Applied Energy 257 (2020) 113972

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

5G network-based Internet of Things for demand response in smart grid: A survey on application potential

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HIGHLIGHTS

- Comprehensive review of cyber security, privacy, and reliability of demand response.
- Comparison of 1G-5G to highlight essential features and application scenarios of 5G.
- Application methods of 5G to demand response by using 5G's advantages.
- Recent advances and planning of 5G for demand response in smart grid.
- Future work for achieving 5G application in smart grid.

ARTICLE INFO

Keywords:
Demand response
Smart grid
5G network
Internet of Things
Application potential

ABSTRACT

Demand response (DR) has been widely regarded as an effective way to provide regulation services for smart grids by controlling demand-side resources via new and improved information and communication technologies. Emerging 5G networks and 5G-based Internet of Things (IoTs) can doubtless provide better infrastructure for DR, owing to 5G's advantages of fast transfer speed, high reliability, robust security, low power consumption, and massive number of connections. However, nearly none of the existing studies have applied 5G technology to DR, which will be the subject surveyed in this paper. First, the concept of DR and recent practical advances are investigated, especially the application of communication technologies to DR. Then, a comprehensive review of the cyber security, consumer privacy, and reliability of DR is presented. These topics received little attention in the past, but they will be among the most crucial factors in the future. In addition, the essential features and typical application scenarios of 5G communication are investigated. On this basis, the advantages, methods, recent advances, and implementation planning of 5G on DR are studied. Finally, the future work that must urgently be conducted in order to achieve the application of 5G to DR is discussed. This paper's application survey of 5G on DR is carried out before 5G technology enters the large-scale commercial stage, so as to provide references and guidelines for developing future 5G networks in the smart grid paradigm.

1. Introduction

1.1. Energy challenges

Energy production, transport, and utilization forms are being transformed around the world. For example, renewable energy sources (RESs) are on the rise, and are beginning to replace traditional generating units in power systems [1]. Distributed energy resources (DERs) are growing. Consequently, more distribution networks are changing from one-way power flow to bidirectional power flow [2]. Moreover, electric vehicles (EVs) and energy storage batteries are becoming widely used, which is changing power utilization characteristics [3]. Therefore, electric power is becoming the most important energy form by which to connect all other energies. However, these changes also bring some new challenges to power systems:

- RESs can bring fluctuations to power systems, due to their characteristics of intermittence and uncontrollability [4]. This calls for

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https://doi.org/10.1016/j.apenergy.2019.113972
Received 23 August 2019; Received in revised form 2 October 2019; Accepted 8 October 2019

Nomenclature

AMI	advanced metering infrastructure
ADN	active distribution network
BS	base station
DER	distributed energy resource
DMS	distribution management system
DR	demand response
DSM	demand side management
ECC	elliptic curve cryptography
eMBB	enhanced mobile broadband
EV	electric vehicle
GOOSE	generic object oriented substation event
HEMS	home energy management system
ICT	information and communication technology
IoTs	Internet of Things
mMTC	massive machine type communication
mmWave	millimeter-wave
MIMO	multiple-input multiple-output
NFV	network function virtualization
PKI	public key infrastructure
PMU	phasor measurement unit
RES	renewable energy source
SCADA	supervisory control and data acquisition system
SDN	software-defined networking
SGCC	state grid corporation of China
SG-eIoT	state grid electric-Internet of Things
SLA	service level agreement
uRLLC	ultra-reliable and low-latency communication
VPP	virtual power plant
WAMS	wide-area monitor system

larger regulation capacities to maintain the system balance between power generation and consumption [5].

- In current operations, traditional generating units are the main providers of regulation capacities. The phasing out of these traditional generating units may cause insufficient regulation capacities in the future [6,7].
- The growth of DERs, EVs, and energy storage batteries put forward higher requirements on electric power equipment, which should be updated to support bidirectional power flow [8]. Besides, some studies also show that DERs and EVs may cause larger peak-valley load differences [9].

1.2. Demand response

Faced with the above issues, we shift our focus from the unilateral control of the power generation side to the bilateral control of both the power generation and consumption sides. This means that regulation services can be provided by adjusting the power consumption of loads, namely by demand response (DR) [10–13].

In [14] and [15], residential loads are controlled to provide frequency regulation services for power systems. The nonlinear behavior models of residential customers are studied in [16] to implement DR in unit commitment of power systems. In [17–20], the authors propose that thermostatically controlled loads are able to provide balancing services under the constraint of guaranteeing user comforts. The coordinated operation of electricity networks and natural gas networks has also been investigated under market paradigm considering DR, which proves that electricity price and natural gas network congestion cost can both be reduced [21,22]. Besides, the effects of different responsive load models have been investigated on unit commitment and generation scheduling schemes [23], which illustrate irrational implementing of DR could result in an increase of system cost [24], especially with unsuitable schemes of DR programs or inappropriate responsive load models [25]. Therefore, reasonable dispatching and modelling methods should be used in DR programs to make positive impact on power systems. For example, it has been proved in [26] that appropriate DR is beneficial for decreasing both power system's operation costs and users' costs.

The precondition of implementing DR is improved infrastructure, especially information and communication technologies (ICTs) [27]. Most previous studies assume that ICTs are mature enough for carrying out DR, i.e. that electricity prices and control signals can be transmitted correctly in time [28,29]. However, in reality, communication delays and transmission errors are unavoidable [30], which is proven to have significant negative impacts on DR and may bring severe oscillations to power systems [31]. Therefore, ICTs with high reliability and fast data transfer speed should be developed to ensure the effectiveness of DR.

1.3. 5G technology for demand response

Recently, fifth generation (5G) cellular network technology is being promoted in many countries across the world, due to its great advantages over previous generations (1G − 4G) in transfer speed, reliability, security, power consumption, and number of connections [32]. The electromagnetic wave frequency spectrum of 5G can reach hundreds of GHz, which is far higher than the current frequency spectrums for 1G − 4G [33]. Therefore, 5G wavelength is shorter, with larger bandwidth to transmit data. In existing studies [33–35], 5G wireless systems have been summarized as occurring in three typical scenarios, i.e. enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (uRLLC), and massive machine type communications (mMTC). On this basis, 5G technology is considered the most important driver for the emerging global Internet of Things (IoTs) [36]. Hence, 5G networks and ubiquitous IoTs will be able to provide better infrastructure for DR.

A number of studies have been done to explore the application potential of 5G networks for the IoTs and for DR in smart grids [37]. For example, tests carried out in a factory automation context have shown that 5G networks can guarantee sub-millisecond radio transmission with a failure rate as low as 10^{-9} [38]. Furthermore, in [39], 5G-based fog and cloud computing methods are proposed to implement massive connectivity and fast communication in EVs to provide ancillary services to power systems. In [40], an extended mobile edge computing scheme is developed to use 5G technology in power systems to reduce backhaul loads and increase overall network capacity. Moreover, in [41] and [42], EVs are designed to participate in DR by transferring bids and power consumption data to the DR aggregator, during which 5G slicing technology is used to enhance data transfer security and guarantee consumers' privacy.

However, existing studies on the application of 5G to DR are far from adequate, because 5G has not entered the large-scale commercial stage, and therefore its full potential has not been studied.

1.4. Contributions

In order to provide more references for 5G application in smart grids, this paper attempts to comprehensively survey the combination of DR with 5G technology and IoTs. The importance and main contributions of this paper can be summarized as follows:

- The concept of DR and recent practical advances are investigated, especially the application of communication technologies to DR. Moreover, a comprehensive review of the cyber security, consumer privacy, and reliability of DR are presented. These topics received little attention in the past, though they will be among the most crucial factors in the future.
- The technologies of 1G − 5G networks are analyzed and compared

to highlight the essential features of 5G, including millimeter wave (mmWave), massive multiple-input multiple-output (MIMO), and ultra-dense cellular networks. On this basis, three typical 5G application scenarios are proposed, namely: eMBB, uRLLC, and mMTC.
- The application of 5G to DR is studied, including the technology's ability to link to massive numbers of flexible loads, fast data transfer speed for remote control, robust security for protecting consumer privacy, high reliability for ensuring DR effectiveness, and low power consumption for promoting 5G devices widely.
- The future work that must urgently be conducted in order to achieve the application of 5G to DR is proposed, including ubiquitous data acquisition, data visualization, real-time state awareness, intelligent distribution networks, precise load control, edge computing, network security, and new business models.

In summary, this paper carries out a survey of the application potential of 5G to DR, and does so prior to 5G technology entering the large-scale commercial stage. This paper can provide important references and guidelines for developing future 5G networks in the smart grid paradigm.

1.5. Organization

The remainder of this paper is organized as shown in Fig. 1. Section 2 presents the concept of DR and recent practical advances, especially the application of communication technologies to DR. The cyber security, consumer privacy, and reliability of DR are also surveyed in Section 2. Then, the essential features and typical application scenarios of 5G are investigated in Section 3. Next, the advantages, recent advances, and planning of 5G for DR around the world are studied in Section 4. Future work important for the application of 5G to DR in smart grids is proposed in Section 5. Finally, Section 6 concludes the paper.

2. Demand response in smart grid

2.1. The concept of DR

DR refers to adjusting users' power consumption (e.g. water heaters, air conditioners, refrigerators, washing machines) in order to maintain power system balance, decrease the peak-valley load difference, and increase the power system's social welfare [10–12]. In order to illustrate the concept of DR more clearly, power systems with and without DR are compared in Fig. 2. Fig. 2(a)–(c) are scenarios without DR, and Fig. 2(d)–(f) are scenarios with DR. It is assumed that frequency deviation is caused by a sudden load disturbance. Then, the power system will pass through three stages, namely: the initial balance state, the occurrence of the load disturbance, and the rebalance state.

As shown in Fig. 2(a), the power system without DR is operating in the balance state. The generation power is equal to the consumption power, which can be expressed as

$$P_G(f) = P_D(f) \tag{1}$$

where $P_G(f)$ and $P_D(f)$ are the functions of the generation power and consumption power relating to the system frequency, respectively. The $P_D(f)$ is a vertical, indicating that the loads have no elasticity, i.e. no DR. In addition, note that in order to simplify the description, the loss of power during the transmission process is neglected here.

As shown in Fig. 2(b), when the load disturbance ΔP_D occurs, power consumption will suddenly increase from P_{D0} to P_{D1}, while power generation cannot be regulated instantly. Therefore, power system frequency will decrease from f_0 to f_1 under the primary frequency regulation of generators.

As shown in Fig. 2(c), under secondary and tertiary frequency regulations, the generators increase the power output ΔP_G to rebalance the power system and finally recover the rated system frequency. The rebalance state can be expressed as

$$P_G(f) + \Delta P_G = P_D(f) + \Delta P_D \tag{2}$$

In the second scenario with DR, i.e., Fig. 2(d)–(f), the load curve $\widetilde{P}_D(f)$ becomes slanted and related to system frequency. Load power will decrease as the system frequency drops; conversely, load power will increase as the system frequency rises. In other words, load power becomes elastic, and can be adjusted with changes to the power system state. However, only the loads participating in DR can be adjusted. Therefore, the load curve $\widetilde{P}_D(f)$ has a lower- and upper-limit. In

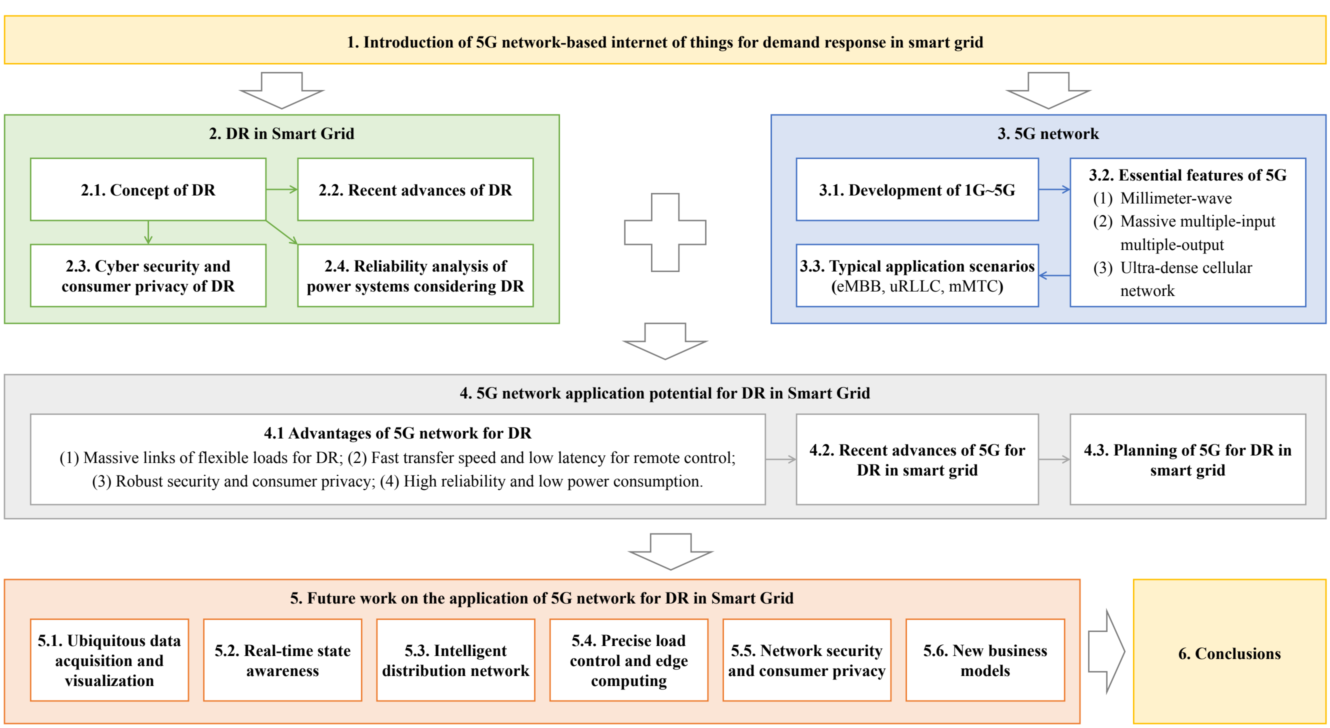

Fig. 1. The structure of this paper.

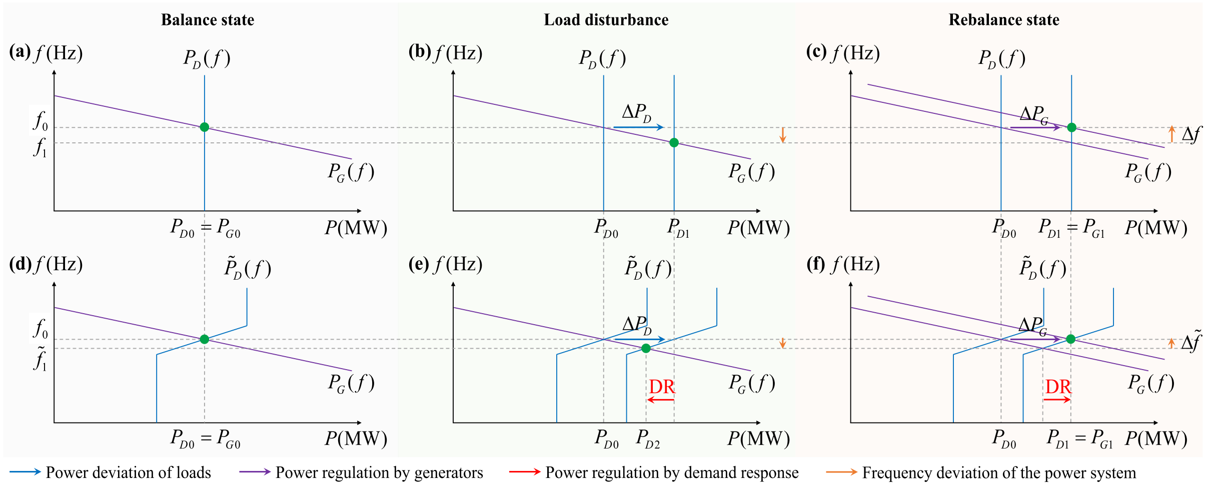

Fig. 2. The power system deviation processes caused by a sudden load disturbance. (a) The system balance state in w/o DR scenario; (b) The sudden load disturbance causes the system frequency deviation in w/o DR scenario; (c) The system rebalance state after the regulation of generators in w/o DR scenario; (d) The system balance state in w/ DR scenario; (e) The sudden load disturbance causes the system frequency deviation in w/ DR scenario; (c) The system rebalance state after the regulation of generators in w/ DR scenario.

Fig. 2(d), the power system is operating in the balance state, which is similar to the scenario in Fig. 2(a). When the same load disturbance ΔP_D occurs in Fig. 2(e), the power consumption will increase from P_{D0} to P_{D2}. Note that P_{D2} is smaller than P_{D1} because of the reduction of loads by DR. Therefore, it can be seen from Fig. 2(e) that the system frequency deviation $\Delta\tilde{f}$ is smaller than Δf in Fig. 2(b).

Finally, as shown in Fig. 2(f), the generators increase the power output ΔP_G to recover system balance. In the meantime, DR will be over, and stop to control loads. Therefore, the essence of DR consists in increasing the load flexibility to maintain power system balance.

Moreover, in some researches, DR also includes onsite standby generated energies, e.g. low power diesel generators, photovoltaic power, energy batteries, and electric vehicles [2,3,10]. Therefore, the rebalance state of the power system with DR can be transformed from Eq. to

$$P_G(f) + \Delta P_G + \Delta P_G^{DR} = \widetilde{P}_D(f) + \Delta P_D + \Delta P_D^{DR} \tag{3}$$

where ΔP_G^{DR} is the generation power from onsite standby energies, and ΔP_D^{DR} is the adjustment power by flexible loads. Both ΔP_G^{DR} and ΔP_D^{DR} belong to the regulation power provided by DR.

Generally, DR can be divided into two categories, the price-based DR and incentive-based DR [43]:

- The price-based DR is to influence users' power consumption by time-varying prices [44], including time-of-use (TOU), critical peak pricing (CPP), and real time pricing (RTP) [45].
- The incentive-based DR is to motivate users to reduce power consumption at some periods by offering payments [44], including the interruptible load (IL), direct load control (DLC), and frequency controlled load curtailment [46]. Besides, some literatures further divided the incentive-based DR into classical programs and market-based programs [47]. The above IL, DLC and frequency controlled load curtailment belong to classical programs, while the market-based programs include demand bidding, emergency DR, capacity market and ancillary services [47].

2.2. Recent practical advances of DR

In this paper, the practical advances of DR in recent years are surveyed mainly in three regions: the European countries, USA, and China.

In Europe, there has been an overall increase of interest in enabling DR in almost all European countries, and notable progress has been achieved in some markets. For examples, the new smart meters are developed by "Enel Info + ", "FLEXICIENCY", and the "Smart Demo Grid" projects, which have a dedicated communication channel with Home Area Networks [48]. On this basis, DR aggregators can meet the requirement that each DR unit supports real-time bi-directional communication with the national control center [48]. In Denmark, some field experiments on refrigerators, wastewater treatment plants, and electric space heaters have been carried out, which verify that this equipment can be regulated quickly to provide power systems with frequency regulation services [49]. In addition, in Romania, advanced metering management systems have been installed in around 1300 households and small economic operators (low voltage consumers) with fibre optics and GPRS, and power line communication systems have been constructed from low to medium voltage systems [50]. The "*Scalable Energy Management Infrastructure for Aggregation of Households*" project developed an appropriate system for enabling aggregators to control large-scale residential appliances effectively, which has been field tested in Norway and Switzerland [51]. Also, the UK government plans to offer a smart meter that will allow two-way communication between suppliers and consumers for every household over the next decade [52].

In the USA, the *Lawrence Berkeley National Laboratory* with SCE, SDG &E, and PG&E created OpenADR to implement DR [53]. On this basis, electricity providers and system operators can communicate DR signals with each other and their consumers using a common language within milliseconds [54]. Moreover, OpenADR 2.0 has also been developed, which includes fast response services, such as frequency regulation services for power systems [55]. In 2013, a project enabling Auto-DR in large commercial buildings was conducted in New York City using OpenADR [56]. In addition, EnerNOC (a DR aggregator) developed a Network Operating Center to directly control the appliances of industrial- and commercial-sized end-consumers, including HVAC systems, lighting, and pumps [57]. Based on the evaluation report of ComEd [58], the benefits of implementing advanced metering infrastructures, wireless, radio frequency communication networks, and IT systems, can exceed the corresponding costs.

In China, over the last ten years, the *State Grid Corporation of China* (SGCC) has carried out many projects to build two-way instant communication systems for carrying out DR. Some examples: intelligent community projects in Beijing [59] and Jiangxi Province [60], an intelligent building project in Shanghai [61], the ubiquitous electric IoTs in Qingdao City [62], and a source-grid-load project in Jiangsu Province [63].

Table 1 lists some DR projects in China. The first of these is the "*Large-scale Source-Grid-Load Friendly Interactive System*" project [63–65], whose main purpose is to control loads on a time scale of milliseconds to avoid the sharp drops in system frequency caused by failures of the Ultra High Voltage Direct Current transmission line. After three phases of construction from 2012 to 2018, around 2600 MW loads have been connected to the optical fibre communication network, and can be controlled at millisecond level [66,67]. Based on the construction plan, by 2020, around 10,000 MW loads will be covered by the optical fibre communication network to achieve precise control at millisecond level [68,69]. Recently, this system has been promoted and constructed in six other provinces in China [67].

The second project listed in Table 1 is the "*Control System Reformation of Air Conditioning Systems in Public Buildings*", which was implemented from 2015 to 2017. Control systems of air conditioners in public buildings were modified to achieve flexible regulation. By 2016, around 1337 public buildings, 500 commercial buildings, and 400 industrial buildings had been transformed, and the total controllable capacity reached 335 MW. In addition, residential consumers' air conditioning systems were also modified starting in 2017, and the controllable capacity will reach 2000 MW by 2020.

To summarize, improved ICTs have made more and more grid companies across the world pay attention to the construction of instant communication systems to achieve grid-consumer interaction. On this basis, consumers can get more information about their own power consumption, and have more opportunities to participate in DR to get benefits. At the same time, the social welfare of the power system can be increased.

2.3. Cyber security and consumer privacy of DR

With the development of ICTs and IoTs, cyber security and consumer privacy have become one of the most critical social issues to the public [71]. In existing DR projects and corresponding communication systems, more attention has been paid to cyber security. Examples include OpenADR in the USA, and "*Control System Reformation of Air Conditioning Systems in Public Buildings*" in China (see Table 1).

OpenADR in the USA can fulfill the industry security requirements and the *National Institute of Standards and Technology Cyber Security* guidelines by maintaining its own Public Key Infrastructure (PKI) [72]. The PKI uses the server and client-side digital certificates to ensure that only clients and servers can communicate with each other. This means that both OpenADR Servers and OpenADR Clients need to purchase the valid OpenADR-specific digital certificates to authenticate communication links. Additionally, Rivest-Shamir-Adleman (RSA) encryption and elliptic curve cryptography (ECC) algorithms are used in OpenADR [72,73]. In this manner, transport layer security can be strongly guaranteed.

The cyber security protection framework in the project "*Control System Reformation of Air Conditioning Systems in Public Buildings*" in China is shown in Fig. 3. Note that there are two types of communication systems for the power systems' operation, i.e. private network and extranet. The system operator is in zone I of the private network, which is the highest level of security for the real-time control of the power system. The monitoring and control of air conditioning systems for DR are in zone III of the private network, which includes the primary station, the information security access platform, the virtual private network, and the monitoring and control terminals. Only information such as electricity bills and DR bonuses are released via the extranet. In this way, the communication systems for the power system and DR control can achieve physical isolation with the extranet. Furthermore, the security encryption chip technology that was developed in this project has been used in the monitoring and control terminals of air conditioning systems, as shown in Fig. 3.

2.4. Reliability analysis of power systems considering DR

Compared with traditional generating units, the regulation power provided by DR has more uncertainties, caused by consumers' social-behavioral factors [74], diverse types of loads [75], and random failures of ICTs [77]. Therefore, DR's uncertainties and the impacts thereof

Table 1
Some projects on the DR and communication network in China.

Project	Location	Year	Communication modes and remarks
Large-scale source-grid-load friendly interactive system	Suzhou, Qinhuai, Huiquan, Maoshan, and Fangxian	2012–2016	Optical fiber communication network. 800 MW, 2000 MW and 2600 MW controllable loads in the first, second and third phases of the project by 2016, 2017 and 2018.
Control system reformation of air conditioning systems in public buildings	Nanjing, Wuxi, Xuzhou, Changzhou, Suzhou, Nantong, Lianyungang, Yancheng, Yangzhou, Zhenjiang, and Suqian	2015–2017	GPRS, CDMA/3G, wireless private network. 1100 public buildings' air conditioning systems (around 150 MW) was reformed in 2013; 237 public buildings' air conditioning systems (around 55 MW) was reformed in 2014; 500 commercial buildings' air conditioning systems (around 100 MW) was reformed in 2015; 400 industrial buildings' air conditioning systems (around 30 MW) was reformed in 2016; more than 2000 MW residential air conditioning systems will be reformed by 2020.
Application of demand side management technology	Changzhou	2015	Wireless private network.
Power optical fiber landing residence project	Changzhou	2016	Lay optical fiber communication network to the industrial, commercial, and residential consumers.
Construction of optical fiber communication for the distributed PV system	Suzhou	2016	All-dielectric self-supporting (ADSS) cable (a type of optical fiber cable).
Free distribution of smart devices in intelligent communities	Changzhou and Suzhou	2016	Provide 100,000 smart terminal controllers for free to around 50,000 residential consumers.
Research and application of low voltage power line broadband carrier technology	Jiangsu Province	2016	Infrastructure transformation for around 200,000 consumers.
Development of the intelligent interactive service platform	Jiangsu Province	2016	Monitor the operating states of flexible loads. Consumers can participate in DR by the APP on the mobile phones.
Construction of the intelligent home and communities	Suzhou	2016	Develop the smart devices and 4G communication network.
Construction of the intelligent buildings	Changzhou and Suzhou	2016	Develop the Building Management System by the Ethernet passive optical network (EPON).
Construction of the management platform for integrated energy	Changzhou City	2017	Monitor and control of the comprehensive energies, including the power system, heating system, gas system, and water supply system.
Friendly interactive system of supply and demand [70]	Suzhou and Changzhou	2016–2020	Focus on the residential consumers. Around 110,000 houses are installed with smart devices.

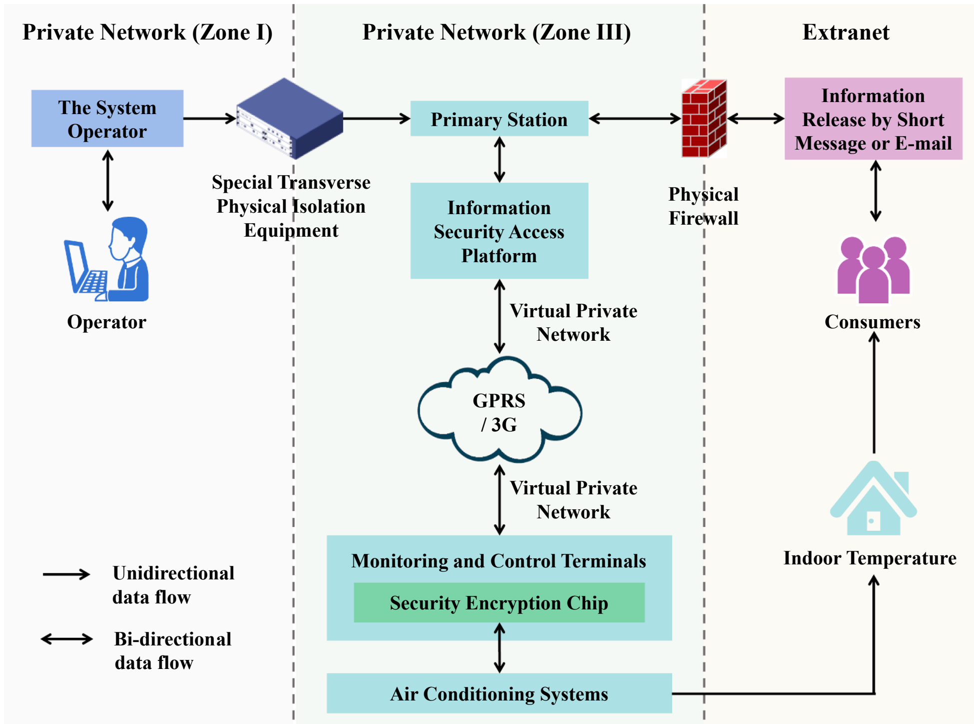

Fig. 3. The cyber security protection framework in the DR project “Control system reformation of air conditioning systems in public buildings”.

on a power system’s reliability should be analyzed to ensure secure and stable operation.

In [74], the regulation power associated with an incentive-based DR is evaluated, combining a technical model of flexible loads and a social-behavioral survey method. The results show that the actual regulation power of DR depends on: load types, geographic positions, ambient temperatures, and subsidy values. Therefore, utilities should comprehensively consider various factors to compare the expenses for reducing peak load by DR and the construction costs of new generating units. In [75], a multi-state reliability model of operating reserve provided by thermostatically controlled loads is proposed in order to consider the loads’ dynamic response during the reserve deployment process. The results show that regulation capacity by DR is different from conventional regulation by generating units, and the

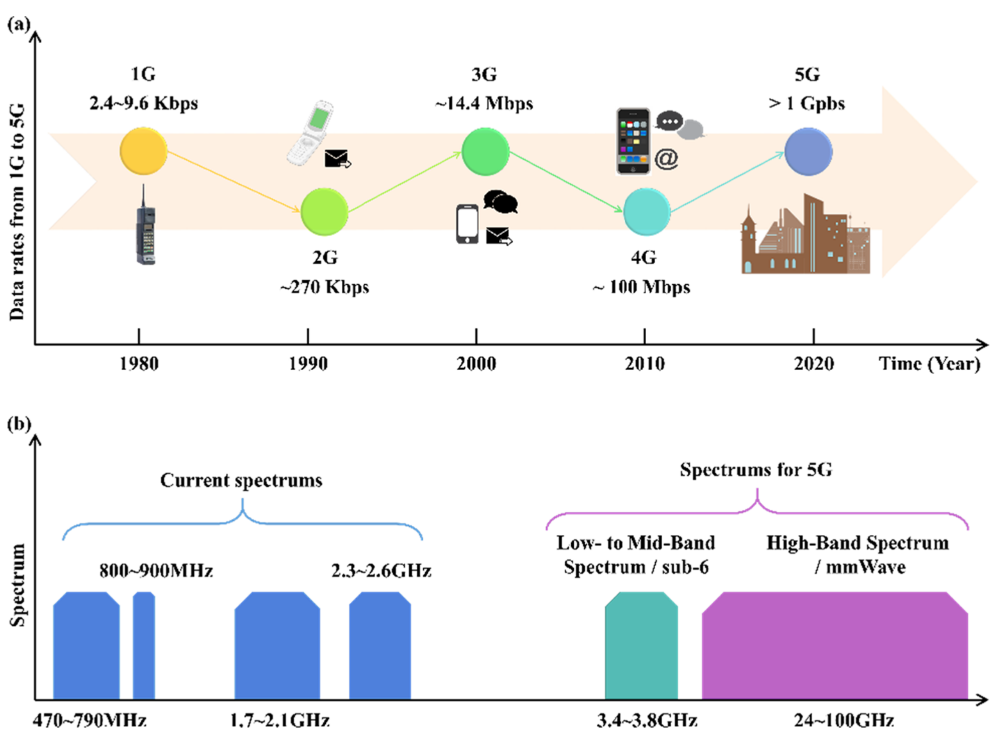

Fig. 4. The development process and frequency spectrum characteristics from 1G to 5G communications [85–89].

short-term reliability of the power system can be impacted by DR. In [76], the reliability-driven and market-driven measures of DR is utilized to develop the risk-cost-based unit commitment model mixed with demand-side resources, which revealed that the cost and risk level of power systems can be reduced by DR.

In addition, reliability-network-equivalent and time-sequential simulation methods are proposed in [77] to evaluate the reliability of power systems with flexible loads. The results illustrate that the curtailment and shifting of uncertainties from consumers' behaviors, random failures during the signal transmission process, and the different types of loads can indeed impact the power system's reliability. This conclusion reminds us that the regulation capacities provided by DR may decrease the system's reliability, rather than the DR certainly always increasing the power system's reliability. In [78], the reliability impacts of DR uncertainties on wind-integrated power systems are analyzed, showing that DR programs can eliminate the negative impacts of wind power volatility on a power system's reliability, while DR uncertainties can significantly affect the efficiency of DR programs.

In summary, DR generally plays a positive role in increasing a power system's reliability [79]. However, the premise here is that the random failures of ICTs are restricted to a small range, and the consumers' social-behavioral factors and load types are fully considered during the regulation process.

3. Essential features and typical application scenarios of 5G network

3.1. Development of 1G − 5G networks

Mobile wireless technologies have been developed for decades, from the first generation (1G) in the late 1970s, to 5G in the 2020s [80]. Each wireless generation has evolved every decade. Fig. 4(a) shows the development process and the data rates from 1G to 5G [80]. It can be seen that the 1G data rate is only between 2.4 and 9.6 Kbps, which belongs to the analog communication, and which can only carry voice calls [80]. After that, the next generations (2G ~ 5G) all belong to digital communication, with 2G transfer speed clocking in at around 100 times that of 1G, and capable of delivering up to 270 Kbps. However, this data rate still cannot transfer rich information, e.g. images. It is mainly used to send text messages [81]. The data transfer rate of 3G technology can reach 14.4 Mbps in stationary state and 350Kbps in mobile state [82], which enabled more applications, such as video calling, multimedia messages, and transfer control signals for DR.

Nowadays, 4G technology is in wide use globally, and can support 300 Mbps with the latest release (number twelve) [82,83]. By utilizing fast transfer speed, the Internet of Things (IoTs) are proposed to connect more devices and achieve intelligent system functions, such as smart homes, smart buildings, and smart electric power and energy systems

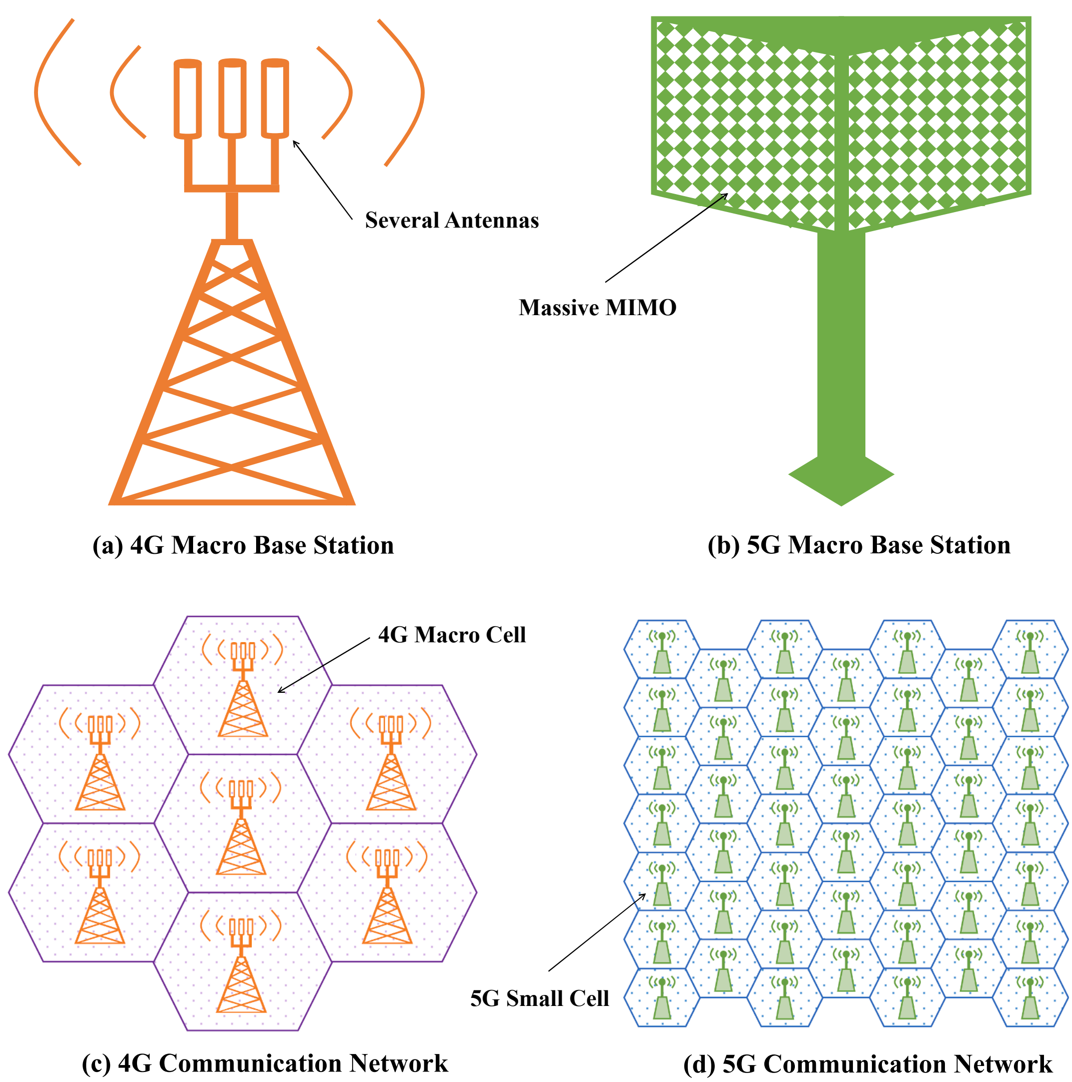

Fig. 5. The essential features of 5G communication. (a) 4G macro base station; (b) 5G macro base station with massive MIMO; (c) 4G communication network; (d) 5G communication network [91].

[84]. However, even though the data transfer rate of 4G is enormously greater than that of previous generations, some problems still exist and hamper the wide application of IoTs, e.g. limits to the number of connected devices, inevitable communication latency, and information security for ensuring consumers' privacy.

Faced with these issues, 5G technology is proposed to achieve faster transfer speed, low communication latency, high security, and massive numbers of connected devices. The main difference between 5G and the previous generations is the electromagnetic wave frequency spectrum, as shown in Fig. 4(b) [85–89]. Compared with the currently used frequency spectrums, the wave frequency for 5G is higher and includes two spectrum ranges. The first spectrum range, named "low- to mid-band spectrum" or "sub-6", is below 6 GHz [82,86]. The other spectrum range, called "high-band spectrum", is between 24 GHz and 100 GHz [88]. Both of 5G's frequency spectrums are higher than the current counterparts, and this fact brings with it a number of different characteristics compared to the previous generations. The essential features of 5G are presented concretely in the next subsection.

3.2. Essential features of the 5G network

(1) Millimeter-wave (mmWave)

The relationship between the wavelength λ and the wave frequency f can be expressed as

$$\lambda = \frac{v}{f} = \frac{c}{f} \tag{4}$$

where v is the phase speed of the wave. As for different kinds of electromagnetic waves, the speed v is regarded as the same and equal to the light speed c. Therefore, the wavelength λ will decrease as the wave frequency f increases [32].

It can be seen from Fig. 4(b) that 5G has the highest wave frequency in the range of 3.4–3.8 GHz and 24–100 GHz. As the light speed is around $3 \times 10^8 m/s$, the wavelength of 5G can reach 3 mm when the frequency is 100 GHz. Therefore, the high-band spectrum of 5G is also called the millimeter-wave (mmWave) [90]. The shorter wavelengths of mmWave can create narrower beams, so that the mmWave can transmit data with higher speed, lower latency, better resolution, and more security [82]. Besides, mmWaves have larger bandwidth and avoid congestion during the transfer process.

(2) Massive multiple-input multiple-output (MIMO)

The components for mmWave (i.e., high-band spectrum) are smaller than the components for the current low-band spectrum, which allows more antennas to be deployed by wireless devices. It is called "massive multiple-input multiple-output" (MIMO) technology [82]. Sketches of 4G and 5G macro base stations are shown in Fig. 5(a) and (b), respectively [91]. The number of antennas in 4G communication equipment is generally 8, while the number of antennas for a 5G device can reach 32 to 256 [92]. It has been proven that massive MIMO technology can achieve dramatic improvements in transfer capacity [84], interference management [93,94], and energy efficiency [95,96]. Moreover, 5G's transmission bandwidth, data throughput, and spectrum efficiency can also be extended and improved by massive MIMO [97–99].

(3) Ultra-dense cellular networks

5G's shorter wavelength and narrower beams indeed increase data transfer speed and security, while also restricting transmission distance: mmWaves' transmission distance is around 100 m [100]. Besides, mmWaves can be easily blocked by obstacles, such as walls, foliage, and people's bodies [82]. Therefore, in order to guarantee the seamless coverage of 5G cellular networks, a larger number of 5G small cells have to be deployed, which is called the ultra-dense cellular network [100]. Generally, the density of macro base stations (BS) for 3G and 4G networks is around 4–5 BS/km^2 and 8–10 BS/km^2, respectively.

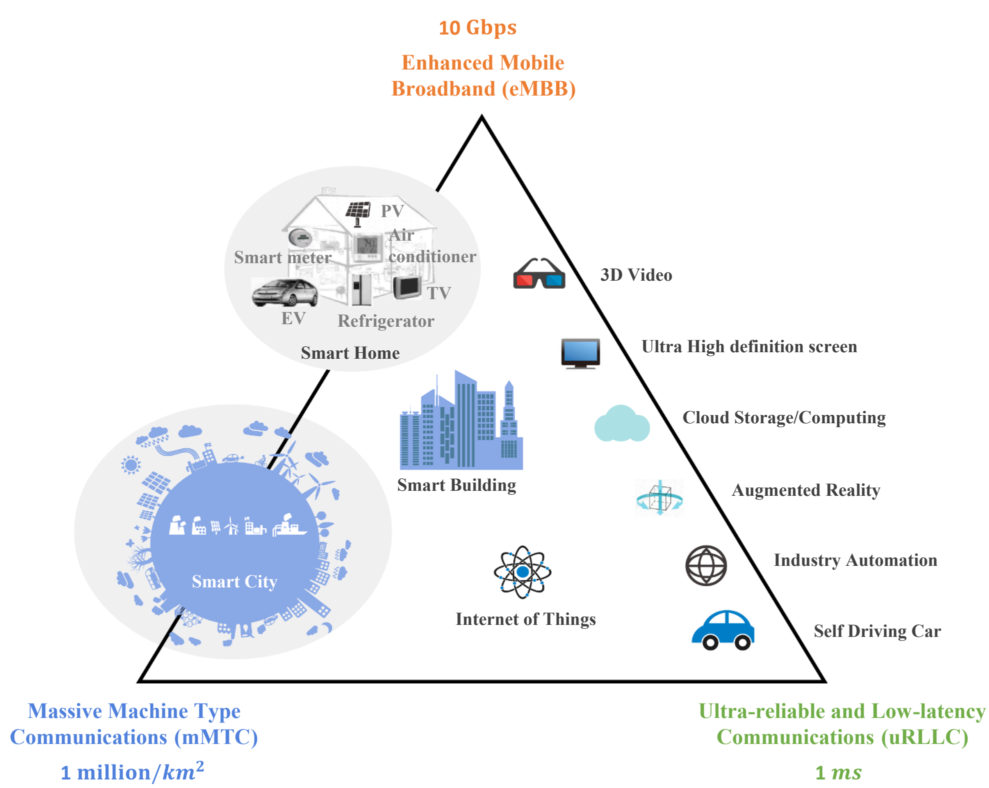

Fig. 6. The typical application scenarios of 5G communication technology, including the enhanced mobile broadband (eMBB), the ultra-reliable and low-latency communications (uRLLC), and the massive machine type communications (mMTC) [33,104].

However, the density of 5G base stations is anticipated to be 40–50 BS/km^2 [100]. A density comparison between base stations for 4G and 5G networks is shown in Fig. 5(c) and (d), respectively.

3.3. Typical application scenarios of the 5G network

As shown in Fig. 6, the typical application scenarios of 5G include: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (uRLLC), and massive machine type communications (mMTC) [33,34]. The eMBB focuses on fast data transfer speed services by providing large bandwidth. Its peak transfer speed can reach 20 Gbps, and the speed can come up to 10 Mbps in each square meter [35]. Therefore, eMBB can be used for 3D video, ultra-high definition screens, cloud storage, cloud computing, and augmented reality. Next, uRLLC aims to achieve remote control with very small latency [101] and high reliability [102]. Latency is defined as the period from the data-sending moment by the base station to the data-receiving moment by terminal devices, which is decreased to 1 ms, and can satisfy the requirements of industry automation and automated driving [38]. Lastly, mMTC is for connecting massive numbers of devices. The number of devices connected to a 5G network can reach 1 million/km^2, making it possible to develop smart homes, smart buildings, and smart cities [103,104].

4. 5G network application potential for DR in smart grids

4.1. Advantages of 5G networks for DR

Based on the above analysis, 5G technologies exhibit lots of advantages for use in smart grids for carrying out DR, such as massive links, fast transfer speed, robust security, high reliability, and low power consumption. All these advantages can significantly influence the effectiveness of DR.

(1) Massive links of flexible loads for DR

Fig. 7 shows three control frameworks of flexible loads for providing DR. Fig. 7(a) is the traditional control method, i.e. by installing the controller on the tie-line between the microgrid and the main grid. When a generating unit failure occurs, when peak load occurs, or when total electricity consumption exceeds the monthly maximum limiting quantity, the controller will cut off all power supply in the microgrid [105]. Obviously, this will seriously impact the users' lives and production. This method of controlling the entire microgrid is mainly implemented by administrative means, especially in situations with insufficient power supply. Lastly, in this framework, each user's financial compensation cannot be calculated accurately, because each user's real-time electric power cannot be measured, which is unreasonable and unfair to users [105].

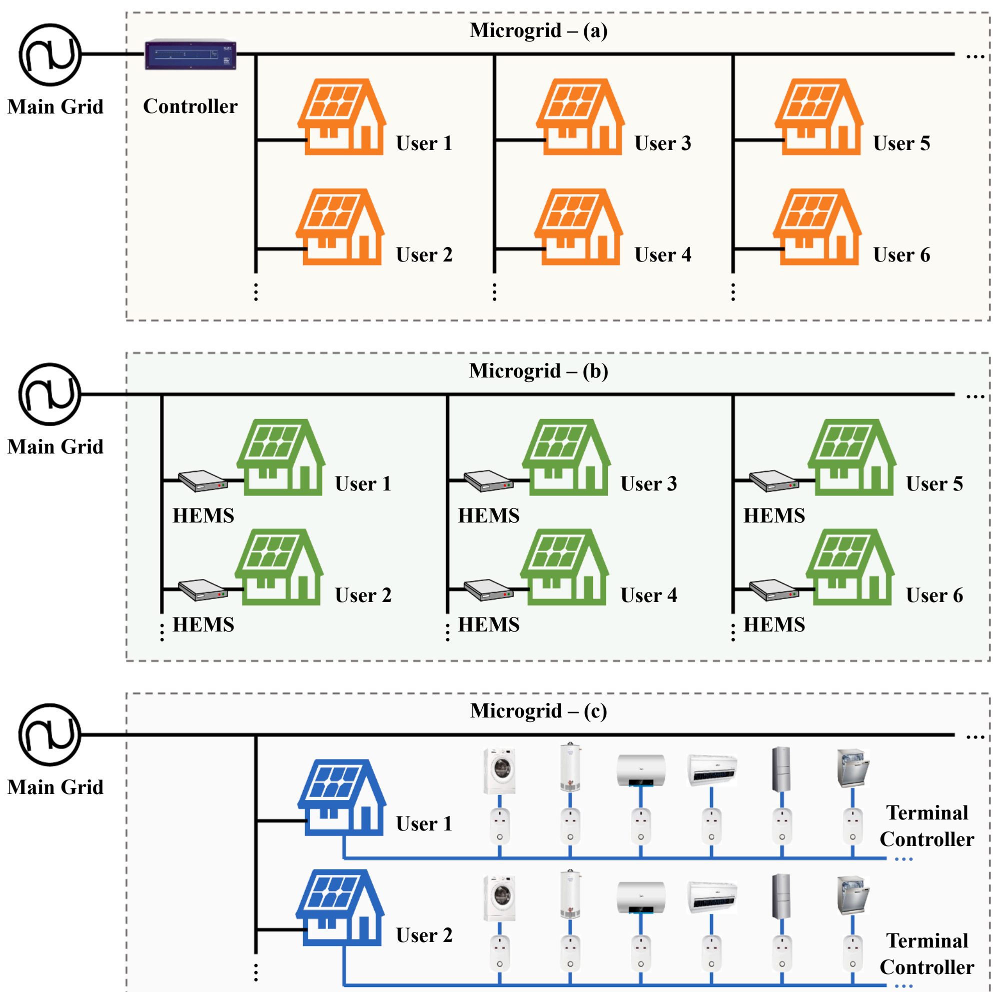

Fig. 7. The massive links of flexible loads for DR. In Microgrid (a), the DR is realized by the controller installed on the tie-line between the microgrid and the main grid. In Microgrid (b), the DR is realized by the home energy management system (HEMS). In the Microgrid (c), the DR is realized by the massive terminal controllers.

As shown in Fig. 7(b), with the development of smart meters, each user's power consumption can be monitored in smaller time intervals [106]. On this basis, the home energy management system (HEMS) is proposed to manage power consumption in each house [107,108]. Only the users who have participated in the DR program need to be controlled in order to cut electricity consumption. There is no need to cut off all power supply in the microgrid, as seen in Fig. 7(a). Therefore, DR becomes more reasonable, and users can get fair and clear financial compensation.

With further improvement of ICTs, especially 5G communication, the mMTC scenario can be used for DR. Because the number of devices connected to a 5G network can reach 1 million/km^2 [33], all appliances can be linked and controlled by the terminal controllers or their built-in controllers. In this way, various loads can be monitored, managed, and adjusted precisely. For example, air conditioners nowadays are mainly controlled to provide DR by switching between on- and off-states periodically [5], but with 5G networks they could be regulated by adjusting set temperatures or compressors' operating frequencies [19,29]. Compared with the on-off control method, the set temperature or compressor frequency adjusting method has less impact on consumer comfort and on appliances' operating life [14].

In summary, the mMTC feature of 5G can achieve massive numbers of links among various loads, which makes DR control more precise and more acceptable by participants.

(2) Fast transfer speed and low communication latency for remote control

RESs are increasing in power systems and beginning to replace traditional generating units, which makes frequency regulation services more important to the prompt maintenance of system balance [5]. Fig. 8 shows a system frequency regulation model with DR [29]. Δf_i and Δf_j are the frequency deviations in the area-i and area-j, respectively. $R_{G,i}$, $B_{G,i}$ and $K_{G,i}$ are the speed droop parameter, frequency bias parameter, and integral gain of the generator, respectively. $T_{g,i}$, $T_{t,i}$ and $T_{r,i}$ are the time constants of the governor, steam turbine, and reheat turbine, respectively. $F_{HP,i}$ is the power fraction of the reheat turbine. $T_{p,i}$ and $K_{p,i}$ are the inertia time constant and frequency damping factor of the power system, respectively. T_{i-j} and $\Delta P_{Tie,i-j}$ are the tie-line time constant and the tie-line power deviation between area-i and area-j, respectively. $\Delta P_{Tie,i}$ is the total tie-line power deviations in area-i.

When power deviation $\Delta P_{L,i}$ occurs, system frequency and area control error ΔACE_i will deviate from the rated values. Then, the generating units will regulate the power generation $\Delta P_{G,i}$ to recover the system frequency. When DR is considered in the power system, the DR aggregator can also receive the ΔACE_i and send control signals to users to adjust power consumption and provide regulation power $\Delta P_{DR,i}$. However, the measurement and data transfer of ΔACE_i have delays [109]. There are also some transmission delays with the control signals, from the time-of-sending by the DR aggregator to the time-of-receiving by each terminal controller [31]. It has been illustrated that the system frequency regulation process will become unstable when delay time is over 0.4–0.5 s [110,111].

If the communication method adopts the 5G network, the uRLLC feature can decrease the delay time to 1 ms, which is small enough to be neglected for frequency regulation services [112]. Therefore, instability and oscillations during the frequency regulation process can be avoided by the 5G network.

(3) Robust security and consumer privacy

Improved ICTs make cyber security and data privacy one of the most critical concerns to consumers [71]. Faced with this issue, 5G network architecture can enhance data transfer security, and support diversified services via end-to-end service level agreement (SLA) assurance [113]. Based on network function virtualization (NFV) [40] and software-defined networking (SDN) [114], 5G physical infrastructure can generate corresponding network topologies and a series of network function sets for tailor-made services, which is referred to as network slices [33]. 5G network slices are separated from each other, and can be regarded as individual structures. The 5G network slice is similar to the private network for the real-time control of power systems in China, as described in Section 2.3 of this paper. Therefore, control signals and power consumption data in DR can be transferred using a customized 5G network slice, which will more securely preserve consumers' privacy [41,42].

(4) High reliability and low power consumption

As mentioned in Section 2.4, the effectiveness of DR is significantly related to the rate of success of data transfer. Random failures during the DR signal transmission process can indeed impact the power system's reliability and stability [77]. Based on the test of factory automation in [38], the uRLLC feature of 5G networks can guarantee submillisecond radio transmission with a failure rate as low as 10^{-9}, which is reliable enough to support DR in power systems.

Moreover, the energy transfer capability of 5G is 100 times greater than that of 4G [35]. This means that the transferred number of bits per Joule of energy can increase more than 100 times with 5G, as compared with 4G. Low power consumption can contribute to the wide promotion and application of 5G-based terminal controllers for achieving the linking of massive numbers of appliances.

4.2. Recent advances of 5G for DR in smart grids

Some research has recently been conducted in order to make full use of 5G's advantages in smart grids. In [115], a 5G network framework is

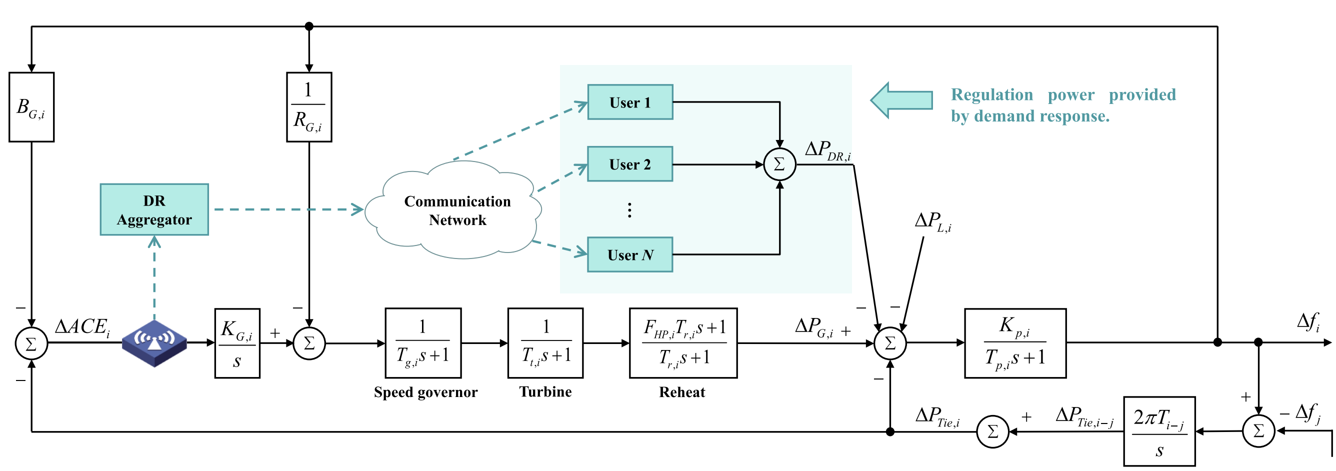

Fig. 8. The transfer function model of power systems with DR.

designed to be used for the generic object oriented substation event (GOOSE) in power systems. This has been tested on the emulated 5G software Open5GCore. The results show that 5G networks are able to transmit time-critical messages (e.g. GOOSE) while satisfying the IEC61850 standard (a standard for power systems automation). In [116], 5G wireless is considered for use in smart grids from an electromagnetic compatibility perspective, which indicates that 5G wireless using the 60 GHz frequency spectrum can be one suitable option for reliable, secure, and cost-effective power system operation. Lastly, in [117], an efficient planning method for 5G small cells is proposed to transmit DR data between aggregators and participant consumers via multimedia broadcast and multicast communication.

Moreover, some researches on mobile edge computing have been done to utilize 5G networks for smart grids. In [118], advanced distributed state estimation methods are placed within the 5G environment by using mMTC and edge computing. The results show that 5G can provide suitable services for mission-critical and real-time applications. In [39], 5G-based fog computing and cloud computing are proposed to connect massive numbers of electric vehicles (EVs) to provide ancillary services for the power system within milliseconds. In [40], an extended mobile edge computing scheme is developed to use 5G technology to reduce backhaul loads and to increase overall network capacity. Furthermore, a privacy-aware power injection scheme is proposed in [41] and [42] for tackling security and privacy issues during the process of massive numbers of EVs providing regulation services to the power system, where 5G slicing technology is also considered.

In sum, some researches on 5G application to smart grids have been done recently. However, these researches were mainly carried out by simulation. Practical tests and demonstration projects are rarely implemented. The following subsection will introduce some actual projects, and the planning of 5G network for smart grids around the world.

4.3. Planning of 5G for DR in smart grids around the world

Due to 5G's advantages—fast transfer speed, high reliability, robust security, low power consumption, and massive links—many countries around the world are stepping up construction of 5G infrastructure, and promoting 5G application to various fields. As for next generation smart grids, electric utilities in North America, China, and Italy are deploying smart meters and even the second generation advanced metering infrastructure (AMI) [119]. Currently, the utility networks for smart meters and AMI mainly adopt radio frequency mesh and power line carrier technologies. These networks will be transformed to 5G wireless, with the growing popularity of 5G technologies.

In Finland, 5G's business value in smart grids is studied in the WIVE project, which is co-funded by the *Finnish Funding Agency for Innovation*, including Nokia, ABB, and Kalmar [120]. The WIVE project focuses on 5G's uRLLC and mMTC features for achieving the remote control of machines with low latency [121]. In addition, the virtual power plant (VPP) project is also being developed in Finland by the energy companies Fortum and Ericsson. This project aims to test 5G and IoTs for carrying out DR [122]. In the VPP project, the batteries will supply power for short periods of time when peak load occurs.

In the UK, 5G networks are considered in order to achieve ubiquitous connectivity in power systems, and to update smart grids to neural grids [123]. Big data, cloud computing, artificial intelligence, edge computing, and pervasive sensing technologies will be used to manage the generating units, distributed networks, renewable energy sources, buildings, consumers, and everything connected to the neural grid [124].

In Europe, the VirtuWind project, supported by the EU Horizon 2020, is being developed in wind parks for control and communication in intra-domain and inter-domain scenarios [125]. Based on 5G's NFV and SDN technologies, the VirtuWind project can reduce the quantity of hardware, and make the control of wind farms faster and simpler.

In China, the SGCC issued the "No. 1 Document" on Jan. 13th, 2019 to guide work over the next ten years, prioritizing above all else the construction of the ubiquitous State Grid electric Internet of Things (named SG-eIoT) [126,127]. The SG-eIoT system will be equipped with comprehensive state awareness functions, efficient information processing functions, and flexible response functions to accelerate the construction of smart homes, and smart cities [128,129]. Additionally, the power wireless private network, Beidou Navigation Satellite System, 5G mobile interconnection, and artificial intelligence technologies are planned to be widely used in the construction of the SG-eIoT system [130,131]. The SGCC predicts that the number of devices connected to the SG-eIoT system will reach 2 billion by 2030, and it will become the largest IoT system at that time [128,129].

5. Future work on the application of 5G networks to DR in smart grids

In the near future, power systems will face more challenges. For example, the increasing penetration of renewable energy sources (RESs) will bring more frequency and voltage fluctuations to power systems due to the intermittent and random characteristics of RESs [132]. The rise of distributed energy resources (DERs) will make more distribution networks change from one-way power flow to bidirectional power flow, known as active distribution networks (ADNs) [2]. Moreover, the power demand is also changing, e.g. rapidly proliferating EVs and distributed energy storage batteries [3].

Despite these many challenges, users' requirements for power quality are becoming higher. For example, some devices require zero interruption of power supply and less fluctuation in system frequency. Therefore, transforming traditional power systems to smart grids is considered one of the most ultimately effective solutions. Smart grids are built based on fast, reliable, and integrated bidirectional communication networks, which are exactly what 5G technologies can support [133,134]. In this section, studies on 5G application in smart grids—that urgently need to be conducted—are put forward.

5.1. Ubiquitous data acquisition and visualization

The mMTC feature of 5G makes it possible to connect all the devices in power systems. Therefore, there will be ubiquitous data from every link of the power systems, including power generation, transmission, substation, distribution, and consumption. Besides these existing data in traditional power systems, DERs, EVs, and energy storage batteries (which are growing trends) can also produce massive data. Hence, more advanced metering infrastructure that can meet various data collection requirements should be developed.

Moreover, in order to achieve accurate measurement of massive data, metering infrastructure should also be capable of high density collection, i.e., high data resolution. For example, previous meters for household users could obtain 1–24 measurement points every day, while current smart meters can obtain 96 measurement points every day, i.e. measuring electric power at every 15 min interval. In 5G networks, the metering infrastructure should obtain more measurement points, e.g. 288 points (every 5 min interval), 1440 points (every 1 min interval), or even more points. It is only in this manner that precise monitoring and control and accurate financial settlement can be achieved [133].

Furthermore, collected ubiquitous data should be displayed in an intuitive way to the corresponding operators or users. For example, the system operator should monitor all the data relating to system balance; the power plant operator should monitor real-time power generation; and users should have access to their power consumption data at any time. The visualization of collected data can makes it easier for operators and users to manage their devices.

5.2. Real-time state awareness

Nowadays, the state awareness of power systems is based on wide-area monitor systems (WAMS) by installing phasor measurement units

(PMU) [109]. However, communication delays are unavoidable, including data uplink delays to the control center, and data downlink delays to each terminal, which may cause power system fluctuations and expand the fault area [31]. The uRLLC feature of 5G can transmit data within 1 ms, which is tiny and contributes to augmenting real-time state awareness capabilities. Therefore, the fault location can be identified ultra-fast using 5G networks, so that the system operator can send control signals in a shorter time to isolate the fault area and guarantee uninterrupted power supply in non-fault areas [135].

Moreover, ultra-fast state awareness can contribute to achieving better state estimation and load forecasting in real time [136]. On this basis, the system operator can have more time to prepare to deal with probable accidents. Therefore, fast real-time algorithms of state awareness, prediction algorithms of cascading failures, and decision-making algorithms of controlling massive action terminals should be further studied.

5.3. Intelligent distribution network

The development of distribution network automation can be divided into three stages [133]. In the first stage, reclosers, circuit breakers, and sectionalizers are the main automatic switching devices, which can work in coordination though they cannot communicate with each other [136]. In the second stage, feeder terminal units, communication networks, and computers are used so that the operator can remotely monitor and control to manage the distribution network. Being built on the second stage, the third stage has automatic control functions, employing supervisory control and data acquisition (SCADA) systems, distribution management systems (DMS), demand side management (DSM) and power distribution geographic information systems [133]. All these functions in the third stage are based on the communication network, which will be improved by using 5G networks.

Future distribution networks will be installed with more DERs, EVs, and energy storage batteries. Most users will have access to DR by intelligently controlling their household appliances and DERs. Therefore, the distribution network operator should have the ability to optimize the power consumption of these multitudinous and diverse loads, and make full use of DERs on the community level [135]. In this way, the distribution network can reduce reliance on the main grid, increase energy utilization efficiency, and decrease energy costs for users.

5.4. Precise load control and edge computing

As shown in Fig. 7, DR changes from cutting down the entire microgrid line to the precise control of various loads. Therefore, we should develop precise load controllers, which are able to monitor the load operating state, transmit real-time operating data, and take action to adjust the load state at the sub-millisecond level.

Furthermore, control algorithms in the controller should also be studied, especially edge computing for enabling local functions [137]. Edge computing is considered a powerful method for addressing many concerns, including communication latency, bandwidth cost reduction, battery life constraint, and data security [138]. Therefore, precise load control may be achieved by edge computing at higher data transfer speed and at lower cost. Moreover, it is essential to make cloud storage and cloud computing collaborate with edge computing.

5.5. Network security and consumer privacy

Power systems are becoming more important among all energy forms, especially with the growth of RESs, DERs, EVs, and batteries. Even though 5G networks can enhance data security via NFV, SDN, and network slicing technologies [33,40,114], there are more open access and potential security risks compared with private optical fibre communication networks and wireless networks, because current private networks for power systems can achieve physical isolation with the extranet, as shown in Fig. 3. However, the physical architecture of 5G networks for power systems uses the same equipment as other functions, so as to decrease the construction cost of 5G networks. Hence, network security and consumer privacy in 5G networks should be further studied. This is a precondition of using 5G for power systems.

5.6. New business models

Traditionally, electricity markets and business models are monopolistic by the government, where users are electricity price takers. Nowadays, several countries have opened electricity markets, where users can buy electricity by negotiating with generation plants [139]. However, these users are mainly large consumers, i.e. at least 10 MW capacities. Small users—e.g. household consumers and small commercial consumers—cannot participate in electricity markets directly. They have to bid or get dynamic electricity prices via aggregators [140].

Small users in near future power systems will have more DERs, EVs, energy storage batteries, and flexible loads. Based on 5G networks and ubiquitous IoTs, all users can buy and sell electricity by themselves. They can sign contracts with the distribution network operator to participate in DR and get benefits. Besides, peer-to-peer transactions within the local community can also be achieved [141].

6. Conclusions

5G networks are emerging and rapidly being deployed around the world, which will bring fundamental changes to all industries. 5G networks can support massive machine interconnections and transmit data very quickly with ultra-reliability and low-latency. These advantages make 5G a better infrastructure for carrying out DR in smart grids. In order to investigate the application potential of 5G networks for DR, this paper first analyzes the recent advancements of DR—such as communication technologies, cyber security methods, and reliability analysis methods. Then, the development and technology of 1G − 5G networks are compared to highlight the essential features of 5G, including mmWave, massive MIMO, and ultra-dense cellular networks. On this basis, three typical 5G application scenarios are proposed, including eMBB, uRLLC, and mMTC.

Based on the technology requirements for DR and the typical application scenarios of 5G, the potential for 5G to be applied to DR is analyzed, touching on massive numbers of links between flexible loads, fast data transfer speed for remote control, robust security for protecting consumer privacy, high reliability for ensuring DR effectiveness, and low power consumption for widely promoting 5G devices. Furthermore, recent advances and planning of 5G for DR around the world are also investigated, e.g. the VPP project in Finland, the neural grid project in UK, the VirtuWind project in Europe, and the SG-eIoT project in China. Finally, future work concerning the application of 5G to DR is proposed. Ubiquitous data acquisition, data visualization, real-time state awareness, intelligent distribution network, precise load control, edge computing, network security, and new business models are considered as important research directions, and urgently need to be developed.

To summarize, this paper carries out a survey of the application potential of 5G to DR prior to 5G technology entering the large-scale commercial stage. Therefore, it provides important references and guidelines for developing future 5G networks in the smart grid paradigm.

Acknowledgements

The research is supported by the National Key Research and Development Program of China under Grant 2016YFB0901100, and the National Natural Science Foundation China and Joint Programming Initiative Urban Europe Call (NSFC–JPI UE) under Grant 71961137004.

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