Communication Accessibility Oriented Deployment Strategy of Hybrid IoT Terminals for Dispatching Large-Scale Flexible Loads in Power Systems

Liya Ma, *Graduate Student Member, IEEE*, Hongxun Hui, *Senior Member, IEEE*, Peng Liu, and Yonghua Song, *Fellow, IEEE*

***Abstract*—The global power system transition highlights the potential contribution of flexible loads as regulation resources for addressing fluctuations from emerging renewable energies. To dispatch flexible loads accurately and instantly, the power systems impose higher requirements of communication accessibility on local access services in communication systems, i.e., massive terminal access, frequent interaction, and cost-efficient accessibility. Thus, to enhance communication accessibility, this paper proposes a bi-level optimization framework to deploy hybrid Internet of Things (IoT) terminals for dispatching large-scale flexible loads by load aggregators to provide regulation resources in power systems. The framework includes: 1) a deployment strategy of hybrid IoT terminals considering various communication performances; 2) a bi-level optimization model integrating the interaction between the power system regulation scheme and the communication system deployment strategy; 3) an iterative algorithm addressing communication demands of load aggregators and the communication performance of different IoT terminals. Moreover, the numerical results demonstrate the proposed strategy can provide effective communication accessibility and further improve local access services.**

***Index Terms*—Local access services, large-scale flexible loads, communication accessibility, communication performance, IoT terminals.**

I. Introduction

A. Motivation

THE GLOBAL power system is striving towards a rapid clean energy transition to advanced low emission power systems [1]. Renewable energy offers significant advantages by emitting minimal to no greenhouse gases in power systems transition [2]. Nevertheless, renewable energies may result in intermittent and fluctuating power output, particularly for wind turbine (WT) and photovoltaic (PV) generators. The daily fluctuations may exceed 500 GW in China in the coming decade, imposing substantial pressure on the power supply and load balance within power systems [3]. It thereby necessitates more regulation resources from both generators and large-scale flexible loads. Significantly, traditional generators provide limited regulation resources due to the diminishing penetration on the supply side. Thus, dispatching large-scale flexible loads by load aggregators (LAs) holds greater potential in contributing regulation resources in power systems [4].

Communication accessibility is the fundamental requirement of local access services for LAs to provide regulation resources [5]. Only when they establish communication accessibility, the LAs can upload the operational data to the power system operator (PWSO) and the PWSO can issue the dispatch signal to LAs [6]. In communication systems, from wireline to wireless technologies (e.g., power line communication (PLC) [7], micropower wireless (MPW) [8], and ZigBee [9]), hybrid Internet of Things (IoT) technologies have been widely applied by the communication system operator (CMSO) to dispatch large-scale flexible loads in power systems and practical industries [10]. The related research can be categorized into three aspects:

(i) The IoT Architecture for Managing Flexible Loads: There are various flexible loads in power systems. Efficiently managing these resources necessitates a hierarchical communication paradigm that encompasses diverse data processing stages, such as load units, load aggregators, and the system operator. Thus, the IoT architecture is essential for power systems of different scales. For instance, González et al. [11] establishes one IoT platform for the components in microgrids involved in hybrid auxiliary services, with a focus on end-users and stakeholders. Spanò et al. [12] and Viswanath et al. [13] design a larger-scale IoT system in power systems, to dispatch large-scale flexible loads through the integration of diverse wireless or wired protocols.

(ii) The IoT-Assisted Power System Operation: The IoT terminals are typically deployed at the load sides, such as buildings, homes, and consumers in parks. They possess communication, computation, and storage capabilities, which are vital for the operation of power systems. Thus, Ciavarella et al.

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Liya Ma, Hongxun Hui, and Yonghua Song are with the State Key Laboratory of Internet of Things for Smart City and the Department of Electrical and Computer Engineering, University of Macau, Macao, China, and also with the University of Macau Advanced Research Institute in Hengqin, Hengqin, Guangdong, China (e-mail: hongxunhui@um.edu.mo).

Peng Liu is with the Zhuhai Power Supply Bureau, Guangdong Power Grid Corporation, Zhuhai 519000, China.

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[14] utilize IoT's communication capability to dispatch power loads for contingency management in power systems. With computation capability adopted, Zhang et al. [15] applies some data-driven algorithm on IoT terminals to conduct edge computing. And Yu et al. [16] and Ma et al. [17] analyze the normal and abnormal situation in power systems using data from IoTs. The non-intrusive appliance monitoring method is implemented for flexible loads in smart homes in [16]. And the device fault is identified in [17] to develop an advanced repair strategy utilizing IoT-collected real-time data.

(iii) The IoT Accompanying Cyber Attacks: With the growing number of flexible loads in power systems, the IoT technologies have become an essential approach to ensure the accessibility of data related to flexible loads [17]. In the future power systems, the deployment of IoT terminals promotes a more open and flexible power and communication systems [18]. However, it results in much more threats for cybersecurity as the attacks can be launched on the IoT terminals, such as denial-of-service attacks [19]. Especially for dispatching large-scale loads and data-based services, the system is high vulnerable due to the increasing number of IoT terminals in [20] and more attacked data in [21], respectively. In this context, Chen et al. [22] investigates how to enhance the system redundancy to mitigate potential IoT accompanying latency attacks.

The existing research studies the application of IoT on flexible load control, as a supporting technical platform, a massive data source, and potential weak sections on cyber attacks. However, the above research gives the assumption that the IoT terminals have already been deployed for the power terminals. Actually, the continuous growth of flexible loads represents significant regulation resources to be dispatched in the power system. However, they do not have specific IoT terminals to provide communication, computation, and storage functions. Thus, it is very urgent to investigate the IoT deployment problem. The deployment of IoT terminals mainly confronts three challenges:

i) Massive Power and IoT Terminal Access: During the power system transition, large-scale flexible loads working as power terminals are involved in providing regulation resources. The involvement leads to significant communication accessibility demands [23]. Thus, extensive IoT terminals will be utilized to implement substantial measurement and control functions to fulfill communication accessibility.

ii) Frequent Interaction Between Terminals: The development of IoT technologies activates the participation of flexible loads in power systems [24]. During the dispatch process, LAs with large-scale flexible loads are expected to upload their local data and receive the regulation signal to and from the PWSO, respectively [25]. This signifies the frequent interaction between power terminals and IoT terminals.

iii) Cost-effective Communication Accessibility: For the local access services, the IoT terminals exhibit varying communication performances, leading to diverse deployment costs [26]. Indiscriminate investments in massive IoT terminals are cost enormous for dispatching large-scale flexible loads by LAs. Cost-effective terminal accessibility is a pressing requirement for local access services in communication systems.

B. Literature Review

The current research is increasingly acknowledging the significance of communication accessibility for LAs. Zhang et al. [27] explore the planning strategy of wireless IoT terminals for effective communication accessibility in power systems. Also, emphasizing wireless IoT terminals, Feng et al. [28] propose a smart power system incorporating an optimal combination of Wi-Fi and Cellular networks. Devidas and Ramesh [29] additionally explore the integration within ZigBee. Wireline communications are also utilized for local access services [30]. The PLC is the primary technology of wireline IoT terminals to achieve communication accessibility for flexible loads, particularly for residential and utility purposes [7], [31]. Specifically, Liu et al. [32] investigate the PLC access systems in European power systems. However, the research work solely focuses on the application of either wireline or wireless IoT terminals. They neglect the potential benefits of hybrid IoT terminals that combine both wireline and wireless technologies, which could enhance the performance of local access services to dispatch flexible loads [33].

Not only are IoT terminals essential for the communication accessibility of LAs, but LAs' regulation strategies also impact the deployment of IoT terminals. It highlights the significance of the interaction between communication and power systems [34], while the current research on local access services is restricted to the pure communication domain. Xu and Wang [35] establish the wireless access and relay network in power systems. Mesh routers and clients are deployed for communication accessibility. However, the communication performance, such as data transmission rate (DTR) and data traffic, is determined without considering the actual communication demands from the PWSO. The deployment of IoT terminals is further investigated in [29] and [36]. In [29], the combination of IoT terminals is constrained by factors such as data latency. In [36], the impact of power networks is reduced to the power pricing model, resulting in the allocation of communication resources in cellular networks. Consequently, these studies fail to account for the impact of the power dispatch strategy on communication accessibility in communication systems.

C. Contributions

To the best of our knowledge, how to deploy hybrid IoT terminals for local access services to dispatch large-scale flexible loads by LAs has not been investigated in power systems. Thus, we propose an optimal deployment strategy of hybrid IoT terminals in power systems. On one hand, we employ diverse communication performance of hybrid IoT terminals for enhanced communication accessibility to dispatch large-scale flexible loads by LAs. On the other hand, the impacts of LAs' regulation strategies are established as communication demands for the deployment strategy of hybrid IoT terminals.

The contributions are illustrated as follows:

1) A deployment strategy of hybrid IoT terminals is developed to provide communication accessibility for LAs with large-scale flexible loads in power systems. Different LAs

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have distinct communication demands influenced by regulation power. According to these demands, this strategy can effectively deploy the quantity and types of IoT terminals to ensure adequate communication performance, i.e., transmission rate, latency, and traffic.

2) A bi-level optimization model is formulated for the interaction of power and communication systems. In the upper-level model, the PWSO acquires the dispatch strategy of LAs and generates communication demands. In the lower-level model, according to the communication demands, the CMSO deploys the hybrid IoT terminals to facilitate communication accessibility of local access services. A percentile-based scenario extraction approach is adopted to streamline the communication demands across multiple dispatch strategies and deliver the expected communication demands.

3) An iterative algorithm is utilized to address the bi-level optimization problem by balancing the power communication demands and communication service performance. Furthermore, the deployment problem for hybrid IoT terminals in the lower-level model is formulated as a mixed integer nonlinear programming (MINLP) problem. The MINLP problem comprises various integer variables, products of integer variables, and bilinear terms. This paper reformulates the MINLP problem into tractable forms employed in off-the-shelf solvers.

The rest of the paper is organized as follows. Section II formulates the deployment strategy of hybrid IoT terminals to dispatch large-scale flexible loads. Section III establishes the communication accessibility-impacted dispatch strategy for large-scale flexible loads in power systems. Section IV develops the bi-level optimization problem, transforms the MINLP problem into tractable forms, and establishes the iterative algorithm. Section V validates the effectiveness and performance of the proposed method in IEEE 33-bus and 123-bus systems. Section VI concludes this paper.

II. Problem Architecture

In the problem architecture shown in Fig. 1, there are two entities in the power and communication systems, namely the PWSO and the CMSO. In the power system, the PWSO dispatches the regulation resources from LAs with large-scale flexible loads to maintain the power balance between power sources and load consumption, while the dispatch process depends on the communication services. Thus, in the communication system, the CMSO implements the deployment strategy of hybrid IoTs for LAs with large-scale flexible loads. By deploying IoT terminals, the CMSO can offer local access services for the dispatch strategy of the PWSO.

The relationship among IoT terminals, flexible loads, LAs, CMSO, and PWSO is further illustrated in Fig. 2. The central part describes the data communication process for dispatching regulation resources. For uplink transmission, first, LAs' operational data is collected by IoT terminals. And then, the data is transmitted to PWSO by the communication networks charged by the CMSO. The data is ultimately received by the PWSO. For downlink transmission, the PWSO issues the dispatch signals by the communication services of the CMSO. The data is received by IoT terminals and finally issued to the LAs. The red line highlights the bidirectional data transmission between the PWSO and IoT, the dispatch strategy can be well conducted. The blue line highlights the dispatch-related entities, i.e., the PWSO and LAs. We can see that the CMSO is positioned between LAs and the PWSO. It serves as an operator providing communication services for data transmission between LAs and the PWSO to dispatch large-scale flexible loads.

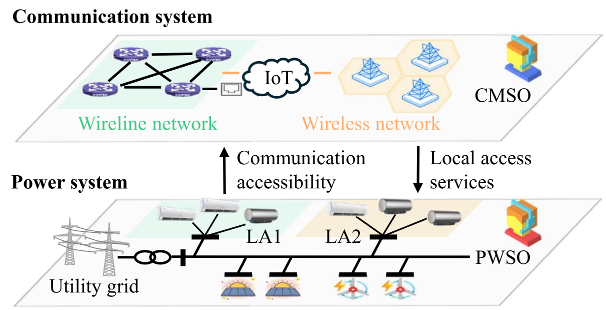

Fig. 1. IoT-based communication accessibility of large-scale flexible loads in power and communication systems.

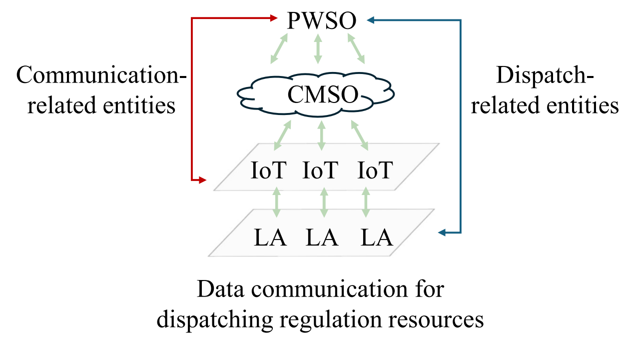

Fig. 2. The architecture among IoT, LAs, the CMSO, and the PWSO.

To further justify the collaboration among the PWSO, the CMSO, and the LAs, we give an example based on the incentive mechanism of Guangdong Power Grid Corporation in China. In Guangdong, China, there are two major entities in power and communication systems. One is the Guangdong Power Grid Corporation acting as the PWSO, responsible for the dispatch of power systems. The other is Guangdong Information and Technology Co., Ltd, serving as the CMSO, responsible for the planning and operation business of the power communication system.

Why does the Guangdong Power Grid Corporation develop an independent company for the power communication system and further establish the incentive mechanism between the PWSO and the CMSO? The Corporation initially has some construction projects to enhance the communication systems for the communication accessibility of power systems. The projects are supposed to be carried out by all the power supply bureaus of the Corporation. But, in realistic situations, these bureaus perceive it as a significant investment. They believe that investing in communication systems would result in a prolonged period before experiencing any enhancement in the power systems. On the contrary, if they channel the investment directly into power systems, such as upgrading

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the power equipment, they can achieve immediate and more direct improvements in the power systems. Thus, these bureaus tend to allocate the investment towards enhancing power devices. This completely contradicts the investment intention of the Guangdong Power Grid Corporation and even their stakeholder, the China Southern Power Grid.

To solve the problem, the Guangdong Power Grid Corporation establishes the Guangdong Information and Technology Co., Ltd to specialize in the power communication business, including the construction and operation of power communication systems [37]. This mechanism effectively solves the above problems. On one hand, the substantial investment is shouldered by the Guangdong Information and Technology Co., Ltd instead of the power supply bureaus. The power supply bureaus thereby can pay much less money to obtain the improved communication services without bearing the burden of significant investment. On the other hand, the communication system business is entrusted to the specific entity, i.e., the Guangdong Information and Technology Co., Ltd, to ensure the security of property and communication service requirements. The Guangdong Information and Technology Co., Ltd generates profits by offering communication services to various power entities, such as LAs, operators, and the bureaus, leveraging its ownership of communication network assets.

To sum up, the above business for power and communication systems in Guangdong, China provides a realistic incentive mechanism. In this work, we utilize the PWSO, the CMSO, and the LAs rather than the above specific company names to illustrate a general framework.

It should be noted that data privacy for any entities is important. There are critical data management rules governing the data communication process (encompassing collection, transmission, reception, and analysis) concerning the PWSO and CMSO. These rules stipulate that the data is forbidden to transfer to any third party other than the PWSO and the CMSO. By this way, the affiliated entities will take their responsibility to prevent the disclosure of users' sensitive information [38]. Under circumstances where legal obligations and responsibilities necessitate, the PWSO and CMSO are permitted to share essential data with governmental bodies and other third parties. And the rules are supposed to be determined and improved collaboratively by both the PWSO and CMSO. Besides, the data from the IoT terminals is transmitted based on effective and safe encrypted data transmission technologies, such as differential privacy-based approaches [39].

III. The Deployment Strategy of Hybrid IoT Terminals to Dispatch Large-Scale Flexible Loads

This section develops a deployment strategy of hybrid IoT terminals. The various communication performances of hybrid IoT terminals are optimally employed by considering the diverse communication demands of LAs. In the objective function, the costs of deploying hybrid IoT terminals and the income from local access services are defined as the components of the CMSO's net income.

A. Objective Function

The objective function of the CMSO is to maximize the net income, which can be formulated into:

$$\max \quad \mathcal{Q}^{\mathrm{CMSO}} = \mathcal{Q}^{\mathrm{dpm}} + \mathcal{Q}^{\mathrm{dtc}} - \mathcal{C}^{\mathrm{eai}} - \mathcal{C}^{\mathrm{m}}, \tag{1}$$

where $\mathcal{Q}^{\mathrm{dpm}}$ and $\mathcal{Q}^{\mathrm{dtc}}$ represent the income from communication performance and data traffic, respectively. The variables $\mathcal{C}^{\mathrm{eai}}$ and $\mathcal{C}^{\mathrm{m}}$ represent the equivalent average capital costs and annual maintenance costs, respectively.

1) IoT Terminal Deployment Costs:

a) Average capital costs: To deploy hybrid IoT terminals, the CMSO covers the capital costs. The expense can be converted over the regulation periods throughout the entire life period of IoT terminals [40]. There are K IoT types considered by the CMSO. The equivalent average capital expenditure is formulated as:

$$\mathcal{C}^{\mathrm{eai}} = \frac{r(1+r)^{Y}}{(1+r)^{Y}-1}\sum_{k\in\mathcal{K}}\mathcal{C}_k, \tag{2}$$

where r and Y denote the discount rate and expected utilization lifetime of the deployed IoT terminals, respectively. The symbols k and $\mathcal{K}$ denote the index and set of IoT types, respectively. The variable $\mathcal{C}_k$ denotes the capital costs of IoT type k terminals.

b) Annual maintenance costs: Each year, there are necessary maintenance costs for these IoT terminals [41]:

$$\mathcal{C}^{\mathrm{m}} = \sum_{k\in\mathcal{K}}\alpha\mathcal{C}_k, \tag{3}$$

where α denotes the maintenance cost coefficient.

2) Local Access Service Income: The communication service in power communication systems comprises the local access service and the remote communication service. As shown in Fig. 3, the local access service enables bidirectional communication between the power terminals and the gateways by deploying necessary IoT terminals for flexible loads. The remote communication service enables bidirectional communication between the gateways and the PWSO using fiber networks, wireless public networks, wireless private networks, and other means. It is clear that the deployment of IoT terminals plays a crucial role as the fundamental infrastructure, as the data must be gathered by IoT terminals before being sent to remote communication networks. And the local access service plays a pivotal role in the logistical foundation of remote communication services, as it ensures data accessibility. In this work, we investigate the communication performance of local access services provided by IoT terminals, including the DTR, transmission latency, and data traffic from flexible loads.

a) Charging for communication performance: Inspired by the pricing scheme in wireless networks [42], when the DTR is lower, the communication charge will decrease with the increasing DTR. It benefits the CMSO by stimulating communication demands. However, for the higher DTRs, the communication charge will increase as the DTR increases to reduce the operation costs.

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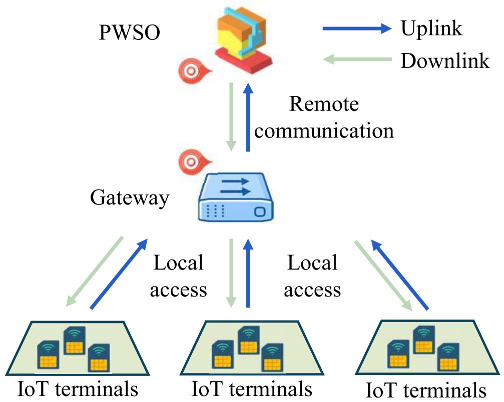

Fig. 3. The structure of the communication service in power systems.

In this paper, we introduce similar charge functions to the CMSO. The CMSO decreases the data transmission costs for LA units, to inspire more communication demands, while increasing the income when the transmission rate exceeds some conditions. The relationship can be defined as a quadratic function, satisfying $f(v^*)' = 0, v^* > 0, f(v^*)'' > 0$. Specifically, the income of the total communication performance is calculated by:

$$\mathcal{Q}^{\mathrm{dpm}} = D \cdot T \cdot \sum_{i\in\mathcal{I}} [a(v_i)^2 - bv_i + c] - \sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}} (\varpi_i^{\mathrm{u}}\tau_{i,t,d}^{\mathrm{u}} + \varpi_i^{\mathrm{d}}\tau_{i,t,d}^{\mathrm{d}}), \tag{4}$$

where D and T denote the 365 days and 24 periods, respectively, indicating all the utilization periods of IoT terminals in a year. The variable v_i is the total DTR of LA i after deploying hybrid IoT terminals. The parameters a, b, and c are cost coefficients. The variables $\tau_{i,t,d}^{\mathrm{u}}$ and $\tau_{i,t,d}^{\mathrm{d}}$ are the uplink and downlink transmission latency, respectively. The parameters ϖ_i^{u} and ϖ_i^{u} are the latency penalty coefficients for uplink and downlink, respectively. Since the lower DTR has a larger income but does not demonstrate lower latency compared to a higher DTR, the second part of the income serves as the penalty for high latency. The symbols d, t, and i denote the index of days, periods in a day, and LAs. The symbols $\mathcal{D}$, $\mathcal{T}$, and $\mathcal{I}$ are corresponding sets, respectively. It should be noted that we consider the charging for DTR is always exist for every period since it is purely related to the IoT terminal deployment.

b) Charging for data traffic: The CMSO also charges for the data traffic, both operational data transmitted via uplink and control signal data transmitted via downlink. The charging scheme is established by:

$$\mathcal{Q}^{\mathrm{dtc}} = \sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}} (\lambda_i^{\mathrm{u}}\kappa^{\mathrm{u}}\Delta P_{i,t,d}^{\mathrm{l}}/\varrho_i + \lambda_i^{\mathrm{d}}\kappa^{\mathrm{d}}\Delta P_{i,t,d}^{\mathrm{l}}/\varrho_i), \tag{5}$$

where λ_i^{u} and λ_i^{d} are traffic unit prices of uplink data and downlink data, respectively. The symbols κ^{u} and κ^{d} denote the unit data traffic of one flexible load unit via uplink and downlink, respectively. The variable $\Delta P_{i,t,d}^{\mathrm{l}}$ denotes the regulation power of LA i. The parameter ϱ_i indicates the average regulation power of one flexible load unit by one LA.

B. Allocation Constraints of IoT Terminals

1) Communication Demand Constraints: In power systems, the PWSO dispatches large-scale flexible loads by LAs. The dispatch strategy is represented by $\Delta \boldsymbol{P}_{t,d}^{*} = [\Delta P_{1,t,d}^{\mathrm{l}}, \ldots, \Delta P_{i,t,d}^{\mathrm{l}}, \ldots, \Delta P_{I,t,d}^{\mathrm{l}}]$. The LAs propose various communication demands for local access services. To be specific, the communication demands of large-scale flexible loads indicate the specific requirements of local data transmission and reception when they are dispatched to provide regulation resources by the PWSO. These requirements include i) the physical constraints of IoT technology access (wired IoTs are not suitable for movable types of LAs [43]); ii) the limitations of the DTR; iii) the constraints on the transmission latency in response to the dispatch strategy; iv) communication protocols based on DL/T 698.45, providing the standardized information model. Satisfying these demands, the CMSO then deploys the hybrid IoT terminals for LAs to dispatch large-scale flexible loads, providing regulation resources. Thus, the IoT terminals should satisfy the following constraints.

a) Hybrid IoT types: There are K types of IoT terminals deployed for LAs in the power systems. Different types of IoTs affect the communication DTR, latency, and costs. Consider that each LA supports multiple types of IoTs and all the flexible loads within the same LA share the IoT terminals. We define the integer variable $\chi_{i,k} \in \mathbb{N}$ to indicate the quantity of IoT type k terminals deployed to the LA i. The set $\mathbb{N}$ encompasses nonnegative integers.

b) DTRs of diverse LAs: The data transmission process between the PWSO and LAs is essential. Initially, LA i uploads its operating status data to the PWSO using the IoT terminals as a DTR of v_i. Subsequently, following the dispatch strategy, the PWSO issues the control signals to LA i with the same DTR. The DTR for uplink and downlink is considered to be uniform, expressed as follows:

$$v_i = \sum_{k\in\mathcal{K}} \chi_{i,k} b_k \cdot \mathrm{lb}(1 + \frac{\sum_{k\in\mathcal{K}} \chi_{i,k} P_k}{M_i + N_0}), \tag{6}$$

where b_k represents the bandwidth of the communication channel when the LA i is deployed with IoT type k. The parameter P_k represents the transmission power of the communication channels. The parameter N_0 denotes the noise power of the communication channel. The parameter M_i represents the electromagnetic interference power when electric devices work [44]. It should be noted that the LA i's DTR doesn't vary with periods or days since it is determined by the terminals.

Besides, the DTR is limited by the requirements of the PWSO, derived by:

$$v_i \ \geq v_i^{-}, \tag{7}$$

where v_i^{-} is the least value based on the requirement of the PWSO. For example, according to the standard GB/T 15148-2024 of China, Technical specifications for power load management system, the DTR is not allowed to be equal or less than 2400 bps.

c) Transmission latency: As shown in Fig. 3, the transmission latency consists of the uplink latency $\tau_{i,t,d}^{\mathrm{u}}$ and

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downlink latency $\tau^{\mathrm{d}}_{i,t,d}$. The uplink latency indicates the transmission time consumed for uplink data transmission from data generation from the IoT terminals to data received by PWSO, forwarded through the gateways. The downlink latency indicates the transmission time consumed for downlink data transmission from the PWSO to the IoT terminals, forwarded through the gateways.

They can be expressed by, respectively:

$$\tau^{\mathrm{u}}_{i,t,d} = \tau^{\mathrm{u,l}}_{i,t,d} + \tau^{\mathrm{u,r}}_{i,t,d},\ \ \tau^{\mathrm{d}}_{i,t,d} = \tau^{\mathrm{d,l}}_{i,t,d} + \tau^{\mathrm{d,r}}_{i,t,d}, \tag{8}$$

where the superscript l and r represent the latency for the data transmission between IoT terminals and the gateway and between the gateway and the PWSO, respectively.

For the data transmission between IoT terminals and the gateway, the latency should satisfy:

$$\Gamma^{\mathrm{u}}_{i,t,d} = \tau^{\mathrm{u,l}}_{i,t,d} v_i,\ \ \Gamma^{\mathrm{d}}_{i,t,d} = \tau^{\mathrm{d,l}}_{i,t,d} v_i, \tag{9}$$

where $\Gamma^{\mathrm{u,l}}_{i,t,d}$ and $\Gamma^{\mathrm{d,l}}_{i,t,d}$ represent the data traffic uploaded by LA i and issued by the PWSO, respectively. And v_i indicates the DTR of the communication link from LA i to the gateway. Based on the simplified model in [45], we derive the data traffic:

$$\begin{aligned} \Gamma^{\mathrm{u}}_{i,t,d} &= \kappa^{\mathrm{u}} \Delta P^{\mathrm{l}}_{i,t,d} / \varrho_i + r^{\mathrm{u}}, \\ \Gamma^{\mathrm{d}}_{i,t,d} &= \kappa^{\mathrm{d}} \Delta P^{\mathrm{l}}_{i,t,d} / \varrho_i + r^{\mathrm{d}}, \end{aligned} \tag{10}$$

For the data transmission between the gateway and the PWSO, the latency should satisfy:

$$\Gamma^{\mathrm{u}}_{i,t,d} = \tau^{\mathrm{u,r}}_{i,t,d} v^{\mathrm{f}},\ \ \Gamma^{\mathrm{d}}_{i,t,d} = \tau^{\mathrm{d,r}}_{i,t,d} v^{\mathrm{f}}, \tag{11}$$

where v^{f} indicates the transmission rate of the communication link. This work considers the communication network between the gateway and the PWSO as the fiber network. Thus, the transmission latency $\tau^{\mathrm{u,r}}_{i,t,d}$ and $\tau^{\mathrm{d,r}}_{i,t,d}$ can be neglected due to the high DTR of fiber. Thus, Eq. (8) is derived by

$$\tau^{\mathrm{u}}_{i,t,d} \approx \tau^{\mathrm{u,l}}_{i,t,d},\ \ \tau^{\mathrm{d}}_{i,t,d} \approx \tau^{\mathrm{d,l}}_{i,t,d}. \tag{12}$$

Thus, the total transmission latency can be limited by:

$$\tau^{\mathrm{u}}_{i,t,d} + \tau^{\mathrm{d}}_{i,t,d} \le T^{\mathrm{la}}, \tag{13}$$

where T^{la} is the data latency limit by the CMSO, which refers to the standard "Technical specifications for power load management system" (GB/T 15148-2024) of China [46].

d) Communication protocols: According to the standard GB/T 15148-2024 of China, Technical specifications for power load management system [46], both the uplink and downlink transmission are suggested to follow the requirements of the standard DL/T 698.45 [47].

2) Deployment Constraints:

a) Coupling relationship between IoTs types and LAs: Generally, the types of hybrid IoT terminals for local access services are divided into two types, i.e., wireline and wireless, as follows:

$$\mathcal{K} = \mathcal{K}^{\mathrm{e}} \cup \mathcal{K}^{\mathrm{s}},\ \forall k \in \mathcal{K},\ e \in \mathcal{K}^{\mathrm{e}},\ s \in \mathcal{K}^{\mathrm{s}}, \tag{14}$$

where $\mathcal{K}^{\mathrm{e}}$ and $\mathcal{K}^{\mathrm{s}}$ are the sets of wireline and wireless IoT types, respectively. The indexes e and s satisfy $e = \{1, \ldots, K^{\mathrm{e}}\}, s = \{K^{\mathrm{e}} + 1, \ldots, K^{\mathrm{e}} + K^{\mathrm{s}}\}$. The symbols K^{e} and K^{s} are the numbers of wireline and wireless IoT types, respectively.

Thus, we further specify binary variables u^{e}_i and u^{s}_i to indicate that the LA i is deployed with wireline or wireless IoTs, respectively, satisfying:

$$u^{\mathrm{e}}_i \cdot u^{\mathrm{s}}_i = 0,\ u^{\mathrm{e}}_i + u^{\mathrm{s}}_i = 0,\ u^{\mathrm{e}}_i, u^{\mathrm{s}}_i \in \mathbb{B}, \tag{15}$$

where the set $\mathbb{B}$ encompasses binary integers.

$$\begin{cases} u^{\mathrm{e}}_i = 1, & \text{if } \exists \chi_{i,e} > 0,\ \forall e \in \mathcal{K}^{\mathrm{e}}, \\ u^{\mathrm{s}}_i = 1, & \text{if } \exists \chi_{i,s} > 0,\ \forall s \in \mathcal{K}^{\mathrm{s}}. \end{cases} \tag{16}$$

The CMSO offers wireline and wireless IoT technologies in communication systems, while there are various large-scale flexible loads by LAs in the power systems. It is complicated to study the allocation of different types of IoT terminals for each type of flexible load. Thus, according to the movability characteristics-based model [48], we categorize LAs with large-scale flexible loads as either movable or immovable loads. These categories are denoted as ρ^{ml}_i for movable loads and ρ^{iml}_i for immovable loads, respectively. For example, on the one hand, movable loads indicates electric vehicles and other mobile loads. On the other hand, immovable loads encompass devices like air conditioners, energy storage, and others. Thus, the external characteristics of LAs can be represented by:

$$\rho^{\mathrm{ml}}_i + \rho^{\mathrm{iml}}_i = 1,\ \rho^{\mathrm{ml}}_i \cdot \rho^{\mathrm{iml}}_i = 0,\ \rho^{\mathrm{ml}}_i, \rho^{\mathrm{iml}}_i \in \mathbb{B}. \tag{17}$$

We assume that the external characteristics (i.e., movable or immovable abilities) of each LA remain constant within one regulation period.

For the CMSO, the different types of wired and wireless IoTs affect the deployment of IoTs, taking into account the movability characteristics of diverse flexible loads. In contrast to wired IoT technologies, the wireless IoT technologies are supposed to be a feasible way for movable flexible loads, such as electric vehicles and loads where the wire is hard to access [43]. Thus, the relationship between IoT types and LAs can be expressed by:

$$u^{\mathrm{e}}_i = 0,\quad \text{if } \rho^{\mathrm{ml}}_i = 1. \tag{18}$$

b) Connectivity constraints for IoT terminals: There are multiple types of IoT terminals available for local access services. The quantity of various IoT terminals denoted by N^{m}_k is calculated as follows:

$$N^{\mathrm{m}}_k = \sum_{i \in \mathcal{I}} \chi_{i,k}. \tag{19}$$

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For the IoT terminals with connectivity constraints, the controller needs to be installed for the terminals. The connectivity is limited by:

$$N_k^{\mathrm{c}} = \lceil N_k^{\mathrm{m}} / \varsigma^{\mathrm{c}} \rceil, \tag{20}$$

where the function symbol $f\lceil x \rceil$ denotes the smallest integer greater than or equal to x. The parameter ς^{c} denotes the maximum quantity of connected terminals for IoT type k.

c) Operational reliability constraints for IoT terminals: For the operation of IoT terminals, they may fail to work as some possibility. Thus, we adopt the simplified N-1 principle for terminals in communication systems. The CMSO deploys the backup terminals for each IoT to provide high-reliability communication accessibility. Thus, the terminal number should be:

$$\begin{aligned} N_k^{\mathrm{or,m}} &= nN_k^{\mathrm{m}}, \\ N_k^{\mathrm{or,c}} &= nN_k^{\mathrm{c}}, \end{aligned} \tag{21}$$

where the parameter n indicates the "N-1" principle for IoT terminals in communication systems. The CMSO deploys $n-1$ backup terminals for each IoT terminal. This work considers one backup terminal for one primary terminal.

The capital costs of IoT type k terminals are expressed by:

$$\mathcal{C}_{\mathrm{k}} = c_k^{\mathrm{m}} N_k^{\mathrm{or,m}} + c_k^{\mathrm{c}} N_k^{\mathrm{or,c}}, \tag{22}$$

where c_k^{m} and c_k^{c} denote unit costs of terminals and controllers, respectively.

IV. Communication Accessibility-Impacted Dispatch Strategy for Regulation Power

A. Objective Function

The objective of the PWSO's dispatch strategy is to minimize the total value of electricity costs and local access service costs in the power systems, which can be formulated into:

$$\min \quad \mathcal{C}^{\mathrm{PWSO}} = \mathcal{C}^{\mathrm{ao}} + \mathcal{C}^{\mathrm{dcs}}, \tag{23}$$

where $\mathcal{C}^{\mathrm{ao}}$ and $\mathcal{C}^{\mathrm{dcs}}$ represent the annual electricity costs and local access service costs, respectively.

1) Electricity Costs: Consider the operational costs of power systems over a year within 365 days. The PWSO dispatches the generation power from the utility grid and distributed energy resource generators. Also, the PWSO dispatches large-scale flexible loads by LAs to provide regulation resources. Thus, the annual electricity cost of the PWSO is calculated as follows:

$$\begin{aligned} \mathcal{C}^{\mathrm{ao}} = &\sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}}\{\sum_{g\in\mathcal{G}}[a^{\mathrm{g}}(P_{g,t,d}^{\mathrm{g}})^2 + b^{\mathrm{g}}P_{g,t,d}^{\mathrm{g}} + c^{\mathrm{g}}] \\ &+ \sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}}(p_{t,d}\Delta P_{i,t,d}^{\mathrm{l}}), \end{aligned} \tag{24}$$

where $P_{g,t,d}^{\mathrm{g}}$ denotes the generation power from generators. The parameter $p_{t,d}$ represents the unit price of regulation resources. The parameters a^{g}, b^{g}, and c^{g} are the cost coefficients. The symbol $\mathcal{G}$ is the set of generators.

2) Local Access Service Costs: Dispatching regulation resources from LAs generates data communication demands. Naturally, the PWSO shall pay for local access services as $\mathcal{C}^{\mathrm{dcs}}$.

$$\mathcal{C}^{\mathrm{dcs}} = \mathcal{Q}^{\mathrm{dtc}} + \mathcal{Q}^{\mathrm{dpm}}, \tag{25}$$

where the detailed local access service costs (i.e., data traffic costs and performance costs) are the negative of the detailed income of local access services for the CMSO in Eqs. (4)-(5).

B. Dispatch Constraints of Generators and LAs

1) Communication Accessibility-Impacted Regulation Constraints: The communication accessibility suggests that with the deployment of IoT terminals, the LA i can be dispatched. However, it can not be dispatched in the absence of deployed terminals. The communication accessibility indicator is expressed by:

$$CA_{i,t,d} = \begin{cases} 1, & \text{if } v_i \neq 0 \\ 0, & \text{if } v_i = 0 \end{cases}, \ \forall i \in \mathcal{I}. \tag{26}$$

The regulation power $\Delta P_{i,t,d}^{\mathrm{l}}$ of LA i is derived by:

$$\Delta P_{i,t,d}^{\mathrm{l}} = \begin{cases} P_{i,t,d}^{\mathrm{l,o}} - P_{i,t,d}^{\mathrm{l,a}}, & \text{if } CA_{i,t,d} = 1 \\ 0, & \text{if } CA_{i,t,d} = 0 \end{cases}, \tag{27}$$

where $P_{i,t,d}^{\mathrm{l,o}}$ and $P_{i,t,d}^{\mathrm{l,a}}$ are the scheduled load power and dispatched power of LA i, respectively.

Moreover, the LAs are expected to adhere to the following constraints:

$$\Delta P_{i,t,d}^{\mathrm{l,-}} \leq \Delta P_{i,t,d}^{\mathrm{l}} \leq \Delta P_{i,t,d}^{\mathrm{l,+}}, \tag{28a}$$

$$P_{i,t,d}^{\mathrm{l,-}} \leq P_{i,t,d}^{\mathrm{l,a}} \leq P_{i,t,d}^{\mathrm{l,+}}, \ Q_{i,t,d}^{\mathrm{l,-}} \leq Q_{i,t,d}^{\mathrm{l,a}} \leq Q_{i,t,d}^{\mathrm{l,+}}, \tag{28b}$$

$$Q_{i,t,d}^{\mathrm{l,a}} = P_{i,t,d}^{\mathrm{l,a}} \tan\arccos\phi_i^{\mathrm{l}}, \tag{28c}$$

where ϕ_i^{l} denotes the power factor of LA i. The subscripts $-$ and $+$ indicate the lower and upper limits of the variables, respectively.

2) Power Constraints for Generators: The generators should satisfy the generation power limitations, derived by:

$$P_{g,t,d}^{\mathrm{g,-}} \leq P_{g,t,d}^{\mathrm{g}} \leq P_{g,t,d}^{\mathrm{g,+}}, \ Q_{g,t,d}^{\mathrm{g,-}} \leq Q_{g,t,d}^{\mathrm{g}} \leq Q_{g,t,d}^{\mathrm{g,+}}, \tag{29a}$$

$$Q_{g,t,d}^{\mathrm{g}} = P_{g,t,d}^{\mathrm{g}} \tan\arccos\phi_g^{\mathrm{g}}, \tag{29b}$$

where ϕ_g^{g} denotes the power factor of generator g.

3) Uncertainties From WTs and PVs: The chance constraint is employed to consider the uncertainties from WT and PV generators in power systems [49], as follows.

$$Pr\{P_g^{\mathrm{w}} \leq P_g^{\mathrm{w,f}}\} \geq 1 - \varepsilon^{\mathrm{w}}, \ \forall g \in \mathcal{W}, \tag{30}$$

$$Pr\{P_g^{\mathrm{pv}} \leq P_g^{\mathrm{pv,f}}\} \geq 1 - \varepsilon^{\mathrm{pv}}, \ \forall g \in \mathcal{S}, \tag{31}$$

where P_g^{w} and P_g^{pv} indicate the generation power of WTs and PVs, respectively. The parameters $P_g^{\mathrm{w,f}}$ and $P_g^{\mathrm{pv,f}}$ are the forecast power of WT and PV generators, respectively. The symbols ε^{w} and $\varepsilon^{\mathrm{pv}}$ are the risk that the generation power exceeds the forecast power of WTs and PVs, respectively. The sets $\mathcal{W}$ and $\mathcal{S}$ include the WT and PV generators, respectively.

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The tractable formulation of Eq. (31) is derived by

$$P_g^{\mathrm{w}} \le P_g^{\mathrm{w,f}} - \varphi^{-1}(\varepsilon^{\mathrm{w}})\delta^{\mathrm{w}},\ \forall g \in \mathcal{W}, \quad (32)$$

$$P_g^{\mathrm{pv}} \le P_g^{\mathrm{pv,f}} - \phi^{-1}(\varepsilon^{\mathrm{pv}})\delta^{\mathrm{pv}},\ \forall g \in \mathcal{S}, \quad (33)$$

where the bias between generation power and forecast power of WT and PV generators follows normal distribution $\varphi(\mu^{\mathrm{w}}, (\delta^{\mathrm{w}})^2)$ and $\phi(\mu^{\mathrm{pv}}, (\delta^{\mathrm{pv}})^2)$. The mean is zero and the symbols δ^{w} and δ^{pv} are the standard deviations of WT and PV generation power, respectively.

4) Power Balance Constraints for Electricity Buses: The nodal power balance of each bus should be constrained by:

$$P_{m,t,d}^{\mathrm{g}} - P_{m,t,d}^{\mathrm{l,a}} - \sum\nolimits_{b\in\mathcal{B}_m} P_b^{\mathrm{br}} = 0,\ \forall m \in \mathcal{M},$$
$$Q_{m,t,d}^{\mathrm{g}} - Q_{m,t,d}^{\mathrm{l,a}} - \sum\nolimits_{b\in\mathcal{B}_m} Q_b^{\mathrm{br}} = 0,\ \forall m \in \mathcal{M}. \quad (34)$$

where the symbols P_b^{br} and Q_b^{br} are the active and reactive power flow of branch b, respectively. The set $\mathcal{B}_m$ includes all the branches directly connected to bus m. The symbol $\mathcal{M}$ is the set of electricity buses.

5) Power Flow Constraints: The power flow model is simplified by employing a decoupled linearized approach in [50], as derived by:

$$P_b = g_{mn}(U_{m,t,d} - U_{n,t,d}) - b_{mn}(\theta_{m,t,d} - \theta_{n,t,d}),$$
$$Q_b = -b_{mn}(U_{m,t,d} - U_{n,t,d}) - g_{mn}(\theta_{m,t,d} - \theta_{n,t,d}), \quad (35)$$

where g_{mn} and b_{mn} denote the real and imaginary part of the admittance of branch b from bus m to bus n, and they satisfy $g_{mn} = r_{mn}/(r_{mn}^2 + x_{mn}^2)$ and $b_{mn} = -x_{mn}/(r_{mn}^2 + x_{mn}^2)$, respectively. The bus n is the index of $\mathcal{B}_m$. The variables $U_{m,t,d}$, $\theta_{m,t,d}$, $U_{n,t,d}$, and $\theta_{n,t,d}$ are the bus m's and n's voltages magnitudes and angles, respectively, satisfying:

$$U_{m,t,d}^- \le U_{m,t,d} \le U_{m,t,d}^+,\ \ \theta_{m,t,d}^- \le \theta_{m,t,d} \le \theta_{m,t,d}^+. \quad (36)$$

All the power flow across the power branches should satisfy the transmission capacity of transmission lines in the power systems, as illustrated by:

$$P_b^{\mathrm{br,-}} \le P_b \le P_b^{\mathrm{br,+}},\ \ Q_b^{\mathrm{br,-}} \le Q_b \le Q_b^{\mathrm{br,+}}. \quad (37)$$

C. Percentile-Based Scenario Extraction

After formulating the optimization model for dispatching large-scale flexible loads in power systems, the PWSO establishes LAs' dispatch strategy to provide regulation resources in one year, as derived by:

$$\mathcal{O} = \{\Delta \boldsymbol{P}_{t,d},\ \forall t \in \mathcal{T},\ \forall d \in \mathcal{D}\}. \quad (38)$$

where the strategy for each period is represented by $1 \times I$ vector of $\Delta \boldsymbol{P}_{t,d} = [\Delta P_{1,t,d}^{\mathrm{l}}, \ldots, \Delta P_{i,t,d}^{\mathrm{l}}, \ldots, \Delta P_{I,t,d}^{\mathrm{l}}]$.

The total regulation capacity satisfies $\Delta P_{t,d} = \sum_{i\in\mathcal{I}} \Delta P_{i,t,d}$, establishing the percentile distribution. Then, to satisfy the communication demands in power systems, the PWSO extracts the percentile-based scenario of regulation strategies. It selects the regulation strategy $\Delta \boldsymbol{P}_{t,d}$ where the regulation power $\Delta P_{\varrho\%}$ exceeds that of other $\varrho\%$ situations in a year, as determined by:

$$\Delta \boldsymbol{P}_{t,d}^* = \arg \min_{\Delta \boldsymbol{P}_{t,d}\in\mathcal{O}} \left|\Delta P_{\varrho\%} - \Delta \boldsymbol{P}_{t,d} \cdot \mathbf{1}_{I\times 1}\right|. \quad (39)$$

V. Problem Formulation and Solution Methods

A. Bi-Level Model

The deployment of hybrid IoT terminals can be formulated as a bi-level optimization model, by balancing communication demands from LAs and communication performance from terminals. In the upper-level problem, the PWSO maintains the system balance by dispatching LAs while minimizing the total costs of electricity and communication sectors:

$$\min \quad \mathcal{C}^{\mathrm{PWSO}} = \mathcal{C}^{\mathrm{ao}} + \mathcal{C}^{\mathrm{dcs}},$$
$$s.t. \quad (24) - (37). \quad (40)$$

The decision variables in the upper-level problem are $\boldsymbol{Dv}^{\mathrm{upper}} = \{\Delta P_{i,t,d}^{\mathrm{l}}, P_{i,t,d}^{\mathrm{l}}, Q_{i,t,d}^{\mathrm{l}}, \Delta P_{i,t,d}^{\mathrm{g}}, P_{m,t,d}^{\mathrm{g}}, Q_{m,t,d}^{\mathrm{g}}, U_{m,t,d}, \theta_{m,t,d}, \forall i \in \mathcal{I},\ \forall m \in \mathcal{M},\ \forall t \in \mathcal{T},\ \forall d \in \mathcal{D}\ \}$.

In the lower-level problem, the CMSO deploys the IoT terminals for LAs. The optimal IoT terminal deployment scheme can be achieved while maximizing the CMSO's net income:

$$\max \quad \mathcal{Q}^{\mathrm{CMSO}} = \mathcal{Q}^{\mathrm{dpm}} + \mathcal{Q}^{\mathrm{dtc}} - \mathcal{C}^{\mathrm{eai}} - \mathcal{C}^{\mathrm{m}},$$
$$s.t. \quad (2) - (22). \quad (41)$$

The decision variables in the lower-level problem are $\boldsymbol{Dv}^{\mathrm{lower}} = \{v_i,\ \tau_{i,t,d}^{\mathrm{u}},\ \tau_{i,t,d}^{\mathrm{d}},\ \chi_{i,k},\ \forall i \in \mathcal{I},\ \forall t \in \mathcal{T}, \forall d \in \mathcal{D}\ \}$.

B. Tractable Formulations

The lower-level model includes multiple nonlinear terms, including polynomial terms, bilinear terms, and products of integer variables. These terms are converted into tractable forms as follows. Consequently, the model is reformulated into a MINLP problem.

1) Polynomial Terms: For DTRs, the constraints involve nonlinear terms. As the bandwidth b_k, along with the transmission power P_k are input parameters, the DTRs v_i are discrete variables. The nonlinear terms in Eq. (6) can be transformed into the product of binary variables and parameters, respectively.

$$v_i = \sum_{k\in\mathcal{K}} \chi_{i,k}[b_k \cdot \mathrm{lb}(1 + \frac{P_k}{M_i + N_0})] = \sum_{k\in\mathcal{K}} \chi_{i,k} v_k, \quad (42)$$

where v_k is the DTR of the IoT type k terminal.

2) Bilinear Terms: The transmission latency constraints involve decision variables v_i, $\tau_{i,t,d}^{\mathrm{u}}$, and $\tau_{i,t,d}^{\mathrm{d}}$. The multiplication of decision variables leads to the bilinear terms. By using the McCormick envelopes [51], these terms can be transformed using the auxiliary variables $w_{i,t,d}$, as shown below:

$$w_{i,t,d}^{\mathrm{u}} = \tau_{i,t,d}^{\mathrm{u}} v_i,\ \ w_{i,t,d}^{\mathrm{d}} = \tau_{i,t,d}^{\mathrm{d}} v_i. \quad (43)$$

The solutions after relaxation remain feasible for the original problem before relaxation. The detailed derivation process can be found in [52]. Besides, the precision comparison between relaxed and final solutions can be found in Appendix.

3) Product Terms of Integer Variables: The income of local access services is the quadratic function of DTRs. We can see that the DTR involves the linear combination of multiple IoT terminals by K integer variables, i.e., $\chi_{i,k}, \forall k \in \mathcal{K}$. The quadratic terms v_i^2 are nonlinear involving products of integer

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variables. Thus, we transform them into linear items by the big M method [53].

C. Iteration Algorithm

The deployment problem of hybrid IoT terminals involves numerous integer variables and their products. The bi-level problem can not be solved by Karush-Kuhn-Tucker conditions in one step [54]. To solve the bi-level problem, we find the consensus constraints. They include the data traffic constraints in Eq. (10) and communication accessibility-impacted regulation constraints in Eq. (27). These constraints are introduced to guarantee the consistency of the interaction powers between the CMSO and PWSO. Referring to [55], the bi-level optimal model will not get an optimal solution until the constraints are satisfied in the iteration algorithm. Therefore, we establish an iteration method to address the bi-level optimization problem in Algorithm 1.

The convergence condition is represented by:

$$\begin{cases} |\mathcal{C}^{\text{PWSO}}[\iota] - \mathcal{C}^{\text{PWSO}}[\iota']| \leq \epsilon_1 \\ |\mathcal{Q}^{\text{CMSO}}[\iota] - \mathcal{Q}^{\text{CMSO}}[\iota']| \leq \epsilon_2 \\ u_i^{\text{k}}[\iota] = u_{i-1}^{\text{k}}[\iota'] \end{cases}. \tag{44}$$

If $\iota' = \iota - 1$, the iteration meets the convergence condition. The strategy is achieved from the iteration ι. If $\iota' = \iota - 2$, the iteration results involve the oscillation due to the integer variables. The strategy is achieved by finding the iteration ι within the minimum social costs $\mathcal{SC}$, as following:

$$\min_{\iota} \ \{\mathcal{SC}[\iota], \mathcal{SC}[\iota']\}, \tag{45}$$

where $\mathcal{SC}[\iota] = \mathcal{C}^{\text{ao}}[\iota] + \mathcal{C}^{\text{eai}}[\iota] + \mathcal{C}^{\text{m}}[\iota]$.

VI. Case Studies

A. Case Settings

We adopt the modified IEEE 33-bus system with the integration of distribution energy resources (DER), i.e., WT generators and PV generators. This modified power system includes two WTs (WT1 at node 18 and WT2 at node 25) and two PVs (PV1 at node 22 and PV2 at node 33), respectively [56]. The regulation price is set as 2 CNY/kWh for the power systems. To simplify, the price is standardized for all LAs regardless of the location. Besides, the average regulation power ϱ_i is set to 10 kWh for LAs 1-10 and 5 kWh for LAs 11-32. Considering PLC, MPW, and ZigBee are specifically adopted in the simulation, the further cost and technology parameters are outlined in Table I. The maximum time delay comprehensively refers to the execution standard in China [46] and the requirement of peak regulation [57]. The simulations are conducted using MATLAB 2022b with Gurobi 9.5.2 [58] and YALMIP toolbox [59].

B. Dispatch Strategy of the PWSO

1) Power Regulation Results: Although there are varying generation power and load consumption, twelve typical scenarios from the annual output power of WT and PV generators in [60] are extracted after clustering. We extract one scenario from each month and finally obtain 12 output power of WT

Algorithm 1 The Iteration Algorithm

Require: Generator and load information for the PMSO; Parameters of hybrid IoT terminals for the CMSO.
Ensure: PWSO's optimal dispatch strategy $\boldsymbol{Dv}^{\text{upper}}$; CMSO's optimal deployment strategy $\boldsymbol{Dv}^{\text{lower}}$.

Initial the iteration index $\iota = 0$ and the iteration times limit V, and initial communication accessibility variables (i.e., $\boldsymbol{CA}[0] = \{v_i\}$).
repeat
  Allocate the communication performance according to the communication accessibility variables $\boldsymbol{CA}[\iota]$.
  Solve the upper-level problem:
  $\boldsymbol{Dv}^{\text{upper}} = \arg\min \ (\mathcal{C}^{\text{ao}} + \mathcal{C}^{\text{dcs}})$.
  Obtain the dispatch strategy $\boldsymbol{Dv}^{\text{upper}}[\iota]$ and calculate the PWSO's total costs $\mathcal{C}^{\text{PWSO}}[\iota]$.
  Extract the percentile-based scenario and transfer the extracted dispatch strategy, i.e., $\Delta \boldsymbol{P}^*_{t,d}$, to the CMSO.
  Solve the reformulated lower-level problem based on tractable transformation:
  $\boldsymbol{Dv}^{\text{lower}} = \arg\max \ (\mathcal{Q}^{\text{dpm}} + \mathcal{Q}^{\text{dtc}} - \mathcal{C}^{\text{eai}}) - \mathcal{C}^{\text{m}})$.
  Obtain the IoT terminal deployment strategy $\boldsymbol{Dv}^{\text{lower}}[\iota]$ and calculate the CMSO's net income $\mathcal{Q}^{\text{CMSO}}[\iota]$.
  Update communication accessibility $\boldsymbol{CA}[\iota + 1]$.
  $\iota = \iota + 1$.
until Convergence conditions are satisfied or $\iota \leq V$.

TABLE I
The Cost and Technology Parameters

Parameter	Value	Parameter	Value
$\rho_i^{\text{ml}}, \ i = 1, \cdots, 12$	1	$c^{\text{p-m}}$ (CNY)	20
$\rho_i^{\text{ml}}, \ i = 13, \cdots, 32$	0	$c^{\text{p-rs}}$ (CNY)	100
λ_i^{u} (kbit)	400	c^{mpw} (CNY)	40
λ_i^{d} (kbit)	248	c^{z} (CNY)	100
$v_1^{\text{u}}, \ v_2^{\text{u}}, \ v_3^{\text{u}}$ (kbps)	100, 100, 250	T^{la} (s)	10
$v_1^{\text{d}}, \ v_2^{\text{d}}, \ v_3^{\text{d}}$ (kbps)	100, 100, 250	r	0.05
ς^{p}	300	α	0.03

and PV generators. Besides, the characteristics of power loads are also utilized to extend the scenarios. Four power load profiles are considered, with one profile for each season. By this way, four scenarios are expended to 12 for 12 months across 4 seasons (i.e., S1, S2, S3, and S4). The strategy provides the preliminary information for the deployment of hybrid IoT terminals. The strategy of the PWSO in twelve typical scenarios is shown in Fig. 4.

The fluctuation of DERs' output power results in variations of the generation power from the utility grid. From January to March, the PVs play a significant role in the generation power of DERs. They can contribute up to a maximum of 11.01% in total generation power. From April to July, the WTs increase their power output and have similar proportion with PVs, especially in April with the share of 16.32% due to the weather changes. In June, the combined power output of all the DERs peaks at 29.42%, the highest among the all scenarios. In July, the WTs' power exceeds the PV, reaching 15.30% over 12.31% of PVs. After that, the PVs are the primary DERs in the power systems since their outputs are roughly double

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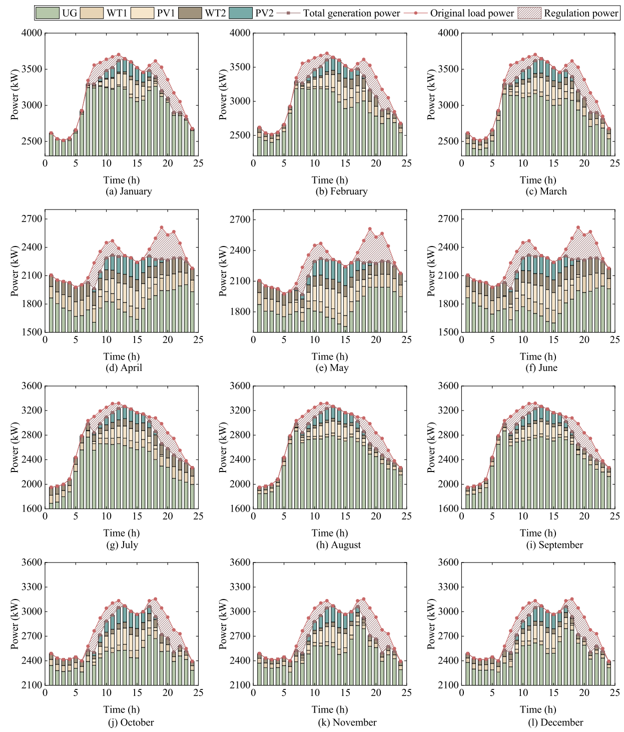

Fig. 4. Dispatch plan in twelve typical scenarios.

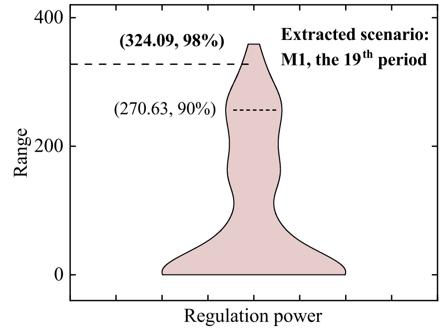

Fig. 5. The distribution of regulation power in twelve typical scenarios.

that of the WTs. The DERs' output power from August to December accounts for 15.16% to 18.82%.

To maintain the power balance, the PWSO dispatches large-scale flexible loads by LAs to provide peak regulation resources across the power systems. Generally, the LAs contribute up to a maximum of 9% regulation resources during peak periods of 8:00-12:00 and 17:00-22:00 in S1, S3, and S4 due to the minimal fluctuation in DERs' power output. However, as a result of the significant decrease in PVs in April and June, the DERs supply reduced power output during the nighttime (e.g., 17:00-22:00). Thus, the PWSO must dispatch flexible loads to provide regulation resources. In particular, the maximum regulation resources reach 334.90 kW with a decrease of 11.36% of total loads.

2) Scenario Extraction: The violin graph in Fig. 5 describes the distribution of regulation power demands over ninety-six periods. In over 50% situations, the power supplied by the utility grid and DERs can meet the load demands in the power systems. The scenario based on percentiles is extracted from Fig. 5. For example, the scenario at the 90th percentile shows the regulation power demand of 270.63 kW during the 21st period in January. The scenario at the 100th percentile represents a regulation demand of 358.82 kW throughout all periods. This paper regards the 98% percentile regulation demand as the extracted scenario, specifically, the regulation power demand of 324.09 kW during the 19th period in January. This suggests that the deployment strategy tends to cover 98% of scenarios during the operation of the power systems.

3) Communication Demands: Following the extraction of the percentile-based scenario, the regulation strategy of each LA throughout all periods is presented in Fig. 6(a). During the 19th period in Jan., the LAs 1-10 offer a higher amount of regulation resources in comparison to LAs 11-32. In the remaining periods across the scenarios, the regulation resources are mainly provided by the LAs 1-10. In this way, the data transmission demands can be more intensively delivered to the CMSO to save communication costs.

Moreover, all related communication demands are illustrated from the perspectives of regulation periods and multiple LAs as follows. In Fig. 6(b), the uplink data traffic between LAs 1-10 and LAs 11-32 exhibits a significant variance and amplification due to the variations in regulation power. This comes from the diverse average regulation capacity parameter ϱ_i. The equivalent regulation power demand results in more data traffic for LAs 11-32 than for LAs 1-10. Additionally, the downlink data traffic varies among LAs across scenarios in a similarly proportional manner rather than a strictly proportional manner, due to the random nature of the data traffic. It follows that the data communication demands (uplink and downlink data volume) vary based on both the internal regulation power of LAs and the traffic load of bi-directional data. Thus, the work is widely applicable to other power data transmission scenarios.

C. Deployment Strategy of Hybrid IoT Terminals

1) Deployment Strategy: To accurately and effectively dispatch the flexible loads, the CMSO develops the deployment strategy of hybrid IoT terminals to provide local access services for LAs within power systems. Fig. 7(a) and (b) describe the quantity and DTR for each LA to provide regulation resources, respectively. The LAs 1-9 have higher DTRs than LAs 10-32 after implementing the IoT terminals of PLC, MPW, and ZigBee. The LAs 1-3, and 6-7 are equipped with three ZigBee terminals to provide a rate of 750 kbps. LAs 4-5, and 8-9 have 1 ZigBee terminals to maintain the rate at 250 kbps. LAs 10-15 and LAs 16-32 are each equipped with two MPW and PLC terminal, respectively, resulting in a reduced rate of 200 kbps.

Apart from the DTR, data transmission latency also impacts the IoT terminal deployment strategy. Fig. 8 describes the communication performance of LAs through the deployment of hybrid IoT terminals based on the extracted scenario (i.e., the 19th period in Jan.). The LAs 1-10 provide larger regulation power, leading to greater data traffic during the data

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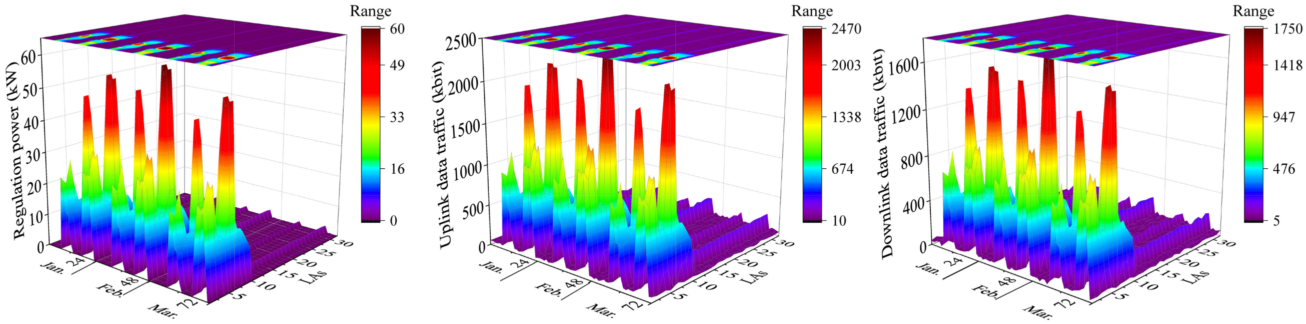
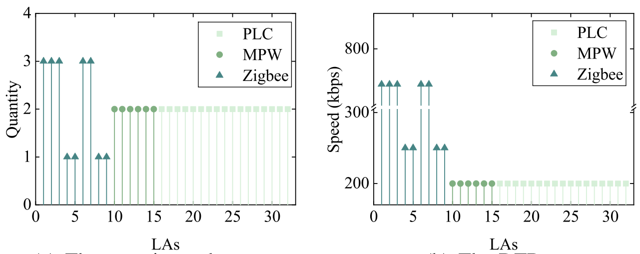


(a) Regulation power (b) Uplink data traffic (c) Downlink data traffic

Fig. 6. The distribution of the PWSO's dispatch strategy and following data transmission demand across scenarios.



(a) The quantity and type (b) The DTR

Fig. 7. The deployment strategy of hybrid IoT terminals across the power distribution network.

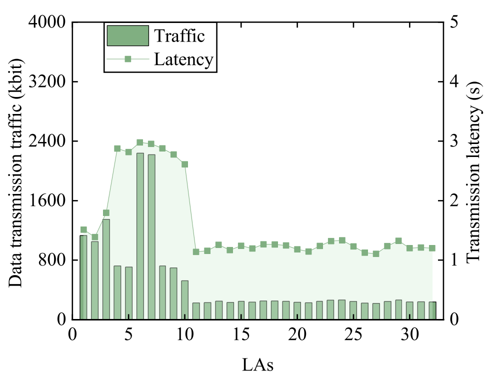


Fig. 8. The communication performance by deploying hybrid IoT terminals.

uplink process. The greater data traffic leads to higher data transmission latency, although the latency consistently remains below five seconds. The latency applies to day-ahead, intra-day, and hour-ahead regulation scenarios. Due to the lower data downlink traffic compared to uplink traffic, the downlink latency naturally meets the limit.

2) Costs and Income: The detailed costs and income of the PWSO and CMSO are outlined in Table II. Given that the regulation price is two CNY/kWh across all LAs temporally and spatially, the regulation power remains consistent across different periods among four typical scenarios. It leads to the fixed generators' costs of 9,738 million CNY and LAs' costs of 1.66 million CNY during one year.

Apart from electricity costs, communication costs are also significant for dispatching large-scale flexible loads. The communication costs of 113.69 million CNY account for around

TABLE II
THE DETAILED COSTS OF THE BILEVEL PROBLEM

The entity	Item	**Value (*e+3 CNY)**
The PWSO	Generators' costs	9738.12
	LAs' costs	1659.51
	Charge for DTR	23.33
	Charge for volume	199.33
	Latency compensation	108.77
	Costs for IoT	113.69
	Total costs	11511.32
The CMSO	Terminal costs	1.13
	Profit from DTR	23.33
	Profit from volume	199.13
	Penalty from latency	108.77
	Net income	112.56

7% of LAs' regulation costs. This constitutes a significant portion of the PWSO. For further elaboration, the data communication services encompass DTR, traffic, and latency. It is easy to see that DTR and traffic are two important indexes for local access services. The regulation resources from LAs generate not only electricity costs but also the costs for DTR and traffic. In the proposed charging scheme in Eq. (4), the lower DTR will be charged more while the higher rate is charged less in the early DTR demand development period. Thus, there are latency compensations for lower DTRs.

The CMSO deploys 34 PLC terminals, 1 PLC relay switch, 12 MPW terminals, and 19 ZigBee terminals for 32 LAs across power systems. Besides, they have a set of identical terminals as backup terminals for the simplified "N-1" principle. The terminal costs amount to 1130 CNY per year, significantly lower than the CMSO's income. This demonstrates that the CMSO mainly generates revenue by offering local access services through profits from the DTR and traffic, as well as penalties for latency.

3) Convergence Process: The termination condition of the iteration process includes two aspects: *i)* the consistent deployment strategy for IoT terminals, the maintenance of consistent objectives of both PWSO and CMSO within specified thresholds; *ii)* the limitation of the iteration times. Fig. 9 visualizes the process of iterative convergence in the bi-level problem. Three kinds of DTRs are deployed across 32 LAs after three iterations. As shown in Fig. 9 (a), the objectives of upper-level and lower-level problems, i.e., PWSO's total cost and CMSO's net income, present convergence after three

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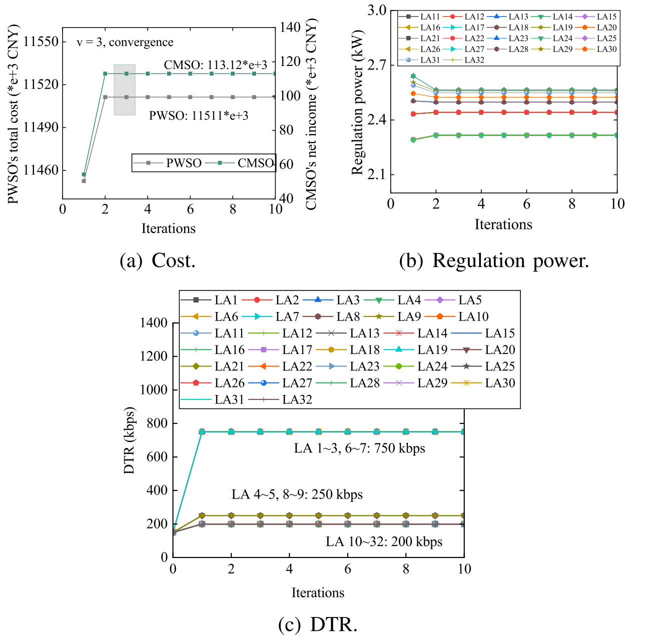
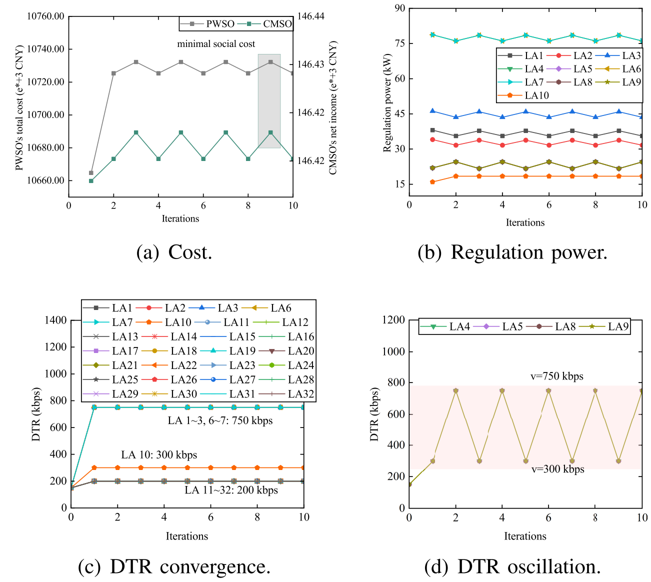


(a) Cost. (b) Regulation power.

(c) DTR.

Fig. 9. The iterative process with convergence.



(a) Cost. (b) Regulation power.

(c) DTR convergence. (d) DTR oscillation.

Fig. 10. The iterative process with convergence and oscillation.

iterations. The interaction power, i.e., the regulation power and DTRs, also exhibits convergence after several iterations in Fig. 9 (b)-(c).

Fig. 9 describes the process of the condition *i)*. The other iteration condition *ii)* operates under the situation in Fig. 10, when the regulation capability of LAs is altered. As shown in Fig. 10 (a), the objectives of upper-level and lower-level problems, i.e., PWSO's total cost and CMSO's net income, present oscillation due to the deployment of integer IoT terminals. The optimal solution can be found in 3rd iteration within the minimal social cost. The interaction power, i.e., the regulation power and DTRs, also exhibits oscillation and convergence after several iterations in Fig. 10 (b)-(d). Specifically, in the case of LAs 4-5 and 8-9, the DTR oscillates between 300 kbps from three MPW terminals and 750 kbps from three ZigBee terminals. In this situation, we select the strategy from the 9th iteration, where LAs 4-5 and 8-9 are equipped with a DTR of 300 kbps from three MPW terminals. This will result in a marginal reduction in social costs compared to the alternative strategy from the 9th iteration.

The performance of the proposed method also depends on the computation time. Each iteration requires approximately 1500 seconds. The optimal strategy is identified by the 3rd iteration of the iteration process. Consequently, the total computation time amounts to 4212 seconds. Given that the proposed method is designed for the deployment of hybrid IoT terminals, it proves to be practical for the coordination of power and communication systems.

D. The Effectiveness of the Proposed Method

Five cases are considered in Table III to validate the effectiveness of the proposed bi-level optimization method. To simplify, the validation is conducted based on four typical scenarios from four quarters in a year. Fig. 11 illustrates the detailed costs and income among five cases and the proposed method. In Case 1, only the dispatch strategy is transmitted to the CMSO, while the IoT terminal deployment strategy does not affect the optimization of the upper-level problem. It follows that the local access service costs in Case 1 are the most among all the cases. The service costs account for around 16.70% in LAs' regulation costs. The high-DTR IoT terminals lead to the lowest latency compensation. Although the CMSO attains the greatest income from local access services, the social costs in Case 1 surpass those in other cases.

TABLE III
CASE SETTINGS

Case	Settings			Interaction	
	PLC	MPW	Zigbee	(40) to (41)	(41) to (40)
Case 1	✓	✓	✓	✓	/
Case 2	✓	✓	/	✓	✓
Case 3	✓	/	✓	✓	✓
Case 4	/	✓	/	✓	✓
Case 5	/	/	✓	✓	✓
Proposed method	✓	✓	✓	✓	✓

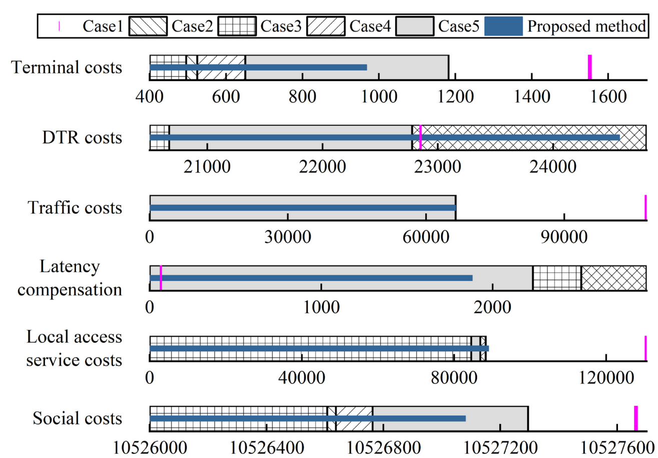


Fig. 11. The detailed cost items among cases.

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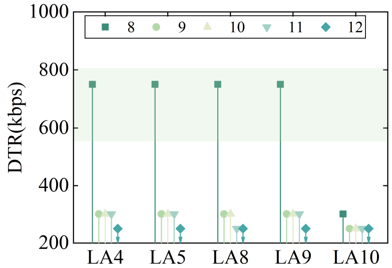


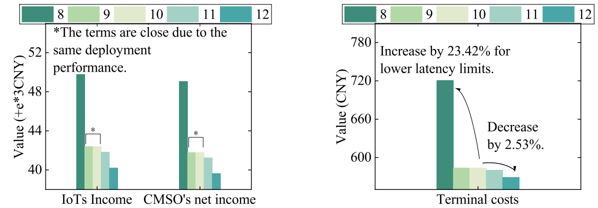
Fig. 12. The impact of the latency requirement on DTR of the deployment strategy.

Apart from Case 1, the traffic costs of the PWSO remain consistent following the interaction between bi-level problems. In other words, the data traffic demands are uniform among cases. In Cases 2-4, the CMSO net income declines by 340 CNY and 466 CNY, respectively, compared to that in the proposed method. Simultaneously, the DTR decreases since the DTRs of PLC and MPW terminals are lower than the other. It leads to an increase in transmission latency regardless of the improved compensation. The DTR of the individual terminal in Case 5 is the most rapid compared to other cases, while the terminal costs are the most elevated. Accordingly, the social cost in Case 5 slightly exceeds that in the proposed method. Moreover, the CMSO's net income decreases by around 2.69% from 88,106.56 CNY in the proposed method to 85,738.80 CNY in Case 5. In other words, the CMSO can obtain higher net income in the proposed method and simultaneously reduce additional social costs of around 100-200 CNY per year.

E. Sensitivity Analysis

Considering the diverse latency limits for various regulation services, we analyze the impact of the latency requirement on the deployment strategy of IoTs in Fig. 12 and Fig. 13. On the one hand, when the latency limit increases from 10s to 12s, the LAs 4-5 and 8-9 decrease by 16.67%. On the other hand, the DTRs of LAs generally increase when the required latency gets more critical, especially for LAs 4-5, and 8-10. When the latency limit decreases from 10s to 8s, the LAs 4-5 and 8-9 change the deployed IoT terminals from MPW to ZigBee for around double DTR of 750 kbps. And the LA 10 slightly increases the DTR by 20%, from 250 kbps to 300 kbps. In terms of the impact on costs, the decreasing 20% latency limits increase the terminal costs by 23.42%, while the same increment deduces that by around 2.53% in Fig. 13(b). However, the income and cost terms for the 9s and 10s requirements are close due to their similar deployment performance.

Then, we study the impact of the average regulation power on the deployment strategy in Fig. 14 to further analyze the influence of power systems on communication systems. When the average regulation power decreases, LAs' data traffic increases. Thus, the average DTR increases within the consistent latency requirement. Specifically, the LAs 4-5 and 8-9 increase by 150% from 300 kbps by 3 MPW terminals to 750 kbps by 3 ZigBee terminals, while LA 10 has a slight increment of 20%. When the average regulation power



(a) Income from IoTs (b) Terminal costs

Fig. 13. The impact of the latency requirement on incomes and costs of the deployment strategy.

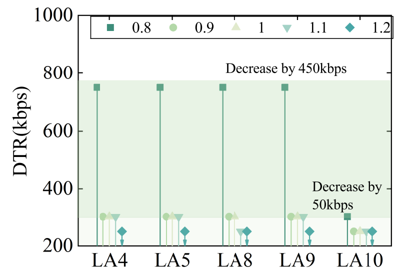


Fig. 14. The impact of the average regulation power on the deployment strategy.

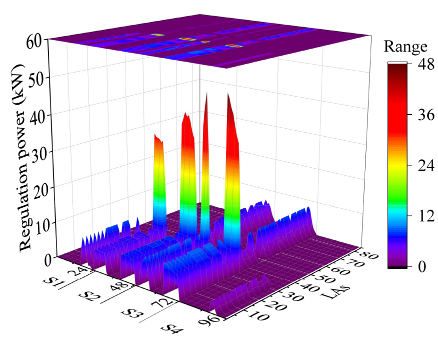


Fig. 15. The distribution of the PWSO's dispatch strategy across scenarios in the modified IEEE 123-bus system.

increases, LAs' data traffic has a much less decrease. The DTR of IoTs for LAs 4-5 and 8-9 decreases by 50 kbps. It follows that the deployment of IoTs is sensitive to more critical communication demands from the power systems.

F. IEEE 123-Bus System

In this section, we verify the effectiveness of the proposed method in the modified IEEE 123-bus system to delve deeper into the scalability. There are two WTs on buses 22 and 111 and two PVs on buses 43 and 59. To simplify, the validation is conducted based on four typical scenarios from four quarters in a year. We discuss the computation scalability of the proposed method. The simulation of the modified 123-bus system finds the optimal solution after five iterations, incurring an increasing calculation time of 10136 seconds. It follows that the computation time is relevant to the system scale. But, since this calculation serves for the deployment, the computation time is not a burden only if it satisfies the deployment time requirement.

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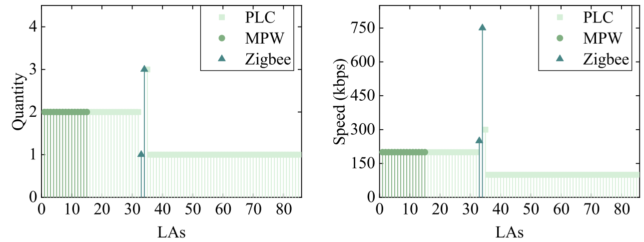

(a) The quantity and type (b) The DTR

Fig. 16. The deployment strategy in the modified IEEE 123-bus system.

For more details, the dispatch strategy of the PWSO is described in Fig. 15. The regulation resource is mainly provided by a small number of LAs, i.e., the LAs 33-35. By this way, the CMSO can centrally deploy high-performance IoTs for large-scale flexible loads to avoid performance redundancy and costly investments. As shown in Fig. 16, the LAs 34-35 at nodes 48-49 utilize ZigBee within the highest DTR of 750 kbps. Besides, the LAs 1-15 serve as movable resources and are equipped with wireless IoT of MPW within the DTR of 200 kbps, while the LAs 16-33, 36-47, 51-56, and 59-80 utilize wireline IoT of PLC within DTR range of 200-300 kbps. Here, 81 of 85 LAs are deployed with various IoT terminals as regular regulation resources.

VII. Conclusion

In this paper, we propose a deployment strategy of hybrid IoT terminals to provide local access services for large-scale flexible loads in power systems. The primary contributions of this work employ: 1) the deployment strategy of hybrid IoT terminals with various communication performances; 2) a bi-level optimization model integrating the interaction between the PWSO and the CMSO; 3) an iterative algorithm delivering communication demands of LAs and the communication performance of various IoT terminals. Finally, the effectiveness of the proposed strategy is validated. In this work, the DTR, latency, and traffic are well established for the local access services, constituting approximately 11.39% of the LAs' costs. By deploying hybrid IoT terminals for LAs, the proposed strategy offers superior performance with an increased average DTR and reduced latency compared to those associated with single IoT types.

This work focuses on the deployment strategy of IoT terminals, primarily serving the communication demands of dispatching LAs in power systems. In the future, data privacy may have potential impacts on the dispatch strategy of power systems and further affect the operation of communication systems. More data privacy impacted deployment approaches for communication systems will be formulated based on the proposed framework.

Appendix

Based on the relaxed solutions and final solutions, respectively, the detailed costs are compared in the following Tab. I. The relaxation mainly affects the cost item of penalty from latency, which decreases by 632 CNY from 109403.71 CNY to 109771.71 CNY. The net income of the CMSO marginally decreases by 0.57%. It is a minimal gap, therefore solutions based on the relaxation method may be preferable due to their lower computational requirements and faster computation speed, as opposed to seeking highly precise solutions.

TABLE I
The Precision Analysis on the Relaxation Method

The entity	Item	Value (e*+3 CNY)	
		relaxed solutions	final solutions
The PWSO	generators' costs	9738.12	9738.12
	LAs' costs	1659.51	1659.51
	Charge for speed	23.33	23.33
	Charge for volume	199.13	199.13
	latency compensation	108.77	109.40
	Costs for ICT	113.69	113.05
	total costs	11511.32	11510.69
The CMSO	ICT device costs	1.13	1.13
	Profit from speed	23.33	23.33
	Profit from volume	199.13	199.13
	Penalty from latency	108.77	109.40
	Net income	112.56	111.92

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Liya Ma (Graduate Student Member, IEEE) received the B.E. and M.E. degrees in electrical engineering from North China Electric Power University, Beijing, China, in 2019 and 2022, respectively.

She is currently pursuing the Ph.D. degree in electrical and computer engineering with the University of Macau, Macau, SAR, China. Her research focuses on the coordinated optimization of power-communication coupling networks for dispatching large-scale flexible resources.

Hongxun Hui (Senior Member, IEEE) received the B.E. and Ph.D. degrees in electrical engineering from Zhejiang University, Hangzhou, China, in 2015 and 2020, respectively.

From 2018 to 2019, he was a Visiting Scholar with the Advanced Research Institute, Virginia Tech, and also with the CURENT Center, University of Tennessee. He is currently an Assistant Professor with the State Key Laboratory of Internet of Things for Smart City, University of Macau, Macau, SAR, China. His research interests include optimization and control of power system, demand response, and Internet of Things technologies for smart energy.

Peng Liu received the B.E. degree in communication engineering from North China Electric Power University in 1995.

He has been working with the Zhuhai Power Supply Bureau, Guangdong Power Grid Corporation, accumulating 30 years of expertise in power communication operation and maintenance. He currently holds the position of senior engineer and superior technician, recognized as a High-Level Talent in Zhuhai City, distinguished as the leading skills expert of Guangdong Power Grid Corporation, and honored as an expert receiving the State Department's special allowance.

Yonghua Song (Fellow, IEEE) received the B.E. degree in electrical engineering from the Chengdu University of Science and Technology, Chengdu, China, in 1984, the Ph.D. degree in electrical engineering from China Electric Power Research Institute, Beijing, China, in 1989, the D.Sc. degree from Brunel University in 2002, the Honorary D.Eng. from the University of Bath in 2014, and the Honorary D.Sc. degree from the University of Edinburgh in 2019.

From 1989 to 1991, he was a Postdoctoral Fellow with Tsinghua University, Beijing, China. He then held various positions with Bristol University, Bristol, U.K.; Bath University, Bath, U.K.; John Moores University, Liverpool, U.K., from 1991 to 1996. In 1997, he was a Professor of Power Systems with Brunel University, where he has been a Pro-Vice Chancellor for Graduate Studies since 2004. In 2007, he took up a Pro-Vice Chancellorship and a Professorship of Electrical Engineering with the University of Liverpool, Liverpool. In 2009, he was with Tsinghua University as a Professor of Electrical Engineering and an Assistant President and the Deputy Director of the Laboratory of Low-Carbon Energy. From 2012 to 2017, he was the Executive Vice President of Zhejiang University, as well as the Founding Dean of the International Campus and a Professor of Electrical Engineering and Higher Education of the University. Since 2018, he has been a Rector with the University of Macau and the Director of the State Key Laboratory of Internet of Things for Smart City. His current research interests include smart grid, electricity economics, and operation and control of power systems.

Dr. Song was elected as the Vice-President of Chinese Society for Electrical Engineering (CSEE) and appointed as the Chairman of the International Affairs Committee of the CSEE in 2009. In 2004, he was elected as a Fellow of the Royal Academy of Engineering, U.K. In 2019, he was elected as a Foreign Member of the Academia Europaea.

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