner models based on simulation methods and experimental data, proving their continuous adjustment characteristics. Literature (Park et al., 2001) analyzes the relationship between the operating performance of variable-frequency air conditioners and the compressor operating frequency, cooling capacity, and cooling efficiency ratio. Literature (Zhang Q. et al., 2016) constructs a dedicated, intelligent testing platform to compare the operating characteristics of variable-frequency air conditioners and conventional fixed-frequency air conditioners, analyzing their long-term operation, dynamic operation, startup, and shutdown processes. The results show that variable-frequency air conditioners can reach the set temperature indoors more quickly and have higher energy efficiency. Literature (Hui et al., 2018b) incorporates the variable frequency air conditioner model into the dynamic response process of the power system, considering the inertia element of compressor adjustment, making the variable frequency air conditioner cluster equivalent to traditional generator units participating in power system frequency regulation. Therefore, variable frequency air conditioners participating in load control are more flexible, have faster response speeds, and have minimal impact on user comfort.

2.2.2 The second typical load: Electric vehicles

The physical model parameters of electric vehicles mainly include battery capacity B_i, state of charge S_i, battery charging/discharging power $P_{c,i}P_{d,i}$, and battery charging/discharging efficiency $\eta_{c,i}\eta_{d,i}$ (Song et al., 2011). Based on the above parameters, the charging/discharging model of electric vehicles can be obtained as the Equation 3:

$$S_i(t+1) = \begin{cases} S_i(t) + P_{c,i} \cdot \eta_{c,i} \big/ B_i, P_{c,i} > 0 \\ S_i(t), P_{c,i} = P_{d,i} = 0 \\ S_i(t) - P_{d,i} \cdot \eta_{d,i} \big/ B_i, P_{d,i} > 0 \end{cases} \tag{3}$$

Furthermore, the electric vehicle model also needs to consider constraints on charging/discharging power and battery capacity (Xiang et al., 2015), expressed as the Equation 4:

$$\begin{cases} 0 \le P_{c,i} \le P_{c,i}^{\max} \\ 0 \le P_{d,i} \le P_{c,i}^{\min} \\ S_i^{\min} \le S_i \le S_i^{\max} \end{cases} \tag{4}$$

Literature (Luo et al., 2011) proposes a charging load calculation model for different types of electric vehicles based on their different electricity usage behaviors. Literature (Zhang Hongcai et al., 2014) presents a spatiotemporal distribution-based electric vehicle charging load prediction model considering electric vehicles' driving and parking characteristics. Based on a single electric vehicle physical model, literature (Wang et al., 2019) constructs a large-scale aggregation state space model for electric vehicles, accurately describing the impact of heterogeneous charging characteristics and random driving behaviors on the capacity of electric vehicles to participate in power system frequency regulation. Literature (Zhiwei et al., 2012) establishes an electric vehicle charging station model and proposes an ordered charging model considering user travel demand and grid load levels to improve the economic benefits of charging stations. Literature (Junhua et al., 2010) constructs a probability model for the random charging and discharging of electric vehicles, jointly considering the random output of wind turbines, achieving the minimum total generation cost economic dispatch of the power system. Literature (Jinghong et al., 2012) establishes a two-stage constant current-constant voltage charging model for electric lithium batteries. It proposes an aggregation model for electric vehicle charging stations in residential areas based on the Poisson distribution. Literature (Hongmei et al., 2015) constructs an electric vehicle charging and discharging model. It proposes a microgrid energy storage capacity optimization operation method based on mixed-integer second-order cone programming, achieving ordered charging and discharging scheduling of electric vehicles and balanced support for microgrids. Literature (Liu et al., 2016; Nosair and Bouffard, 2015; Wang et al., 2005; Yaping et al., 2017; Zhang Fang et al., 2014) establishes a dynamic capacity degradation model for electric vehicle batteries and proposes an optimized scheduling model for electric vehicles considering charging and discharging losses, achieving multiple objectives optimization such as charging station profits, user benefits, and travel demand optimization.

3 Typical load control methods

Compared with the regulation capacity provided by traditional generating units, the regulation capacity provided by individual loads is minimal, requiring the control of large-scale loads. Load resources are geographically dispersed, with significant differences in operating characteristics, and they need to ensure diverse individual user electricity demands. Based on the existing control architecture, load control methods can be divided into three types: centralized, distributed, and hybrid.

3.1 Centralized control method

The centralized control method has a clear structure and can achieve real-time solid consistency control of load clusters, making it the current primary load control method. Literature (Hui et al., 2017) proposed a centralized control method for adjusting the set temperature of temperature-controlled loads, changing the operating power within the range users allow to provide operational reserves for the power system. Literature (Dong et al., 2015) adopted a centralized control architecture. It proposed an improved weighted coefficient queuing algorithm, considering the individual preferences of users participating in the system's dynamic response, achieving direct control of temperature-controlled loads such as air conditioners and heat pumps. Literature (Bhattacharyya and Crow, 1996) proposed a centralized control method based on fuzzy logic, which improves the dynamic response performance of loads and user satisfaction and reduces user electricity costs. Literature (Chu et al., 1993) used dynamic programming to control loads directly, targeting the minimum load reduction to solve the problem of insufficient generating capacity during peak summer loads in power systems. Literature (Laurent et al., 1995) integrated the advantages of linear programming and dynamic programming, proposing an optimization method based on column generation, which meets the requirements of electric water heaters while participating in peak shaving of power systems. Literature (Meng, 2015) proposed a centralized frequency control strategy for temperature-controlled loads and coordinated with electric vehicles to participate in power system frequency regulation. Literature (Qi et al., 2017) constructed a temperature-controlled load model for the cluster of electric water heaters. It proposed a new serialization control strategy to provide frequency control shedding auxiliary services to the power system.

However, centralized control methods also have drawbacks. For example, there are delays in sensing measurement, signal transmission, operation calculation, and terminal execution, leading to lag in load control (Zhang et al., 2015). Literature (Samarakoon et al., 2012) established a hardware and software platform to test communication delays during load direct control processes. The results showed that the load could eventually be disconnected, but the communication delay was between 3.3 and 4.6 s. Literature (Vrettos et al., 2018) conducted experiments on commercial buildings participating in power system frequency regulation, proving that communication delays cannot be ignored and require about 20 s to eliminate their effects. Currently, the primary methods to solve communication delays in centralized control are load state estimation and design feedback controllers. Literature (Babahajiani et al., 2018) proposed a fuzzy proportional-integral controller connecting generating units with adjustable loads. When delay-induced success rate fluctuations occur, the generating units can receive fluctuation signals and change their operating states, reducing the impact of delays. Literature (Singh et al., 2017) linearized communication delays using the Padé approximation method and quantified the effects of communication delays on power fluctuations. Literature (Ledva et al., 2018) proposed a stochastic predictive controller and Kalman filtering state estimation method to reduce the impact of communication delays.

3.2 Distributed control method

Compared with centralized control, distributed control has better scalability, privacy, and reliability and is suitable for controlling numerous and geographically dispersed loads. However, distributed control has higher requirements for communication networks, data transmission, and terminal computing capabilities, and the development of IoT technology has promoted the application of distributed control in load control fields.

Literature (Li et al., 2020) proposed a distributed consistency control algorithm considering time-coupled characteristics, achieving robust control of large-scale load resources in scenarios with partial information loss and theoretically proving the convergence and optimality of this method in load control. Literature (Jia et al., 2013) took refrigerators as typical temperature-controlled loads. It proposed a distributed control strategy based on system frequency fluctuation amplitude and user participation level as decision metrics, dynamically adjusting the refrigerator's operating cycle to maintain the stable operation of microgrids in islanded states. Literature (Su et al., 2018) proposed a dispersed active power control strategy for large-scale temperature-controlled load groups by solving the coupled Fokker-Planck equation probability model, achieving load response in power system emergencies. Literature (Shi et al., 2019) separately proposed load-distributed control methods based on stable recovery technology, achieving primary and secondary frequency control for temperature-controlled loads. Literature (Cai et al., 2019) and (zhang et al., 2017), respectively, based on deep learning load prediction technology and load self-learning coordinated control technology, ensuring load distributed control while maintaining user comfort. Therefore, distributed control methods generally install terminal controllers on the load side to monitor parameters such as local system frequency deviation for load control, avoiding the communication delay issues generated in centralized control. However, compared with the measurement devices (phasor measurement unit, PMU) in centralized control (Measurement of electrical and magnetic quantities. C37.118.1-2011, 2011), the measurement accuracy of control terminals is lower, leading to control deviations (Douglass et al., 2013).

Note that the local control method is also a kind of method, which is a general concept by using the local or edge control devices. In this paper, the distributed control method is a kind of local control method by using the edge control devices and exchanging operating states with neighboring devices.

3.3 Hybrid control method

The hybrid control method combines the advantages of centralized and distributed control, ensuring efficient control and high consistency of load clusters while improving system scalability and responsiveness. However, the cost of the control system is relatively high. Literature (Kaiqiao et al., 2016) proposed an ordered charging layered control strategy for electric vehicles. The main control center obtains the charging load guidance curve through a two-stage optimization model of peak shaving and valley filling. Each secondary control center selects a centralized or distributed control strategy to follow the charging load. Literature (Hui et al., 2019) proposed a load hybrid control architecture based on dual-end measurement and retrospective correction. It uses PMUs to monitor power system frequency deviations as accurate values. Then, through terminal controllers monitoring local frequency deviations and combining with precise historical data sent by PMUs, real-time correction of local measurements is performed, improving load control accuracy. The control center sets the load response threshold in advance, avoiding real-time communication and eliminating control delays.

Additionally, literature (Wenting et al., 2016) proposed a hybrid control architecture for non-ideal communication states such as packet loss and error codes, aggregating loads such as electric heat pumps as a virtual power plant to participate in dynamic regulation of power systems, as shown in Figure 4. Literature (Bao et al., 2015) and (Weckx et al., 2014) designed a hybrid control method to involve temperature-controlled loads in system frequency regulation. By setting predetermined frequency response thresholds and minimum shutdown times for temperature-controlled loads, they achieved smooth regulation of temperature-controlled load aggregation groups, reducing power system frequency deviations and oscillations. Literature (Yao et al., 2018) proposed a hybrid dual-layer control architecture based on virtual automatic power generation control and distributed control, increasing the adjustable capacity of temperature-controlled loads to accommodate many renewable energy sources.

4 Market mechanism of load regulation

4.1 Load regulation mechanisms in mature markets

Load control involves technical issues such as modeling and control and economic considerations. Like power generation units having regulation costs, load control also involves market economic issues. Currently, load control mechanisms can be categorized into price-based and incentive-based, as shown in Figure 5 (Albadi and El-Saadany, 2008). Price-based mechanisms influence users' electricity consumption by varying electricity costs during different periods, mainly aiming to increase system revenue or reduce generation costs. Therefore, price-based mechanisms are market-oriented load control models (Xie et al., 2018), including time-of-use pricing, real-time pricing, and peak pricing. Incentive-based mechanisms require users to sign contracts in advance with fixed or time-varying subsidies, aiming to reduce electricity consumption during peak loads and ensure system stability (Hongtu et al., 2010). Thus, incentive-based mechanisms

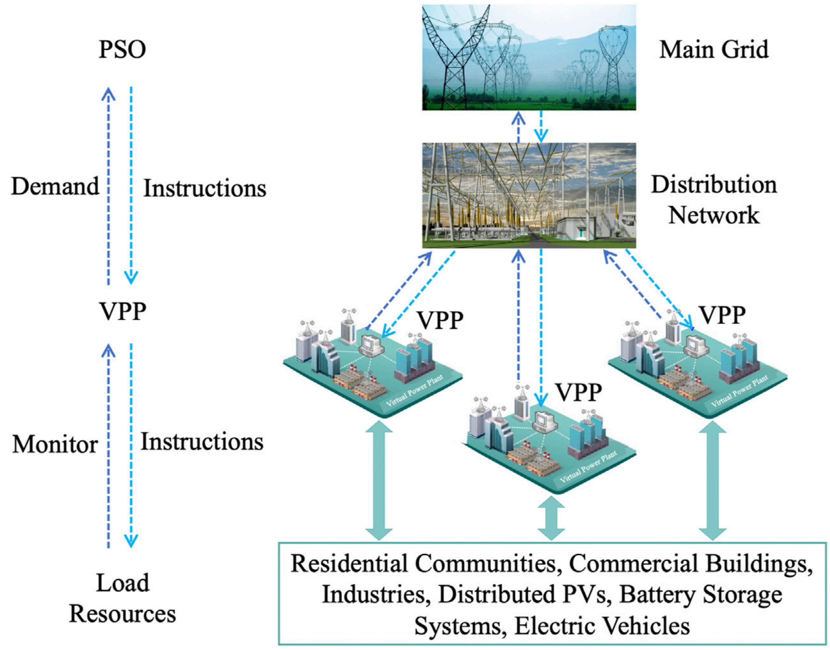

FIGURE 4
Structure of virtual power plants.

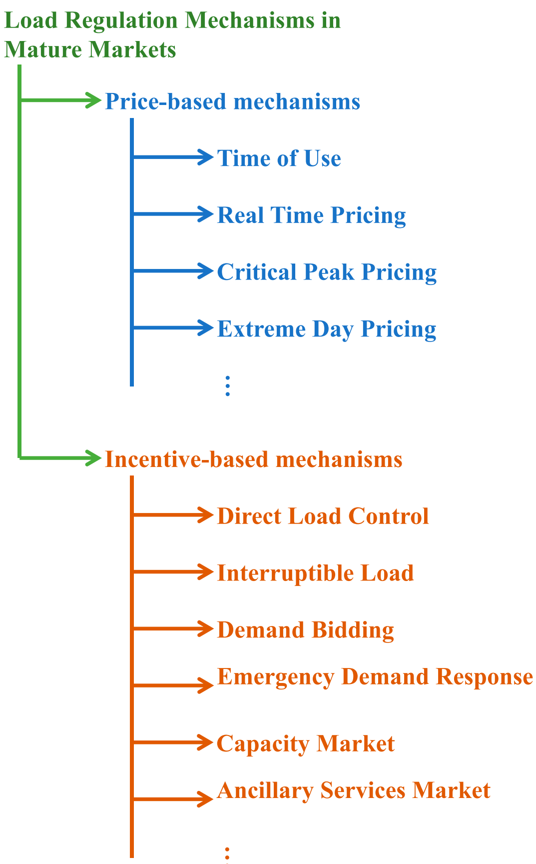

FIGURE 5
Load regulation mechanisms in mature markets.

ensure system stability, including interruptible loads, demand-side bidding, emergency demand response, and others (Ruan et al., 2013).

The IoT has facilitated broader device connectivity in the power system, enabling small and medium-sized users to participate in the load control market. Literature (Nyeng and Ostergaard, 2011) constructed terminal controllers, data interfaces, and communication systems to enable small users to respond to dynamic electricity prices, reducing user electricity costs by approximately 7%. Literature (Siano and Sarno, 2016) studied distribution network operators participating in real-time electricity markets and used marginal electricity prices to influence small users in adjusting temperature-controlled loads, reducing system operation costs. Literature (Ding et al., 2013) analyzed the Ecogrid EU project, a major innovative grid pilot project in the EU, where smart meters and electricity data monitoring devices were installed for small users. Real-time electricity prices influenced user electricity consumption, demonstrating that users can assist power systems in integrating more renewable energy.

Furthermore, the widespread deployment of IoT-enabled smart terminals has led to the application of blockchain technology in load control market mechanisms, ensuring faster and more reliable data transmission and enhanced privacy protection (Kai et al., 2020, Zhang Ning et al., 2016). Literature (Chen et al., 2018) designed a decentralized trading system based on blockchain for distributed adjustable load resources. Literature (Jian et al., 2017) proposed a multilateral trading mechanism for distribution grid markets based on smart contracts, enabling real-time local transactions of distributed generation and load resources, eliminating deviations between operating power and planned quantities.

Literature (Wang et al., 2020) proposed an electric vehicle charging rights trading mechanism based on blockchain, facilitating load distribution among different charging stations and ensuring the safe operation of transmission and distribution equipment. Literature (Bin et al., 2018) proposed a multilevel bidding mechanism in a non-trust environment, achieving effective trading of adjustable loads while protecting user privacy. Literature (Tai et al., 2016) focused on multi-energy systems and constructed a transaction system based on heterogeneous blockchain technology, enhancing market transaction security.

4.2 Load control mechanisms in non-mature markets

Many power systems worldwide need more mature market models, making it challenging to implement load control even by installing intelligent meters and terminals. Taking China as an example, the government determines the electricity prices for both power generation units and users through catalog prices, giving little decision-making power to the power generation side regarding grid prices. Users must accept the prices set for their category (Zeng et al., 2016). Therefore, users need more motivation in non-mature markets to participate in load control.

Currently, in these unified pricing markets, most load control projects are based on administrative measures with limited consideration for user demands, resulting in relatively unfair treatment for users (Zeng et al., 2013). In recent years, power companies have compensated users after load shedding, but these compensations are usually fixed prices that do not reflect real-time market costs (Zeng et al., 2015). Therefore, compared to mature markets with open competition, power companies in non-mature markets cannot directly implement price or incentive mechanisms (Yi et al., 2017). Inspired by the widespread use of coupons in the industrial sector, literature (Zhong et al., 2013, Chen et al., 2017) proposed a load control market strategy based on coupons. In this strategy, after electricity users voluntarily participate in response projects, they receive corresponding coupon rewards. The specific execution involves a real-time iterative bidding framework where an aggregator provides coupon face values to end users, who then submit load adjustment quantities based on these values. The aggregator optimizes the face values to maximize revenue and publishes new coupon face values to users in a cyclic process, eventually determining coupon face values and response capacity.

However, small and medium-sized end users (e.g., residential users) need more time or expertise to submit load adjustment quantities accurately. Most residential users need to be aware of their load power during different periods and are unlikely to accurately give feedback on load adjustment quantities to aggregators. To address this issue, the national critical R&D program “Friendly Interaction System Between Urban Users and Power Grid Supply and Demand” proposed a demand response points incentive model, fully considering the operability of users and power grid enterprises (Hui et al., 2022). In this model, users receive points notifications every 15 min, with positive points indicating an increase in points for electricity usage during that period and negative points marking a decrease (Yi Ding et al., 2019). Positive points typically occur during low load periods, encouraging users to increase electricity usage, while negative points occur during peak load periods, enabling users to decrease electricity usage. Points are settled monthly, and users with a positive point total can exchange them for corresponding reward money. In contrast, users with an opposing point total have their points reset to zero, avoiding increased electricity costs for users during the demonstration phase and alleviating user concerns about participating in load control. The positive and negative points market strategy reduces the difficulty of user participation in load control, respects users’ autonomous choices in participating in adjustments, and is a beneficial supplement to electricity price policies in non-mature markets.

5 Limitations and prospects of load regulation

5.1 Limitations of load regulation technology

5.1.1 Load modeling technology

As the scale of load control increases, the accuracy of control capacity becomes increasingly crucial for the safe operation of power systems, necessitating the establishment of accurate load models. However, current load models based on classical models or historical statistical data need help to describe diverse loads’ real-time states and operating conditions, resulting in delays or even failures in load response. Taking industrial loads as an example, traditional models only focus on power consumption. At the same time, it fails to comprehensively reflect real-time production processes, dynamic equipment parameters, and product quality, among other factors. Dispatching authorities may issue commands when equipment cannot respond, leading to response failures. Therefore, load models that can interact with load entities in real-time must be constructed, comprehensively describing the operational states throughout the entire lifecycle of loads to achieve an accurate assessment of load control capabilities.

5.1.2 Load regulation technology

Existing load control primarily involves direct switching or adjusting power output. However, under the Internet of Things (IoTs), load resources include small and medium-sized users’ loads with small capacities and high uncertainties, compounded by operating time, space, and load types. Ensuring user comfort during control processes is challenging, making it difficult to apply traditional control methods uniformly.

Furthermore, with the deep coupling of electricity with heat, cold, natural gas, distributed energy, and other forms of energy, the connotation of load control is continuously expanding. Leveraging the conversion and complementarity of different energy forms can uncover more extensive and in-depth control potentials at the comprehensive energy system level. However, current load control mainly focuses on electricity, making controlling multi-dimensional load resources such as heat, cold, and natural gas challenging. This leads to challenges in coordinating loads in integrated energy systems.

5.1.3 System resilience by regulating loads

Power systems are susceptible to natural disasters and human attacks, such as Typhoon Hato in 2017, causing widespread blackouts in Macau and other cities, and the 2019 blackout in Venezuela due to a cyberattack (Rui, 2018, Antiy Institute, 2019). In this context, resilient power systems emerged, referring to the ability to prevent, withstand, respond to, and quickly recover from extreme events (Ju et al., 2019). Resilient power systems primarily address small probability, high-loss extreme events beyond the traditional "three lines of defense" framework (Qiu et al., 2020).

Research on resilient power systems focuses on natural disasters like typhoons and floods, as well as human-made disasters like cyberattacks. The stages of accidents include primary systems like transmission and distribution lines, transformers, and secondary systems like communication networks and sensing devices (Zhaohong et al., 2020). However, current research mainly focuses on resilience assessment, unit planning, mobile energy storage resource scheduling, etc., with limited attention to load resources with significant control potential. Addressing extreme events that are low-probability in power systems through unit construction or energy storage configuration is costly. Utilizing existing loads as adjustment resources for extreme events is cost-effective with large capacities. For example, some insignificant loads can be shed at some extremely dangerous or urgent conditions. Additionally, due to the low probability of extreme events, it will not frequently impact user energy consumption. However, specific research in this aspect still needs to be completed.

Given the limitations of load control technology, the following prospects are outlined from three perspectives.

5.2 Prospects of load regulation technology

5.2.1 Digital twin-based load modeling technology

The development of the Internet of Things (IoTs) has expanded the application of digital twin technology to load modeling (Bo et al., 2020). Digital twins can leverage real-time monitored load data from the IoT to establish mechanical and data-driven models of loads. These models can then be used through simulation software to precisely describe, diagnose, and predict load entities (Zhang et al., 2019).

Digital twin technology inherently suits load modeling, enabling a bidirectional mapping between physical load objects and digital spaces. It accurately simulates multi-dimensional characteristics of loads, such as structure, state, and temporal aspects. Additionally, with the scalable nature of digital twins, dynamic replacement and integration of loads at multiple physical, hierarchical, and scale levels can be achieved. However, large-scale application research based on IoT and digital twin technology in load control still needs to be improved, necessitating further research on precise mapping of loads based on digital twins, virtual-real dynamic interactions, software-defined states, intelligent intervention operations, and other related technologies (Pierre, 1987).

5.2.2 Data-driven adaptive load regulation technology

Adaptive control technology is not new to power systems and has been applied in fields like generator excitation control and frequency control since the last century (Chen et al., 2020). With the development of IoT and the participation of various energy resources such as electricity, heat, cold, and natural gas in system control, further research is needed on applying adaptive control technology in integrated energy systems. This includes constructing control methods based on energy types and load endowments to tap into the potential of different energy forms of loads (Yin et al., 2019). Researching data-driven model-free adaptive control technology can achieve adaptive control of multi-input-output, nonlinear, and large time-delay energy types of load resources. Furthermore, considering the large scale of future load control resources, research on IoT-based distributed adaptive control of loads, edge computing, and other technologies is needed to reduce data communication requirements for large-scale load control, thereby enhancing network communication and load control reliability.

5.2.3 Enhancing system resilience with load regulation technology

In an IoT environment, the potential of load control can be explored in three stages: prevention, response, and recovery, to improve the system's adequacy to extreme events and the speed of recovery after events.

In the prevention stage, research on abnormal system monitoring, accident prediction, impact mechanisms, risk assessment, and load control strategies is needed to enhance the system's disaster warning capabilities. In the response stage, research on fine-grained identification of loads is necessary to identify critical loads and prioritize their power supply [126]. Additionally, research on optimizing the scheduling of loads such as electric vehicles can serve as temporary power sources to improve system adequacy. In the recovery stage, research on operating control strategies for black-start power sources on the load side is essential, along with load supply level recovery methods under limited monitoring data, to maximize system recovery speed, business production value, and user electricity experience.

6 Conclusion

Starting from the background of the high proportion of new energy power systems and the rapid development of the Internet of Things, this paper discusses the development opportunities and enormous potential of load control. This paper outlines the technical characteristics of load control under the IoT and studies the modeling methods of loads and methods for quantifying control capabilities. Based on this, this paper conducts an in-depth comparative analysis of control strategies for different load resources, exploring optimization methods for power system adjustment resources after load control. Considering the close relationship between load control implementation and market policies, this paper further studies the load control mechanisms in mature electricity markets abroad and immature electricity markets domestically. Finally, this paper analyzes the shortcomings of current load control technologies. It provides prospects for future research, including digital twin-based load modeling, data-driven load adaptive control, and load control technologies to enhance system resilience. This paper will provide valuable literature on the development and application of load regulation technologies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

QZ: Writing–original draft, Writing–review and editing. JW: Writing–original draft, Writing–review and editing. YY: Writing–original draft, Writing–review and editing.

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Conflict of interest

Authors QZ and YY were employed by Economy Research Institute of State Grid Zhejiang Electric Power Company, Hangzhou, China.

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