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ABSTRACT

Ubiquitous Internet of Things refers to the interconnection and interaction of information at any time, any place, anyone, and anything. The ubiquitous power Internet of Things (UPIoT) refers to the application of ubiquitous IoT technology in power systems. Its implementation has the following advantages for power grids: connecting the devices that should have been connected; sharing the data that should have been shared, and the value of data can be used more efficiently. Different from the smart grid, which is designed to build a multienergy integrated network and distributed management intelligent system with intelligent judgment and adaptive adjustment ability, the essence of UPIoT is to realize holistic perception and ubiquitous connection of energy. This paper introduces a technical architecture proposed by China State Grid Corporation, based on which the key communication and information technologies of UPIoT are analyzed in detail from the four elements of UPIoT. The challenges of implementing UPIoT are also introduced.

I. INTRODUCTION

A. Motivation

The traditional power grid is composed of a large quantity of loosely interconnected synchronous AC grids,[1] which is required to realize the functions of production, transmission, and distribution of electricity. In the power plant, electricity is generated by burning coal and other fuels, and the generated electric energy is transmitted to the remote load center through the high-voltage transmission line, and the power distribution system reduces the voltage to distribute the electric energy to the end-user. To ensure that the power produced by the power plant matches the needs of the users, the power grid is uniformly controlled and monitored. From 1870 to 1970, the traditional power grid operated well.[1] However, with the explosive growth of electronic equipment and the generation of high-power power sources such as electric vehicles (EV), the operation of power grids faces enormous challenges. With the use of inefficient appliances, and the lack of intelligent technology, reliable communication and monitoring, and electricity energy storage mechanisms,[2–4] the phenomenon of energy waste in the power grid is very serious.

Smart grid (SG) provides an effective and reliable solution to these challenges. SG has a variety of information and communication technologies that can improve the reliability, security, stability, efficiency, and scalability of the power grid.[5] SG uses the real-time electricity price, self-healing (detection failure and recovery), power consumption scheduling, and other methods to maintain the balance between power generation and consumption[6] according to the demands of consumers, so that the energy production volume and demand are closely matched.[2–4] SG deploys a large number of instruments (reaching hundreds of millions or even billions) in power plants, transmission lines, distribution centers, and customers to monitor, analyze, and control the power grid. Therefore, connecting these devices together and performing distributed monitoring, analysis, and control through high-speed, ubiquitous and two-way digital communication technologies have become the main concerns of SG. IoT is the best way to achieve these functions. IoT technology combines all kinds of sensing devices such as images, audio, video, and positioning. Through the integration of IoT devices, it is possible to realize the monitoring, and control of large-scale scenes by collecting, processing, and transmitting information between objects.[7] At present, IoT has been widely used in the positioning and traceability, dispatching command, remote control, decision support, and other aspects of all walks of life.

However, with the reform of the electricity price system, and the development trend of large-scale high-density access to new energy, the power grid is facing three big challenges now. On the one hand, the reliability of social power supply is required to be higher; uncertainty disturbance sources are increasing day by day and the power grid configuration caused by power electronic equipment makes the power grid safe and stable operation under great pressure.[8] On the other hand, influenced by the liberalization of the power market, the reduction of electricity transmission and distribution price, and the deceleration of electricity growth, the operation of power grid enterprises has encountered great challenges.[9] Besides, the changes in the forms of the social economy such as Internet economy and digital economy have brought great challenges to the traditional power industry. Therefore, in response to this situation, China State Grid Corporation (CSGC) proposed the concept of ubiquitous power Internet of things (UPIoT), arguing that the most urgent and most important task at present is to build UPIoT.[9] Subsequently, the concept quickly received responses from a large number of domestic research scholars and various related meetings were held.

CSGC defined UPIoT as "fully applying modern information technologies such as mobile internet and artificial intelligence (AI), and advanced communication technologies to achieve the interconnection and human-computer interaction around all the aspects of the power system, and finally form a smart service system with comprehensive state perception, efficient information processing, and convenient and flexible application."[10] Compared with the existing research on the Internet of Things in the power system, the ubiquitous power Internet of Things emphasizes the ubiquitous connection, the sharing of data, platform services, and intelligent terminal.

There are four aspects between UPIoT and existing research on the applications of IoT technologies in power systems.

First, compared to existing research on the applications of IoT technologies in power systems, the ubiquitous power Internet of Things proposed by the State Grid is more systematic. CSGC regards UPIoT as a strategic technology that is as important as the smart grid. It has specific directions and objectives, not just the application of IoT in small subareas of the power system.

Second, they have different backgrounds. As analyzed in the third paragraph of the manuscript, UPIoT is proposed in this context: with the reform of the electricity price system, and the development trend of large-scale high-density access to new energy, the power grid is facing three big challenges now. On the one hand, the reliability of social power supply is required to be higher; uncertainty disturbance sources are increasing day by day and the power grid configuration caused by power electronic equipment makes the power grid safe and stable operation under great pressure. On the other hand, influenced by the liberalization of the power market, the reduction of electricity transmission and distribution price, and the deceleration of electricity growth, the operation of power grid enterprises has encountered great challenges. Besides, the changes in the forms of the social economy such as Internet economy and digital economy have brought great challenges to the traditional power industry.

Third, the problems they can solve are different. UPIoT can solve the following four challenges:

- Enterprise operation: the barriers between disciplines and specialties are prominent, so the data are not effectively connected and shared. There is a big gap with the goal that all kinds of collected data can be used everywhere once acquired. The cross-professional process is not coherent, the goal is not coordinated, and the operation is not standardized. The participation and satisfaction in the process of customer-friendly electricity consumption and supply demand interaction need to be improved.
- Power grid operation: the data are incoherent; the real-time sharing is not good enough; the value of data in improving the safe operation level, efficiency of power grids, and the quality of work are not fully played, and no obvious effect has been achieved. The capacity of large-scale energy optimal allocation is not fully reflected. The lack of a flexible interprovincial clearance trading mechanism for clean energy and the interprovincial barriers are prominent.
- Emerging business: it has not yet formed a large-scale and systematic development trend; lacking market-oriented management mode and Internet thinking; and difficult to respond quickly to changes in customer needs; weak social resource integration ability, inadequate open and sharing cooperation, and the driving role of the industrial chain is not obvious.
- Infrastructure: the coverage of terminal acquisition and monitoring is insufficient, lacking unified planning, design, and standards, and failing to achieve unified material link management; the coverage of the communication access network is insufficient; the utilization rate of platform software and hardware resources is not high, the flexibility of data storage, processing, and application is not strong, and the ability of rapid response to demand changes is insufficient.

Fourth, their goals are different. UPIoT develops in the four directions of ubiquity, intelligence, sharing and platform in connection, terminal, data, and service. The ultimate goal is to fully apply modern information technologies such as mobile internet and artificial intelligence, and advanced communication technologies to achieve the interconnection and human-computer interaction around all the aspects of the power system, and go hand in hand with SG to complement each other and finally form a smart service system with comprehensive state perception, efficient information processing, and convenient and flexible application. As Yusheng Xue, a member of the Chinese Academy of Engineering, said, "the convergence of SG and UPIoT will be an indispensable support for energy transformation."[11]

B. Comparison with existing research

Our research on key technologies of UPIoT-aided SG is different from previous research on IoT, SG, and IoT-aided SG. First, we introduce the concept of UPIoT proposed by China State Grid Corporation. Second, we introduce the communication technology and information technology of UPIoT in detail from the perspective of the framework of UPIoT. There are a large number of attempts in the literature which covered IoT and IoT-aided SG. In this section, we present the previous works on IoT and IoT-aided SG, to justify how we are different from them. Our contributions are also included.

1. Researches on IoT

IoT is defined as a network that connects any object to the Internet for monitoring, tracking, management, and location identification based on the exchange of information and communication protocols between various smart devices.[12] In Refs. 13–16, the authors focused on the review, architectures, vision, applications, and challenges of the IoT. In Refs. 17 and 18, the authors argued that social IoT has become a hot topic. The security issue is a big issue that must be considered for IoT applications. In Refs. 19–21, the authors introduced the threats of various aspects of IoT, and successfully detected various DDoS/DoS attacks with a neural network method with an accuracy of 99.4%. In Refs. 22–24, the authors summarized the standardization of the IoT. Besides, some scholars have studied the software-defined network (SDN) of IoT,[25] data mining,[26] uplink scheduling of LTE (Long Term Evolution),[27] and context-aware computing.[28]

2. Reviews on IoT-aided SG

In today's energy ecosystem management system, IoT has a huge impact on the development of SG.[29] The deployment of IoT in SG has several advantages:

- Enhance reliability, flexibility, adaptability, and energy efficiency;[30]
- reduce the number of communication protocols;[31]
- improve control of household appliances;[32]
- achieve on-demand information access and end-to-end service provision;[32]
- enhance scalability and interoperability.[33]

There are some articles about the combination of SG and IoT. Figure 1 shows a complete understanding of the SG with the help of IoT in the future. In Ref. 34, the author introduced the application of IoT in SG and briefly outlines opportunities, challenges, and future directions. However, the author did not analyze the related technologies of IoT-aided SG systems. In Ref. 35, the author focused on the application of IoT in power and energy systems from the value and importance of IoT in the power grid, and evaluated the role, impact, and challenges of IoT in transforming power and energy systems. The survey[36] analyzes how IoT can assist SG, including the existing architecture, applications, and prototypes of the IoT-assisted SG system. Besides, the authors highlight the unresolved issues, challenges, and future research directions of the IoT-aided SG system. In Refs. 37 and 38, the authors analyzed the security of the Internet of Things-assisted SG. In Ref. 38, the author proposed a software-defined network (SDN), network behavior analysis (NBA), deep learning model, and deep packet inspection (DPI) attack confirmation. A conceptual security monitoring framework for a concept forensics-driven security monitoring framework is also included.

There are some existing applications of IoT-aided SG systems such as electric vehicle information management system, demand-side management, smart distribution, advanced metering infrastructure (AMI), online monitoring of power transmission, etc.[36] In the rest of this section, we describe the existing applications of IoT-aided SG systems.

a. Electric vehicle information management system. The charging system of an electric vehicle is composed of a power supply system, a charging device, and a monitoring system. The power supply system is responsible for the output and management of electricity. The charging device contains AC and DC chargers that charge and discharge the electric vehicle. AC chargers charge at a slower rate, while DC charging is much faster than AC. The monitoring system is responsible for monitoring the charging system in real-time to ensure its safe operation. The entire monitoring system is supported by IoT, which enables the power supply and real-time monitoring system to transmit information to the control station, so that a GPS-equipped electric vehicle can locate the nearest suitable charging station for charging. A large number of electric vehicles will have a huge impact on the distribution network after they are put into operation.[39,40] The mobility and energy storage characteristics of electric vehicles bring great opportunities for the realization of new energy sources[41,42] and load management[43] during peak and trough periods on the load side. Of course, they are inseparable from IoT technology.

b. Demand side management (DSM). DSM programs are composed of conservation and energy efficiency programs, fuel substitution programs, demand response programs, and residential or commercial load management programs.[44] The objectives of residential or commercial load management programs are to reduce or shift consumption (by guiding users to use less electricity during peak power demand periods and to use more electricity during low valleys).[45] It aims to minimize the cost of consumers, reduce the operating costs and energy losses of the power grid, and shift the peak load to the trough; thus, the stable operation of the power grid can be ensured.[46] IoT devices collect energy requirements for various household appliances and transmit them to the home control unit. The control unit then adjusts the energy consumption of the home appliance based on the user's preferences. The home energy management system (HEMS) is one of the best applications for DSM. In Ref. 47, the author outlines the information and communication technologies required for HEMS and load scheduling techniques. Similarly, in Ref. 48, Hussain Sharee *et al.* also reviewed the research related to HEMS and introduced the application of artificial intelligence in load scheduling.

c. Smart distribution. Smart distribution technology is one of the largest applications of IoT in the power grid. It is based on the traditional transmission and distribution system, combining modern power technology, modern measurement and control technology, computer technology, communication technology, and power electronics technology.[49] The intelligent distribution has the following advantages:[50] (1) strong interaction ability and support for interaction with users. (2) Strong self-healing ability. (3) High power quality and system reliability. (4) Good compatibility and support of a large amount of access to distributed energy. (5) Higher asset utilization. With IoT technology, smart distribution can identify and resolve failures. At present, some smart distribution projects have been launched, for example, the Henan Hebi IoT Demonstration Project in Hebi, China.[51]

d. Advanced metering infrastructure (AMI). Traditionally, utility companies have manually collected power consumption information at the site at specific time intervals. This method is not only inconvenient, but also time-consuming and labor-intensive. These issues can be addressed by the technology of AMI. AMI is a complete network and system for measuring, collecting, storing, analyzing, and using user's electricity information. It is composed of a smart meter installed in the customer, a measurement data management system located in the power company, and a communication system connecting them.

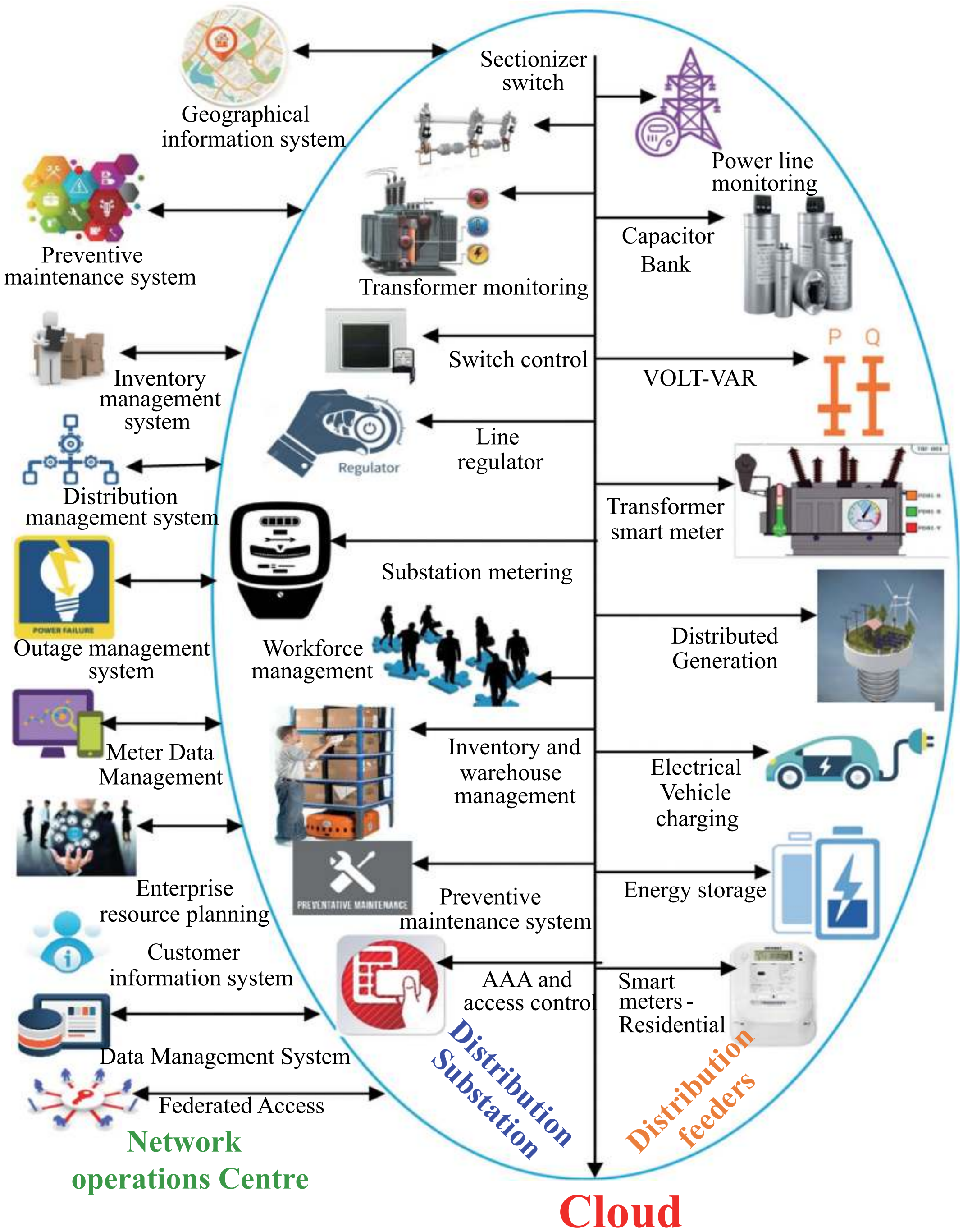

FIG. 1. Future smart grid with the help of IoT.[29] Reproduced with permission from S. S. Reka and T. Dragicevic, Renewable Sustainable Energy Rev. **91**, 90–108 (2018). Copyright 2019 Elsevier B.V.

A typical smart metering system is composed of metering and communication infrastructures. The communication infrastructures include network, home area network (HAN), wide area network (WAN), and control infrastructure. Metering infrastructures consist of time of use pricing, data management system, and advanced meter reading. With the help of IoT technology, AMI enables two-way communication between consumers and utility companies because AMI cannot only measure energy consumption information, but also transmit energy and electricity price information of utility companies to consumers,[52] so that consumers can adjust their power needs.

e. Online monitoring of power transmission lines. The power transmission line is one of the important components of the power grid. Therefore, its normal operation is one of the important conditions for ensuring safe and stable operation of the power system. Online monitoring of transmission lines is one of the important technologies for transmission line protection and diagnosis.[53] Factors affecting the safety of transmission lines include extreme weather, the surrounding environment (such as temperature), and man-made damage. Therefore, the transmission system needs to have the ability to quickly handle faults to ensure the reliability of the power grid. Based on online monitoring, we can quickly locate the fault and fix it. Wireless sensor networks are characterized by low cost, easy installation, and large-scale coverage. They are an important and promising technology for online monitoring of power transmission lines. The sensors are mainly installed in the transmission line between the transmission towers (monitoring the state of the transmission lines) and the transmission towers (monitoring the status and environmental parameters of the transmission towers), and the communication between them is realized by IoT.

3. Novelty and contributions

We have presented the surveys on IoT and IoT-aided SG; however, as presented above and to the best of our knowledge, none of the above attempts have introduced the concept of UPIoT proposed by China State Grid Corporation, technology architecture, and related technologies. Our effort and intention are to provide a survey that covers the concept, architecture, related technologies, and challenges for UPIoT.

The contributions of this article are as follows:

- An overview of the application of IoT in SG;
- an introduction of the concepts and characteristics of UPIoT;
- a detailed introduction to the technologies required for UPIoT, combined with current advanced information and communication technologies;
- descriptions of some challenges of UPIoT.

The rest of this paper is organized as follows: the second part briefly introduces the concept and characteristics of UPIoT. The third section describes key communication technologies and information technologies in detail. The fourth part analyzes the technical challenges of UPIoT. The conclusions of this paper are included in the last section.

II. UPIoT AND THE ARCHITECTURES FOR UPIoT-AIDED SG SYSTEMS

A. UPIoT and its characteristics

UPIoT refers to the interconnection and interaction of their respective devices and people between power generation companies, power electric power companies, suppliers, and power users, that is, the "ubiquity" of information and data. It can be interpreted from three aspects: "ubiquitous network," "power network," and "Internet of Things":[54] Internet of Things is a concrete manifestation of UPIoT. "Power network" is a specific application object of Internet of Things technology; the ubiquitous network describes the basic characteristics of the future UPIoT systems, that is, smooth communication can be achieved at any time, any place, and anything.

With the help of modern information technologies such as mobile internet and artificial intelligence and advanced communication technologies, UPIoT can realize the physical interconnection, information interconnection, and commercial interconnection of different energy systems. It features holistic perception, ubiquitous connectivity, open sharing, and integration innovation.

- Holistic perception: operational status and environmental information from power plants, distribution networks, load side, and energy storage equipment are acquired dynamically by using a variety of sensing technologies, such as sensors and radio frequency identification (RFID).
- Ubiquitous connectivity: the use of proprietary networks or mobile IoT technology to realize full space-time connection of related information and data of equipment of the power system and users, that is, the realization of information transmission everywhere and all the time.
- Integration and innovation: massive data are transmitted to a unified platform through communication technology for sharing and unified management, realizing real-time interaction of data, making data truly effective, and exploiting its maximum value.
- Opening and sharing: through the creative integration of various innovative elements, the information in different times and space of different equipment and users can be interconnected. Thus, the whole business can be realized online, the power grid can be safely and stably operated, the intelligent integrated energy service platform can be built, the power market can be developed, and the transformation of the power grid can be promoted.

B. Architectures for UPIoT-aided SG systems

The hierarchical structure (three or four layers) is a very common structure in the IoT architecture,[55] such as the sensing layer, the network layer, and the application layer. The sensing layer deploys various IoT smart devices to monitor device status. The network layer collects device information through various communication technologies and connected smart devices, and then IoT collects information about devices with the help of various communication technologies and the connected intelligent devices of IoT. The application layer controls the SG[56] through the application interface. In Ref. 57, the author proposed the "terminal-field network-remote communication-master station system layer" architecture based on the characteristics of SG and communication system. The terminal and the field network correspond to the sensing layer in the three-layer architecture, the remote communication corresponds to the network layer, and the master station system layer corresponds to the application layer. However, these architectures only consider the individual characteristics of IoT or SG, and are not scalable, so they are not suitable for large-scale deployment.[58] In Ref. 59, CSGC proposed the architecture of "sensing layer-network layer-platform layer-application layer" from the four elements of UPIoT (namely, the acquisition of terminal equipment information and the intelligence of terminal devices, data transmission, integration, and analysis of data, and application of information). At present, it is recognized by many research scholars.[60,61] as shown in Fig. 2. To the best of my knowledge, there is no other architecture for UPIoT, that is, it is the first ever architecture proposed for UPIoT. In fact, the architecture UPIoT is proposed based on the architecture sensing layer-network layer-application layer for

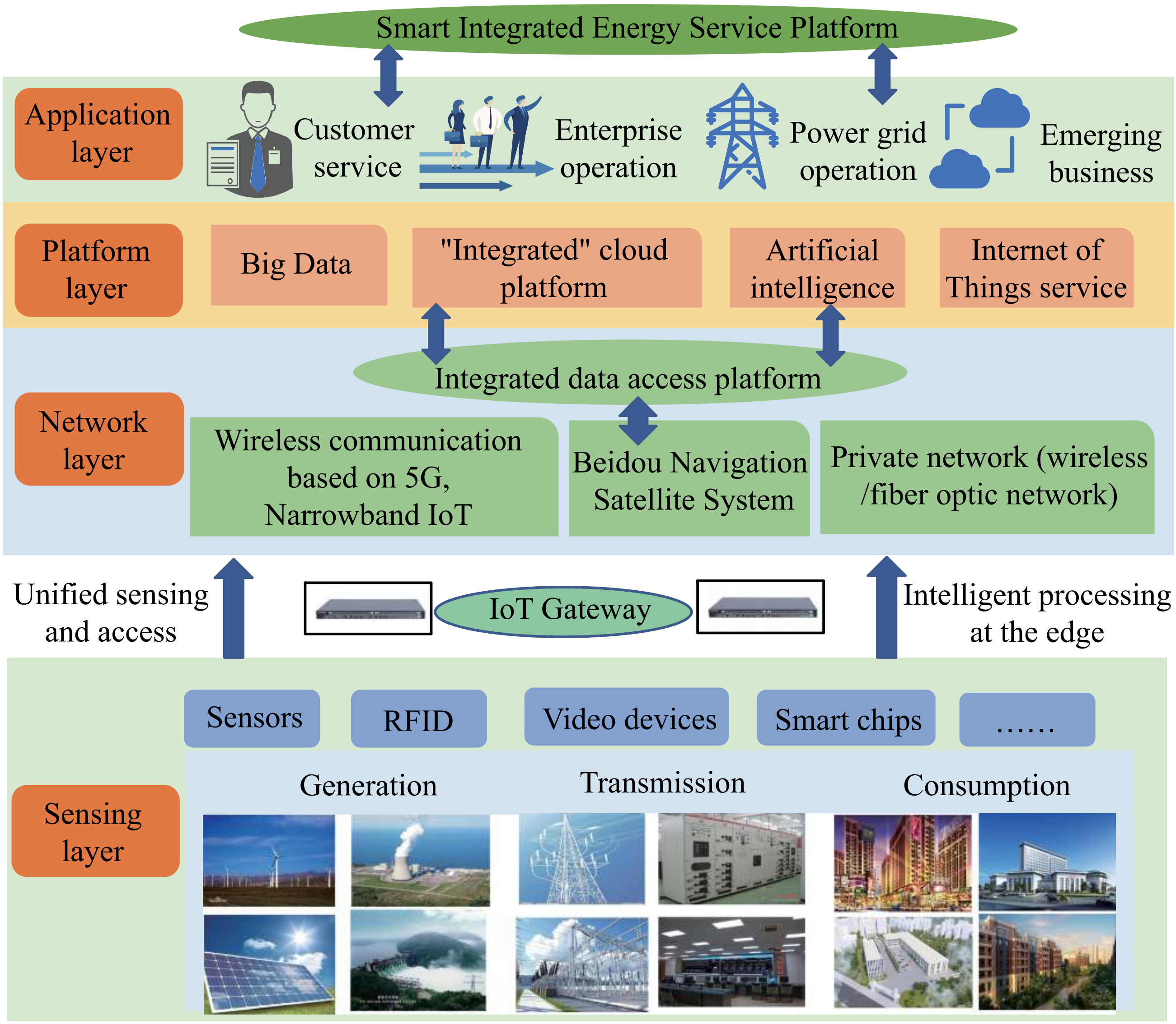

FIG. 2. The technical architecture of UPIoT. The architecture contains four layers: sensing layer, network layer, platform layer, and application layer. The sensing layer includes various information sensing devices (such as sensors, RFID, video devices, and so on) and intelligent sensing systems in the area of SG. The network layer mainly contains various networks and their transmission devices. The platform layer consists of the advanced information technology (such as big data, artificial intelligence, and so on). The application layer mainly includes customer service, enterprise operation, power grid operation, and emerging business.

Internet of Things.[62] Compared with the architecture for Internet of Things, "platform layer" was added to the architecture for UPIoT to realize the "Integrated" cloud platform, the unified data center for all business, and other functions, and finally realize the ultimate goal of forming a smart service system with comprehensive state perception, efficient information processing, and convenient and flexible application.

Sensing layer: in the sensing layer, real-time collection and local signal processing of terminal information (including physical quantity, state quantity, electrical quantity, environmental quantity, electrical quantity, etc.) can be realized by using cognitive and recognition technologies such as smart chips and smart sensors and so on. Besides, edge computing can be used to process some regional computing tasks at the gateway, to reduce the computational pressure of the platform layer server cluster,[63] or to perform edge calculation locally, to achieve intelligent terminal devices and complete local automation.[64]

There are three requirements for the perception layer. The first one is the realization of standardization and unified access for terminals. The term "standardization" exactly refers to the standardization of the operating system. The second one is sharing of resources such as communication and computing. The third one is the realization of data fusion and edge intelligence at the source end to reduce the pressure to the server cluster. Using edge computing to process some regional computing tasks at the gateway is a good way to reduce the computational pressure of the platform layer server cluster.

Network layer: the network layer uses the existing Internet, mobile communication network, satellite communication network, and other basic network facilities to achieve full coverage of power in all aspects of "generation-transmission-distribution-consumption." The information of the sensing layer is accessed and transmitted at the network layer.[65]

There are no specific requirements for the network layer because the network layer has clear specifications regardless of the communication protocol. Transmission methods are divided into wired and wireless, a total of more than a dozen. The most commonly used wired ways include RS485 and power line carrier communication, and wireless includes ZigBee, LoRa, Narrowband IoT (NB-IoT), and LTE. They are likely to be used in the Ubiquitous Internet of Things. The specific form of transmission needs to be selected according to the distance, function, and power consumption requirements of the device and the platform or gateway.

Platform layer: in the platform layer, the data processing capability and the synergy capability of the cloud computing (CC) and edge computing can be greatly improved with the help of the IoT management center and the data center.[66] Massive information resources can be integrated into a large interoperable network through computing ability,[67] to solve the problems of data storage, retrieval, using mining, and security privacy protection.[68] In this way, all kinds of collected data can be used everywhere once acquired.

Application layer: after the platform layer sends the information to the application layer, the application layer processes the received information and makes a decision. The application layer feeds back the decision information to the platform layer and the network layer to control the terminal device of the sensing layer. In this way, the application layer can realize state monitoring,[69] fault self-healing,[70] asset evaluation, etc., to promote the safe and stable operation of the power grid, and build a smart integrated energy Internet.

III. KEY TECHNOLOGIES OF UPIoT

Compared with smart grids, UPIoT is more concerned with data interconnection and information sharing between different devices. In essence, the elements of UPIoT can be divided into four parts: terminal device data collection and terminal intelligence, data transmission, data integration and analysis, and information application. In this section, we will introduce the key technologies of UPIoT in detail based on the analysis of the second part.

A. Sensing layer: Smart chips, smart sensors, RFID

With the continuous access of power equipment, the types, quantities, and ranges of sensing objects will be greatly expanded, and the requirements for volume, energy consumption, and performance of sensing devices will also continue to increase. The smart chip can make the terminal intelligent through edge computing. Chip technology can be widely used in power transmission, substation, distribution, and electricity sales. It is used in large-area applications of control devices and security modules, so that the physical data, state data, environmental data, electrical data, and other information of the power grid equipment can be obtained in real-time, quickly and safely, and processed locally. In the future, sensing technology will continue to develop in the direction of miniaturization, integration, high security, and anti-interference.

Smart sensors communicate bidirectionally with external systems for acquiring, processing, and exchanging information, and receiving and processing external commands. In addition, smart sensors have the function of self-calibration, self-compensation, and self-diagnosis.[71,72] Compared with general sensors, smart sensors have the following three advantages: (1) high-precision information acquisition can be achieved through software technology and at low cost, (2) be provided with certain programming automation capabilities and (3) functional diversification. Therefore, smart sensors have been widely used in power systems. In Ref. 73, the author introduced the application, opportunities, and challenges of wireless sensors in SG. Another survey[74] has focused on the role of wireless sensor networks in energy efficiency in residential energy management. A high-speed sensor that is used as a synchronous phasor or phasor measurement unit (PMU) can be used to simultaneously measure the real-time phasors of voltage and current to achieve monitoring, protection, and control of the power system.[75]

Radio frequency identification (RFID) is a wireless communication technology that can identify specific targets by radio signals without mechanical or optical contact (i.e., noncontact identification) between the system and a specific target, i.e., noncontact identification. RFID has three functions of monitoring, tracking, and supervision.[76] RFID can work in a variety of harsh environments and has the advantages of fast recognition speed, large data capacity, long service life, and dynamic real-time communication.[77] In Ref. 78, the author analyzed the application and challenges of RFID in IoT.

B. Network layer: Communication network

Advanced communication technology is an important part of the development of UPIoT. The communication services in the power system are divided into three types of services: power grid terminal control, information collection, and mobile application. As shown in Fig. 3, different communication services will have different communication requirements. These requirements are briefly described below.

Latency: the latency requirements are different for different applications. Some key technologies require fast information transfer with strict latency constraints, such as distribution automation in the substation (within 4 ms). For applications that are as high as some latency requirements, higher network latency can be tolerated, such as smart meters in AMI (sending their readings every 15 min).

Data rate: different applications in the SG will have different data rate requirements. Some applications for transmitting video and audio data require high data rates to transmit information, such as situational awareness systems. The bandwidth used by smart meters, PMUs, etc., is between 10 kbps and 100 kbps.[79]

Reliability: communication reliability is a critical important indicator of the power grid. It is an important factor to ensure the stable and reliable operation of the power grid. Network fault is one of the most important factors affecting communication reliability, which will seriously affect the reliability of the power grid. Network failures include many aspects, such as links (node failures), overloads, and so on. Critical applications require very high reliability for data communications and should always ensure continuity of communication, such as distribution automation.

Security: security is the highest priority for SG applications.[80] As a key infrastructure, the power grid needs to be able to withstand

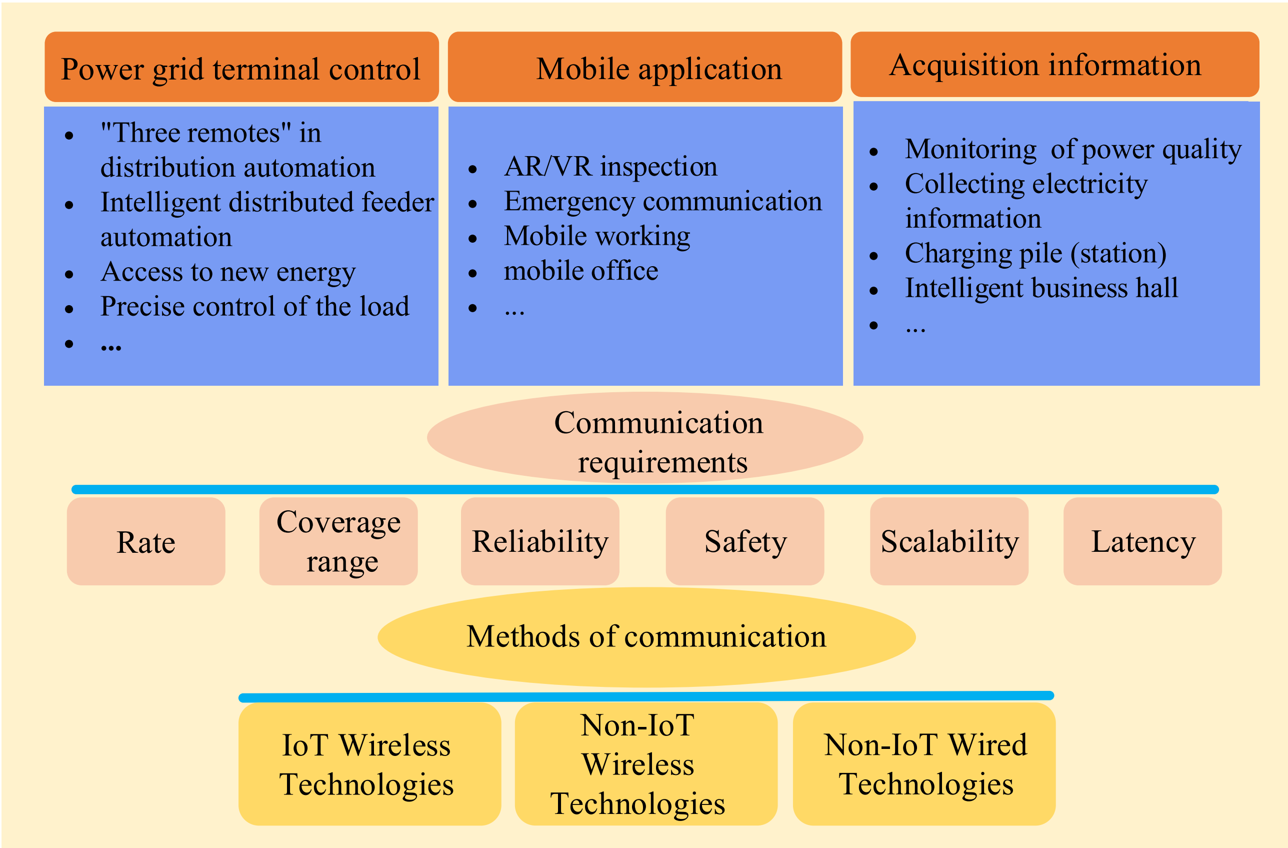

FIG. 3. Types of communication services. The communication services in the power system are divided into three types of services: power grid terminal control, information collection, and mobile application. Different communication services will have different communication requirements (such as reliability, rate, and so on). The methods of communication consist of three categories: IoT-Wireless Technologies, Non-IoT Wireless Technologies, and Non-IoT Wired Technologies.

attacks and failures. Therefore, the communication infrastructure requires strict security requirements in terms of restoring after cyber attacks and protecting customer privacy,[81] especially for some critical applications. Authentication, encryption, and intrusion detection are some of the important security mechanisms in the power grid that prevent, detect, and mitigate such network attacks.[82]

Scalability: countless devices (such as smart meters, smart sensors, renewable energy, etc.) are involved in SG. Therefore, scalability is a very intuitive requirement in SG communications. Therefore, scalability should be handled through the integration of advanced Web services, reliable protocols, and advanced features such as self-configuration and security.

The methods of communication are divided into three categories: IoT-Wireless Technologies, Non-IoT Wireless Technologies, and Non-IoT Wired Technologies. The three major types of communication technologies will be specifically described below.

1. IoT wireless technologies

a. ZigBee. ZigBee is a wireless communication technology which features low-cost, low-power, low-complexity, and low-data-rate. It is applicable to microgrid,[83] home automation,[84,85] energy monitoring,[86,87] and automatic meter reading[88] in SG. ZigBee is considered by the National Institute of Standards and Technology (NIST) to be the most suitable communication technology for home area networks (HAN).[89] Many vendors for AMI, such as Itron, Elster, and Landis Gyr, integrate ZigBee with smart meters to control IoT devices in home appliances[65] or inform users of real-time energy consumption information.

b. 5G. 5G is regarded as the foundation of the development of IoT. It has many advantages, such as large connection density, small end-to-end delay, strong mobility, high peak rate, and so on. It is widely used in distributed monitoring and control,[90,91] and plays an important role in the realization of UPIoT. The main types of 5G slices are Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC), and Ultrareliable and Low Latency (uRLLC). Applying different 5G slice (as Table I shows) to different scenarios is the key to realize holistic perception and ubiquitous connection of power systems. In the future, the construction of UPIoT is inseparable from the participation of 5G. For all its advantages, security and privacy issues still need to be addressed.

TABLE I. Application types of 5G slices.

Scenarios	Status monitoring, unmanned inspection, etc.	Intelligent charging station/pile, distributed power access, etc.	Voice information such as power dispatching and emergency communications	Low-latency information such as distributed distribution automation and load control
Related slice	eMBB video slicee	mMTC mass access slice	mMTC mass access slice	mMTC mass access slice

c. LoRAWAN. LoRAWAN is a low power wide area network (LPWAN) communication technology for wireless battery-powered devices[92] in IoT. The coverage range of LPWAN is wide (15 km in urban environments and 2–3 km in suburban environments[93]), so it is widely used in neighborhood networks (NAN) and wide area networks (WAN). Also, LoRAWAN features mobile and interoperable for secure two-way communication and localization services. The data rates of LoRAWAN range from 0.3 Kbps to 50 Kbps, but in most cases, it will be set to the maximum. The LoRaWAN network server can adjust the radio frequency (RF) output and data rate of each IoT device through the adaptive data rate to increase the network capacity and battery life of IoT devices.[92]

d. Z-Wave. Z-Wave is a low-power radio frequency (RF) communication technology. With a data rate of 100 Kbps and a coverage of 30 m, Z-Wave is widely used in home automation.[94] It does not interfere with WiFi and other wireless technologies working in the 2.4 GHz band, such as ZigBee. With high scalability, Z-Wave is capable of controlling 232 devices[95] and supporting the entire mesh network without using any coordinator.

e. Narrowband IoT. Narrowband IoT (NB-IoT) is a low power cellular technology that provides extensive indoor coverage for thousands of low data rate and low power devices.[96] The NB-IoT technology operates primarily in the 900–1800 MHz band and covers a range of up to 35 km for Home Area Networks (HAN) and NAN, such as home automation and AMI.[97] Besides, low cost (as low as $5) makes it an excellent choice for large-scale applications in SG.

Table II summarizes the comparison of each IoT Wireless Technologies, including their advantages, disadvantages, and applications.

2. Non-IoT wireless technologies

a. Wireless mesh. A wireless mesh network is a flexible network of nodes, where new nodes can join the group and each node acts as a standalone router. The high scalability, self-organization, and self-healing properties of this topology greatly improve the reliability of the network, which can improve network performance, balance network load, and expand network coverage.[98] The wireless mesh can achieve wide coverage (both urban and suburban areas) and large capacity because of the multihop routing technique. However, the density of smart meters is not sufficient to cover the entire communication network, so wireless mesh networks are difficult to implement in rural areas, which once again illustrates the importance of achieving UPIoT.

b. Power wireless broadband private network (PWBPN). Power wireless broadband private network (PWBPN) is designed based on the dedicated frequency band, which can provide ubiquitous, reliable, efficient, and secure access for the transmission and distribution of the power grid. The technical advantage of PWBPN is that it can coordinate various service requirements, build a unified access platform that the terminal services can be accessed flexibly, efficiently, and quickly. Therefore, PWBPN features expanding the end devices, improving the access capability of power grid service, ensuring the transmission quality, and enhancing the service security.

c. Beidou satellite navigation system. The Beidou satellite navigation system is a technology of Chinese independent innovation and has now achieved regional coverage including the entire territory of China. In the aspects of power generation, transmission, substation, and power distribution, the Beidou satellite navigation system can be used for high-precision positioning,[99] short message communication, and high precise-time[78] to meet the requirements of precise positioning of power equipment and collection of power information in remote areas. In this manner, the management level, ubiquitous connectivity, and synchronization reliability can be improved. Based on the Beidou satellite navigation system technology, a menu-based service for the power industry has been developed.[100] These services consist of four parts: (1) online monitoring of power assets; (2) precise running time service module; (3) data of remote monitoring and management of power sales and operation; (4) personnel safety for operation and maintenance and emergency communication module.

3. Non-IoT wired technologies

a. Fiber-optic communication. Fiber-optic communication features high data rates of up to 40 Gbps, ultralow latency, and high reliability. It is often used to connect the backbone of substations and control centers to transmit large amounts of real-time information over long distances, playing an important role in SG. There are three advantages for fiber optic communication: (1) it is capable of transmitting data packets over long distances (approximately several kilometers) up to tens of giga bits per second. (2) It is robust to resist radio and electromagnetic interference, making it an ideal choice for high voltage environments. (3) The combination of the characteristics of optical and ground communication enables optical power ground wire (OPGW) for long distance transmission at high data rates. Therefore, the OPGW can be used to construct transmission and distribution lines.[101] However, the deployment of fiber optic equipment and terminal units is costly and they are difficult to update.

b. Power line communication. Power line communication (PLC) reduces the installation cost of communication infrastructure by using existing power lines to transmit high-speed data of approximately 2–3 Mbps from one device to another. The data of the smart meter can be transmitted to the data concentrator via the PLC, and then transmitted to the utility control center using other wireless communication technologies (such as cellular networks) since the smart meter is directly connected to the concentrator.[102] The PLC infrastructure covers a

TABLE II. Comparison of wireless technologies.

Technology	Main features and applications
ZigBee	Data rate: 50 kbps, coverage range: 10–100 m Latency: 15 ms, cost: low Advantages: low power usage; low complexity; low deployment cost Disadvantages: low data rates; limited energy of battery; low processing capabilities; short-range Application areas: energy monitoring; smart lightning; home automation; automatic meter reading
5G	Data rate: up to 20 Gbps, Coverage range: 10–100 m (depending upon cell size) Latency: <1 ms, cost: high Advantages: low latency; high reliability; high bandwidth; high speed; capability of handling a large number of devices Disadvantages: low range; high infrastructure setup cost; security and privacy issues Application areas: distributed monitoring and control
LoRaWAN	Data rate: 0.3–50 kbps, Coverage range: 3–8 km (urban), 15–22 km (rural), 15–45 km (flat) Latency: average 2 s, Cost: low Advantages: low-power; long-range; no interference with different data rates; low cost secure bidirectional communication Disadvantages: – Application areas: management of operation and equipment; online monitoring of power transmission lines and tower
Z-Wave	Data rate: 9.6–40 kbps, Coverage range: 30 m (indoor) 100 m (outdoor) Latency: 100 ms, Cost: low Advantages: no interference with other wireless technologies; reliable; low latency; scalable Disadvantages: not suitable for NAN and WAN; short-range Application areas: home automation
Narrowband Internet of Things (NB-IoT)	Data rate: uplink: <250 kbps, downlink: <230 kbps, coverage range: <35 km Latency: <10 s, cost: low Advantages: ultralow power consumption; low cost; low complexity Disadvantages: latency Application areas: home automation; AMI

wide range of urban areas within the service of utility companies, so it is suitable for SG applications in urban areas. However, due to the harsh signal propagation environment of the PLC and the high noise, and data transmission through the power line may be unreliable.

C. Platform and application layers: Cloud computing, fog computing, big data, and artificial intelligence

In the sensing layer, the equipment in the "energy production end-energy delivery end-energy consumption end" has generated amounts of data. These data are difficult to be used efficiently due to different sources, different types, and different lengths. Therefore, it is necessary to establish a unified data platform standard,[103] to achieve terminal standardization and unified access of data to improve data quality and real-time sharing.

After the massive data of the power system are transmitted to the integrated data platform of the power system, information technology such as big data, cloud computing, and artificial intelligence can make reasonable analysis and deep mining of these massive data to realize the effective use of power information.

1. Cloud computing (CC)

CC is a computing model that provides on-demand access to configurable resources such as computing, networks, servers, storage, applications, services, and software. CC is divided into three categories, namely, Infrastructure as a Service (Iass), Platform as a Service (Paas), and Software as a Service (Sass).[180] Iass means that users can get services from a complete computer infrastructure over the Internet; Paas can provide users with full or partial application development; Sass provides a complete, ready-to-use application.[181] In addition, CC can also be classified into the private cloud, public cloud, and hybrid cloud by operation mode, as shown in Table III.

CC provides three deployment models of public cloud, private cloud, and hybrid cloud for implementing SG. The public cloud is the main model of the CC, in which users pay for using the SG service. A private cloud is an on-premises deployment that works like a private network. If a basic private cloud is used in the SG, each SG utility has its own data center and provides its services, ensuring reliability and confidentiality. The private cloud is more secure than the public cloud, but the public cloud has far more computing resources than the

TABLE III. Classification of cloud computing.

Classification	Types	Definition	Typical example
Classification by operation mode	Private cloud	Often owned by the enterprise or organization, specific cloud service functions are not directly open to the outside world.	eBay
	Public cloud	Enterprises or institutions use external clouds to serve users outside the enterprise or institution, i.e., enterprises or institutions outsource cloud services to public cloud providers. This can reduce the cost of construct cloud computing facilities.	Amazon, Google Apps, Windows Azure
	Hybrid cloud	Includes hybrid applications of private and public clouds. Guarantee control over parts such as sensitive data through private clouds while reducing costs through outsourcing.	There are few practical applications
Classification by service mode	IaaS	Enhanced virtualization capabilities are achieved by providing or managing IT infrastructure for customers. Infrastructure mainly refers to physical resources such as computing, storage, data, and network equipment resources.	Amazon S3, SQL Azure Amazon EC2, Zimory, ElasticHosts
	PaaS	Provide a platform to support the development of applications and services. The platform mainly refers to the operating system in the cloud computing environment.	Force.com, Google App Engine, Windows Azure (Platform)
	SaaS	Provide software and application services with specific business functions and processes for customers.	Google Docs, Salesforce CRM, SAP Business by Design

private cloud. In this case, the hybrid cloud solves this problem. It features the security of the private cloud to save important internal data in the local data center, and the public cloud computing resources to complete the work more efficiently and efficiently, which is more complete than the private cloud or the public cloud.

The cloud computing system consists of four parts: cloud platform, cloud storage, cloud terminal, and cloud security. The cloud platform is composed of cloud infrastructure, cloud platform components, cloud service center, and cloud security suite. It manages a large number of hardware resources such as central processing unit (CPU), memory, and switches, and integrates one data center or multiple data centers with virtualization technology. At present, there are many applications based on cloud computing services for SG, as shown in Table IV.

2. Fog computing (FC)

With the large increase in the number of smart devices connected to the IoT, it is impractical to transmit all data to the cloud for processing because of the high cost and high delay requirements.[182] FC extends CC to the edge of the network. It is characterized by low latency and location awareness, extensive geographic distribution, mobility, a very large number of nodes, and heterogeneity.[183] Table V compares the characteristics of FC and CC. As shown in Table V, compared with CC, FC has great advantages in many aspects. It can solve the applications and services that are not suitable for CC, including the following aspects: very low and predictable latency is required, geographically dispersed, fast-moving, and so on. The literature[184] introduces the representative application scenarios of FC, analyzes the problems that may be encountered in designing and implementing FC systems, and discusses the opportunities and challenges of FC. In Ref. 185, the author studied which can be solved by cloud computing in SG, which subdomains and services need to be solved by fog computing, and introduced the opportunities and challenges of fog computing in SG.

3. Big data

With the explosive growth of data in all segments of the smart grid, we have ushered in the era of big data. In SG, AMI is the primary source of data.[186] When 1 million metering devices collect data every 15 min, the total amount of data will reach 2920 Tb. However, in addition to the data in the AMI, there are many other smart devices, such as sensors, thermostats, etc., in the entire SG, which are also collecting large amounts of data.

To fully exploit the potential value of these data and using effectively, big data technology has become an indispensable part of information technology in the realization of UPIoT. China State Grid Corporation established the Big Data Center on May 21, 2019 to lay the foundation for the realization of UPIoT and provide digital support for energy Internet companies.[187]

In fact, big data analytics technology has developed very well in SG, which plays a critical role in SG making decision, as shown in Fig. 4. In the SG environment, the applications based on big data mainly include five aspects, namely, electric vehicles (EV), power generation, renewable energy, asset management, and collaborative and demand side management.

With the increasing number of electric vehicles (EVs), many problems such as energy management, battery capacity, and EV's state get great concerns from researchers. EVs are one of the typical applications of big data technologies. Many of the issues above can be handled with big data technologies. For example, in Ref. 112, the author proposed an estimation of distribution algorithm (EDA) based on big data technologies to realize the intelligent allocation of electric energy to EVs. In Ref. 113, the author presented a methodology based on Monte Carlo Simulation (MCS) to estimate the possible EV state (i.e., their locations and periods of connection in power systems). In Ref. 114, the author proposed a data-driving

TABLE IV. Some applications of cloud computing in SG.

Application	Branches	Brief introduction	References
Energy management	DSM	To meet the scalability and economic efficiency of DSM; Cost-oriented optimization model for a cloud-based ICT infrastructure to allocate cloud computing resources in a flexible and cost-efficient way.	104
		To satisfy the requirements of large-scale real-time computing capabilities to handle the communication and the storage of huge transferable data; Providing a cloud computing framework for a group of smart energy hubs.	105
		To improve the energy utilization efficiency in a smart community; A cloud-based user-side integrated energy management; A two-level model is proposed that relies on an energy hub and load aggregators.	106
	Microgrid management	A control model with the hierarchical structure based on cloud computing architecture; Resource allocation and management can be realized in an economically efficient manner; Integrating the past and present data to make the collected information more accurate and provides more flexible service for users.	107
	Dynamic pricing	Proposing a real-time dynamic pricing model for electric vehicles charging and discharging service and building energy management, in order to reduce the peak loads; A decentralized cloud computing architecture based on software-defined networking technology and function virtualization.	108
Information management	Information management cloudward	Different domains for cost-effective information management cloudward; Propose a cloud-based SG information management model and present a cloud and network resource optimization framework to solve the cost reduction problem in cloud-based SG information storage and computation.	109
	Cloud-based demand response (CDR)	Demand response program based on the distributed optimization model; Solving the problem of the existence of an ideal communication network; Defining a cloud-based demand response (CDR) model which is implemented as a two-tier cloud computing platform.	110
	State estimation (SE)	State estimation (SE); Proposing and validating a Cloud-IoT-based architectural solution for SE in SG that combines cloud capabilities and edge computing advantages and uses virtualization technologies to decouple the handling of measurement data from the underlying devices.	111

TABLE V. Comparison of FC and CC.

	Cloud computing	Fog computing
Location of service	Within the internet	At the edge of local network
Location awareness	No	Yes
Number of computing nodes	Few	Very large
Location of service	Within the internet	At the edge of local network
Geodistribution	Centralized	Distributed
Latency	High	Low
Security	Undefined	Can be defined
Attack on data enroute	High probability	Very low probability
Support for mobility	Limited	Supported
Distance between client and server	Multiple hops	One hop

queuing model for EV charging demand with the help of big data analysis on smart measurements.

On the power generation side, the role of big data analysis is mainly reflected in the power generation planning[115–118,120] and economic load schduling.[121–131] Their data source includes technology cost and performance data, generating cost data, budget, and capacity constraint data, Ramp-rate limit data, load demand, operating zones data, and so on; combining big data analytics technologies and energy collected through ubiquitous IoT technology can significantly improve energy efficiency and reduce production costs.

Renewable energy is a significant part of modern energy systems. The main renewable energy sources in the SG are wind and solar, but their output power is extremely unstable and is mainly affected by the weather. This uncertainty poses a great challenge to the balance of supply and demand in the power system. The introduction of big data analysis technology has given a solution to this problem. Based on large-scale weather data analysis, wind power prediction,[132–134] solar power generation prediction,[135,136] hybrid wind-solar power generation prediction,[137,138] microgrid optimal load distribution,[139,140] etc., can greatly improve the stability of the power system.

Asset management (such as resource sharing, inventory management, etc.) is a major challenge for power generation companies and

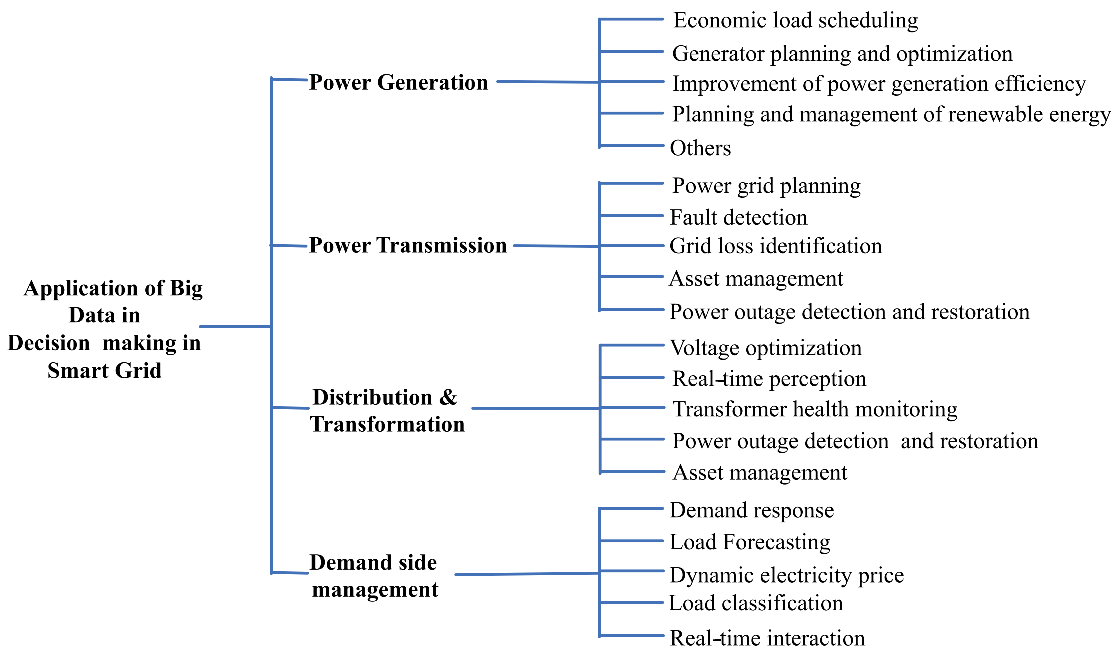

FIG. 4. Application of big data in SG making decision.

electric power companies. Big data analysis plays a major role in improving the efficiency of asset management. Using big data analytics technology, data can be shared throughout production, transmission, transformation, distribution, and consumption processes to optimize resource allocation and increase resource utilization.[141–143] The combination of large amounts of data collected by sensors with big data analysis techniques and visualization techniques enables real-time monitoring and fault diagnosis of power systems.[144,188]

Demand-side management is one of the most widely used areas of big data analytics technology.[189] Through monitoring and analyzing energy consumption data in real-time, electric power companies can perform load forecasting, load classification and dynamic pricing. Several methods of load prediction are proposed in Refs. 145–148, including neural networks approach, support vector regression, particle swarm optimization (PSO) based methods and ant colony optimization. Load classification uses different clustering methods to group different load profiles, which can be used to identify energy consumption patterns of different users. With load classification, different energy saving schemes can be developed for different users.[151–153] Dynamic pricing refers to the electric power companies to guide customers to use electricity according to the user's power consumption information to set different electricity prices to reduce the peak-to-average ratio (PAR) in load demand.[190] In Refs. 149 and 150, the authors used the methods of least squares support vector machine (SVM) and economic modeling to realize the concept.

4. *Artificial intelligence*

Artificial intelligence has strong optimization processing power and strong learning ability in dealing with high-dimensional, time-varying, and nonlinear problems in computational intelligence, perceptual intelligence, and cognitive intelligence. Artificial intelligence (AI) has strong optimization processing power and strong learning ability in dealing with high dimensional, time-varying, and nonlinear problems in computational intelligence, perceptual intelligence, and cognitive intelligence. They can learn from examples, and with the ability of fault tolerance as they can handle noisy or incomplete data. Also, they can do with nonlinear problems and once trained can perform prediction and generalization at high speed.[191]

The application of artificial intelligence technology in power systems can realize the combination of intelligent sensing and physical state, data driving and simulation model auxiliary decision and operation control, thus solving various challenges faced by power system systems, and improving the security and reliability of system operations. Table VI summarizes the application of artificial intelligence in energy forecasting (including wind energy,[154–157] photovoltaic and solar power[158–161]), load forecasting,[162–165] managing electric vehicles (including congestion management,[166,167] load balancing,[168,169] and electricity markets[170–172]), fault diagnosis,[173–175] cyber security,[176] and power generation planning.[177–179] It is worth noting that AI technology is inseparable from big data, and the two complement each other and work together.

IV. CHALLENGES OF UPIoT

A. Barriers between businesses

Professor Sun Hongbin of Tsinghua University believes that the mission of UPIoT is to break down barriers between different energy sources such as cold, heat, gas, and electricity that hinder the formation of an open shared energy ecosystem.[192,193] It is necessary to be broken through from the perspective of an integrated energy system. Each department of the power grid has independent systems and services. Each branch of the power grid has its own system and business. Therefore, it is one of the challenges to be tackled that how to conduct unified analysis and complementary integration of massive data, so as

TABLE VI. Some research on the application of big data in SG.

Applications	Branches	Characteristics	References
Electric vehicles	Energy management	Charging and discharging data; An Estimation of Distribution Algorithm (EDA); Optimally manage a large number of EV's charging	112
	Ev's state	A methodology based on Monte Carlo Simulation (MCS); Estimate the possible Ev's states about locations and periods of connection	113
	Battery capacity	Smart meter measurements; A data-driven queuing model; EV charging demand	114
Power generation	Power generation planning	Technology cost and performance data; Constraint programming and compromised modeling	115,116
		Generating cost data, budget and capacity constraints data etc.; Portfolio-theory, dynamic programming	117,118
		Generating units data, carbon emission data; Constraint programming, fuzzy possibilistic model	119,120
	Economic load dispatch (ELD)	Ramp-rate limits data, load demand, operating zones data; Differential evolution based methods	121–123
		Transmission loss, generator parameters, Load demand; Biogeography-based optimization (BBO) algorithm	124,125
		Generator parameters, load demand; Harmony search based methods	126–128
		Operating zones data, transmission loss, Load demand; Particle swarm optimization (PSO) based methods	129–131
Renewable energy	Wind power forecasting	Past power measurements, wind speed, and direction; Time series models, support vector machine (SVM), artificial neural network, quantile regression, Self-organized map	132–134
	Solar power forecasting	Meteorological forecasts of solar irradiance, past power measurements, relative humidity and temperature; Artificial neural network, autoregressive (AR) models	135,136
	Hybrid wind-solar power generation	Energy storage data, wind, and solar power generation, load demand; Operational management, time series analysis	137,138
	Microgrid optimal load distribution	Distributed generator parameters, load demand; Multiobjective optimization, single-objective optimization	139,140
Asset management and collaborative operations	Operation and control	Operation conditions data, substation data; Random fuzzy model, automated analysis	141
	Asset management	Operating observations, network data, component reliability data; Service-oriented architecture, condition assessment techniques	142,143
	System reliability Improvement	Equipment data, load data, failure data; Fault tree analysis, risk importance measures	144
Demand side management	Load forecasting	Wind speed, cloud cover, temperature information, historical load data; Neural networks approach, support vector regression, PSO based methods, ant colony optimization	145–148
	Dynamic pricing	Variable pricing or real-time pricing, user behavior data, power supply data, load demand; Least-squares SVM, economic modeling	149,150
	Classification (load and consumers)	Consumption data, load profiles; K-means clustering, Fuzzy c-means (FCM) clustering, Hierarchical clustering	151–153

to achieve operational maintenance, measurement, finance, and other services.

B. Challenges in the architecture of UPIoT

After more than 10 years of development, the Internet of things has made great progress in the application of SG. However, there are still some shortcomings in the sensing layer, the network layer, and the platform layer, mainly in the following aspects:

- At the sensing layer, IoT has insufficient coverage at the power generation side, distribution side and other terminals (i.e., many terminal devices are not yet connected to the Internet); the level of terminal intelligence and bidirectional interaction is low, and the ability of edge computing and intelligent processing is not available yet; there is a lack of unified planning design and standards.
- At the network layer, the communication access network (i.e., all devices between the backbone network and terminal user) has

insufficient coverage; there is a lack of end-to-end ubiquitous communication network solutions and the ability of network resource allocation is insufficient.
- At the platform level, there is a lack of cross-professional IoT management, and open sharing for IoT applications is insufficient.

In view of the above deficiencies, they can be improved from the following directions: first, improve the holistic sensing ability to achieve the function of energy transmission, conversion, utilization, and the equipment and user status of each link can be fully perceived; second, improve ubiquitous connectivity to achieve real-time connectivity of internal devices, users and data. Third, improve the ability of integration and innovation, and then promote the deep integration and data integration of SG and UPIoT.

C. Security and privacy issues

Security issues are major challenges in building UPIoT. For example, when UPIoT runs on the open Internet, attackers may potentially affect the real-time balance between energy production and consumption by manipulating data generated by smart objects or sent from utilities. It could cause considerable financial losses for utilities and power assets.[194] In the process of transmitting massive data to the unified platform, it is the second challenge in building UPIoT to be addressed that how to prevent data leakage, resist network attacks to ensure reliable and fast transmission of data.

Another challenge in achieving UPIoT is privacy. The energy efficiency can be improved by frequent data collection and analysis. The smart meter collects a large amount of information from the household appliances at the required time interval. Therefore, this method comes at the cost of privacy. In the context of the Internet of Everything, how to protect the privacy of users becomes extremely important and difficult.

V. CONCLUSION

At present, there is still a large number of electrical instruments in SG that are not connected to the Internet yet, and a large amount of basic data are still not acquired due to various difficulties. It is an inevitable tendency that applying ubiquitous IoT technology to power systems to achieve UPIoT. At present, China is setting off a research boom in UPIoT. The importance of UPIoT is self-evident. The operation of "strong smart grid" and "the ubiquitous power Internet of Things" is an important material basis for building a world-class energy Internet enterprise, and a new strategy for the development of power informatization in the new era (Table VII).

In this paper, the concept, architecture, and key technologies are analyzed in detail; and the challenges of UPIoT in UPIoT are briefly introduced. At present, UPIoT is in the initial development, and there are a few related studies. We have introduced the important work that has been done in the field of UPIoT-aided SG systems, but there is still more work to achieve a better and complete implementation of the UPIoT-aided SG system. In the future, our research work will be devoted to the extensive application of UPIoT, such as the application in the distribution network.

TABLE VII. Some research on the application of Artificial Intelligence in SG.

Applications	Branches	Characteristics	References
Energy forecasting	Wind energy	Short-term wind power forecasting, neural networks, and wavelet transform; spatial estimation of wind speed in a coastal region, artificial neural networks; wind speed forecasting, time-series	154–157
	Photovoltaic and solar power	Long-term ahead Photovoltaic (PV) power output correction, insolation prediction with fuzzy and applying neural network; Short-term solar power prediction, support vector machine, artificial neural networks; Prediction of daily global solar irradiation data, Bayesian neural network	158–161
Load forecasting	…	Support vector machine and ant colony optimization; Hybrid PSO-SVM; Recurrent support vector machines with genetic algorithms; Wavelet neural networks with data prefiltering	162–165
Managing electric vehicles	Congestion management	Stochastic optimization, Graph-based search, and mathematical programming, and probabilities theory; Decentralized or centralized	166,167
	Load balancing	Mathematical programming, utility-based agent coordination; Decentralized or centralized	168,169
	Electricity markets	Mathematical programming, auctions, and stochastic optimization, game-theoretic analysis; Decentralized or centralized	170–172
Fault diagnosis	…	Self-evolving neural network, artificial neural networks, fault prognosis in wind turbine, photovoltaic systems;	173–175
Cyber security	…	Contextual anomaly detection, use in the discovery of malicious voltage control actions in the low voltage distribution grid; Artificial neural network model	176
Power generation planning	…	Power Generation Expansion Planning With Emission Controls, power distribution system planning; Genetic algorithm (GA)-Benders' decomposition, a nonlinear model and a GA-based heuristic, artificial neural networks	177–179

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