Received: 30 June 2021 | Revised: 29 August 2021 | Accepted: 9 September 2021

High Voltage

DOI: 10.1049/hve2.12159

REVIEW

Application status and development trends for intelligent perception of distribution network

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Associate Editor: Fuping Zeng

Funding information

National Key Research and Development Program of China, Grant/Award Number: 2019YFE0102900

Abstract

Intelligent perception is the cornerstone of digitalisation of power grid. Due to the closest connection with users, the information perception ability of distribution network directly affects the reliability of power supply. Distribution network has a wide range of geographical distribution and equipment types. The application of intelligent perception is with high complexity and dynamics under the limitation of both technology and management. Therefore, the study first sorts out the current application status of intelligent perception technology and equipment in distribution network from three application fields including distribution automation, metering systems, and inspection. Then, the constraints of existing intelligent perception applications and the key points of further research are pointed out. Finally, the development trends of intelligent perception technology in distribution network are presented from the three aspects of basic technology, perception equipment, and advanced applications. With the improvement of sensing, communication, energy acquisition, chips and perception equipments, the depth and breadth of advanced applications in distribution network will be expanded. The research results can provide references for the follow-up research and practice of intelligent perception in distribution networks.

1 | INTRODUCTION

Under the strategic background of the digitalisation of power grid and the construction of the energy Internet, the construction of the digital grid puts forward higher requirements for the depth, breadth and accuracy of information perception [1]. It requires the real-time perception of the equipment status, operating environment and operating status of each link of power generation, transmission, transformation and distribution [2]. Moreover, a series of data analysis and application can be conducted using the huge amount of sensor data in combination with the new technologies, such as cloud computing, big data analysis, Internet of things, mobile Internet and artificial intelligence. The intelligent perception is the lowest-level data portal of the power Internet of things in many scenarios, that is, the 'Ubiquitous Power Internet of Things' and 'Distribution Internet of Things' of China State Grid [3–5], 'Digital Power Grid' of China Southern Power Gird Corporation [6, 7] and 'Cloud-Tube-Edge-End' architecture of cyber-physical systems [8, 9]. The intelligent perception serves an extremely important role in the digital transformation of the power grid, and it serves as the necessary foundation for power dispatch, monitoring and protection, safe operation and maintenance and online monitoring.

As the last 1 km part of the power system, distribution network is closely connected with users. The reliability of power supply is the focus of distribution network's power supply and service quality. The ability of intelligent perception of distribution network directly affects the reliability of power supply. At present, distribution network realizes real-time perception of distribution network operation status and electricity consumption information measurement through the distributed deployment of distribution terminals and monitoring terminals at the primary side, and electricity meters and concentrators at the secondary side. On this basis, a wide-area sensor network is established to fully control and connect to the sensing terminals in a real-time manner [10]. It builds the distribution automation (DA) system, production management system, advanced measurement infrastructure, power quality monitoring system and user energy efficiency management system. At the application level, it realizes status diagnosis, intelligent decision making, intelligent control, etc., and supports applications in three areas: DA, electric energy metering systems, operation and maintenance. For example, based on the current and voltage sensing of different amplitudes and the frequencies of the equipment itself and lines, distribution network operation status sensing [11, 12] and fault handling [13] are realized. Based on electricity consumption information measurements, it can realize user electricity consumption behaviour analysis [14], load forecasting [15] and comprehensive energy management [16]. Based on intelligent monitoring terminal, inspection instrument, unmanned system, etc., it can realize the status perception, active prediction and early warning, and auxiliary diagnosis of power distribution equipment and substation [17, 18]. Through the monitoring of external environmental variables such as lightning, temperature and humidity, all-weather and all-round status monitoring and risk warning of power distribution equipment in important areas can be realized [19].

Distribution network equipment has the characteristics of wide geographical distribution, various equipment types, diverse network connections, and variable operation modes. Distribution network perception methods involve multiple dimensions such as electrical variables, physical variables, environmental variables, and behaviour variables, etc. The digital integration of the physical network of the power grid and the spatial environment, with its temporal and spatial complexity and dynamics, has higher requirements for intelligent perception. There are some problems in the existing research of distribution network perception technology and application: (1) The existing technologies cannot yet meet the needs of comprehensive perception. The distribution network perception needs to consider both technology and management, so there are restrictions on aspects such as cost, installation, deployment, operation and maintenance [20]. It is impossible to directly transplant the perception technology of the main network, resulting in insufficient accuracy and frequency of sensor measurement, which cannot effectively reflect the real state changes. Besides, the high-stability communication link and networking mode are not mature enough, and the distributed sensing equipment is limited by the ability to obtain and thus the utilization rate is low. (2) The perception equipment has a low level of intelligence and perception mainly depends on manual work. Due to the cost and management, the basic technologies of sensing, energy acquisition and communication in the widely distributed equipment are not advanced. As a result, it is difficult to support the massive data acquisition requirements of distribution network system situation awareness and equipment operation status control [21]. It mainly relies on manual decision making and it is difficult to support the precise management of distribution network. (3) The breadth and depth of support for intelligent advanced applications by distribution network perception such as systems, equipment, and users are insufficient. Under the new power system background, a large number of integrated energy equipment such as renewable generation and energy storage are connected to the distribution network side [22]. It is necessary to strengthen the measurement and monitoring of the distribution system to deal with the challenges brought by distributed power sources and electric vehicles to distribution network.

In recent years, there is rapid progress of basic theoretical methods and cutting-edge technologies [23] in the fields of sensing materials, information communication, equipment manufacturing technology, edge computing, artificial intelligence, etc. They have effectively solved a series of scientific questions, such as sensor measurement, high-speed communication, collaborative integration, intelligent applications, etc. It will promote the comprehensive interconnection, intercommunication, and interoperability of distribution network equipment and realize the comprehensive perception, data integration and intelligent application of distribution network, which will bring huge opportunities for the improvement of distribution network's intelligent perception of observability, controllability and intelligence [24].

In summary, this study first presents the application status, restrictive factors of distribution network perception technology and equipment in the fields of DA, electric energy metering systems, operation and maintenance. Then, the development trends of intelligent perception technology in distribution network are presented from the three aspects of basic technology, perception equipment, and advanced applications. There is an urgent need to break through common technologies, such as advanced device sensitivity mechanisms and system packaging technology, high-speed and high-reliability communication, high-efficiency energy acquisition, high-computing power and high-security chips, to support all elements of distribution network and automatic perception of the entire process. It needs to improve the integration of sensing equipment, primary and secondary integration, and edge intelligent technology to reduce the cost of sensing terminal applications and meet the needs of extensive deployment of sensors and massive data collection in various links. Under the development trend of advanced sensing and sensing equipment, it should expand the advanced application of distribution network perception in the aspects of accurate situation perception, lean management, stereoscopic disaster defence, and integrated energy management. This study aims to provide ideas and procedures for further research and application of intelligent perception of distribution network. The real-time analysis and adaptive optimization decision making could be better achieved under the integration of distribution network system, equipment, users and environment, in order to support the rapid development of new power grid.

2 | APPLICATION STATUS OF INTELLIGENT PERCEPTION OF DISTRIBUTION NETWORK

Generally, the perception of distribution network is divided into three categories: DA, electric energy metering systems, operation and maintenance. Intelligent perception of electrical, physical, and environmental quantities are involved in Figure 1, such as distribution lines, power distribution rooms, station areas and vehicles inspections.

2.1 | Intelligent perception applications in DA

DA systems constitute distribution network wide area measurement system (WAMS), supervisory control and data acquisition and distribution network energy management system (EMS), including phasor measurement unit (PMU), feeder terminal unit (FTU), distribution terminal unit (DTU), transformer terminal unit (TTU), etc [4]. The field equipment realizes the functions of wide-area real-time monitoring, state estimation, model parameter identification and wide-area backup protection of distribution network.

FTU and DTU collect the operating conditions of the distribution system and various monitoring and controlling information, including electrical energy parameters, switch positions, phase-to-phase faults, ground faults, and fault parameters. Then, they execute the commands issued by the power DA master station. FTU mainly collects the data of nearby fault recording indicators, circuit breaker status and environment. DTU mainly collects the automation parameters of protection devices, transformers and other equipment, and realizes remote control of the switch equipment of various electrical circuits. The communication method can be 4G/5G and LoRa, etc. The fault indicator is installed in overhead lines and overhead cable lines by suspension. Fault detection and location are performed by capturing the transient waveform signal at the time of the fault. The communication method is GPRS and 4G, etc.

DA perception applications are mainly divided into two categories: operating status perception and fault handling.

Operating status perception mainly includes status estimation, power quality monitoring, and equipment failure early warning. The state estimation implements distribution network modelling through the WAMS system, involving identification methods for parameter models of distribution networks, loads, distributed power sources, and realizes topology identification and distributed power identification, etc. Power quality monitoring aims at the high-density, decentralised and network-wide characteristics of harmonic pollution in the medium and low voltage distribution network under the background of large-scale distributed harmonic source access, and senses the voltage qualification rate and harmonics, including harmonics and inter-harmonics measurement in distribution grid, multi-harmonic source positioning and harmonic source responsibility division, etc. Harmonic measurement needs to change from deterministic slow time-varying harmonic measurement to fast dynamic harmonic tracking under random

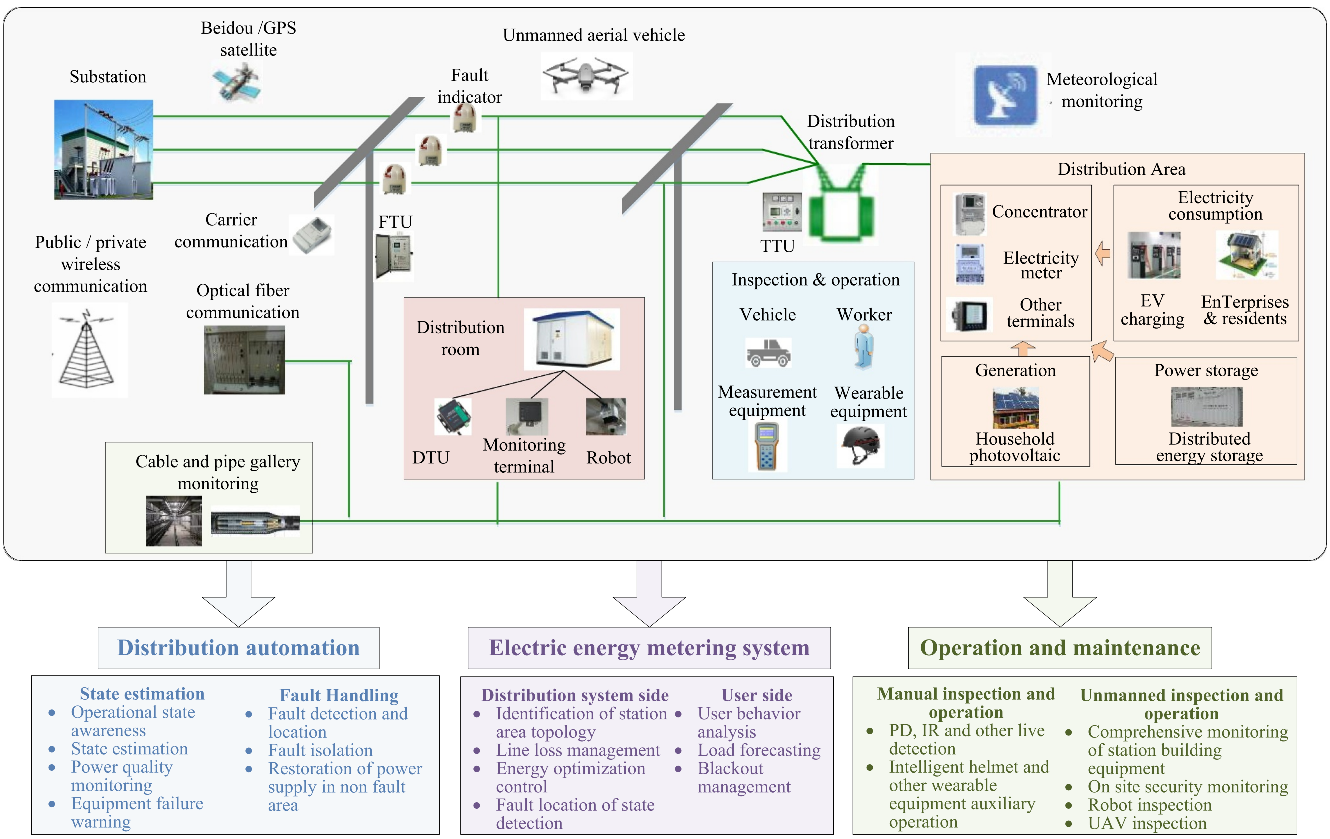

FIGURE 1 Application status framework of intelligent perception of distribution network. DTU, distribution terminal unit; FTU, feeder terminal unit; TTU, transformer terminal unit

conditions, and it is necessary to improve the accuracy and anti-noise ability of the detection sensor [25, 26]. The equipment failure early warning is based on the equipment operating environment and operating conditions to provide early warning of equipment failures. It can also provide early warning of abnormal equipment based on the early arc fault signals that appear intermittently before the fault tripping of distribution network equipment.

Fault handling includes fault detection and location, fault isolation, and rapid power restoration in non-faulty areas. Distribution network fault location is mainly applied to FTU and transient recording faults, which are mainly divided into section location and precise location [27]. In terms of protection and control, the feeder automation (FA) system mainly relies on FTU and DTU to automatically complete the fault section location, isolation and power supply restoration functions of the distribution network line. Currently, there are lots of centralised FA applications [28, 29]. This process requires the cooperation of distribution network automation master station and communication. Distributed FA deploys fault location and isolation functions to the intelligent monitoring terminal of each switch. Optical fibre communication and wireless 4G use adjacent terminals to exchange fault detection information to determine the location of the faulty section, and then trip the switches on both sides of the faulty section to complete the fault isolation. This reduces the power outage time from the original hours to minutes or even seconds. Real-time and accurate information exchange between terminals requires high real-time communication and synchronization accuracy. FTU and other distribution network terminal connections are following real-time control and protection requirements, which should be within 20~100 ms, and the single terminal transmission flow rate is 20 kbit/s. Currently, Ethernet passive optical network (EPON), optical fibre Ethernet, and 4G hybrid networking are widely used.

The application status shows that common basic technologies such as sensing and communication need to be further improved. On the other hand, according to the distribution characteristics of power distribution monitoring stations and grid structure form, the optimised application of power distribution terminal equipment is carried out combined with reliability, construction cost, and distribution requirements.

2.2 | Intelligent perception applications in electric energy metering systems

There is a large amount of electricity distribution perception data, with about 30 million electricity customers, and the monthly growth of data is more than 1 TB. The applications are mainly divided into two sides: the power distribution system side and the user side.

On the distribution system side, it includes station topology recognition, line loss management, power distribution optimization control, and fault detection, etc. The detection of the operating status of the station area includes the identification of the station area topology by using the characteristics of the communication signal between TTU and smart meters, and the automatic identification of the stopped station area is based on the TTU and electricity collection information [30]. Line loss management combines TTU and user data to perform lean management of medium and low-voltage distribution network line losses, and at the same time, identify abnormal conditions such as power theft and leakage according to changes in line loss at different times [31]. Electricity information acquisition system and EMS are used in the optimal control of electricity distribution to realize optimal control of distributed energy, renewable energy power generation, and battery energy storage units [32].

On the user side, it includes user behaviour analysis and user load forecasting. In the analysis of user behaviour, the association model between the electricity consumption parameters is established based on the electricity consumption information data to realize multiple load identification [33]. The user category is identified through the electricity consumption data to provide targeted active services, and simultaneously enhance the power grid management and control capabilities and users' electricity consumption experience. User load forecasting is based on user electricity consumption information and grid load information, predicting the electricity load curve, load time and spatial distribution of each cycle, etc., which can provide information support for grid planning and electric energy deployment.

The application status shows that, on the one hand, since the sensing information of TTU and electricity meters is mainly steady-state data with the collection period at 15-min interval, a large amount of transient information related to the operating state of the system and equipment has not been collected or effectively used. Existing data has insufficient support for system equipment operation status monitoring, accurate location and early warning of faults and harmonics, and cannot be pre-detected for fire safety hazards such as arcs, leakage, and temperature overruns, and faults cannot be accurately located. On the other hand, the data volume is large, and the spatial-temporal characteristics and the correlation have not been effectively mined. There are problems such as the unclear relationship between ‘transformer-line-distribution box-user’ and the low level of automatic recognition of the topological relationship of the station area, which affects the accuracy of optimal control and load forecasting.

2.3 | Intelligent perception applications in operation and maintenance

The operation and maintenance of distribution network equipment is weak. The operation and maintenance personnel basically realize the management of distribution network equipment by means of repairs or replacement. At present, the distribution network status perception method is mainly manual inspection, supplemented by the station integrated sensing terminal, inspection robot, and unmanned aerial vehicle (UAV) inspection.

In terms of manual inspection, the main method is to transplant the detection technologies of high-voltage power systems [34]. In the aspect of insulation fault detection, methods of partial discharge are used to determine the insulation failures. Infrared detectors are used to detect heat failures of a large number of exposed electrical connectors in various station equipment and overhead lines. In terms of inspection process control, wearable inspection equipment such as smart helmets and glasses has been gradually applied to achieve on-site inspection operation quality and personnel safety control. Manual inspection is the main means of distribution network status perception. However, there is a structural shortage of professional operation and maintenance personnel in distribution network, and the human resources of front-line operation and maintenance management do not match the growth rate of distribution network, resulting in high cost and long period of manual inspection. Therefore, how to improve the efficiency of manual inspection and the quality of operations will be the direction of technological development.

In terms of automatic inspection, the integrated monitoring terminal unit (MTU), robots and UAV have become widely developed in recent years, achieving automatic detection of power equipment status by replacing manual inspection. The integrated monitoring terminal is equipped with high-definition visible light cameras, infrared thermal imagers, sound equipment and other intelligent detection devices as well as intelligent analysis algorithm software to complete rapid data collection, real-time information transmission, and intelligent analysis and early warning. The robot is installed in the switch room by means of guide rails. It uses visible light and infrared image recognition technology to complete the independent identification and judgement of equipment operating status [35], including identifying meter readings, indicator status, mechanical indication status, switch position, equipment overheating, etc. It also uses transient earth voltage and ultrasonic to detect partial discharge live detection of switchgear. The UAV is a rotary-wing UAV with a hovering camera function and has high flexibility [36, 37]. Combined with manual inspections, it is suitable for inspections of poles, insulators, wires, fittings, etc. At the same time, the UAV has the advantage of high-altitude viewing angle, which can be used for operation assistance at distribution network operation site, providing operation and maintenance personnel with more azimuth perspectives, ensuring operation safety, and realizing remote video transmission to control the entire operation site.

The application status shows that cost reduction and efficiency increase in inspections are the future development trend. On the one hand, under the existing manual inspection management mode, the inspection results are automatically reported and identified through the Internet of Things and information technology. Remote linkage and operation quality control between the site and command personnel can improve the efficiency of manual inspections. On the other hand, the intelligent process of unmanned systems will gradually replace manual inspections. Improving the reliability and effectiveness of unmanned systems on the basis of low cost will be the focus of research. For example, the existing station inspection robot adopts guide rail installation, which has high installation and maintenance costs. They are mainly used in switch stations, and the general applicability of power distribution rooms is low. Drone inspections currently have weak battery life that are not suitable for inspections of power distribution lines in long-distance and complex environments. At the same time, distribution network equipment has a complex structure and many types. For example, a large number of distribution network poles and towers have multiple types of equipment such as cables, switches, pole-mounted switches, and pole-mounted transformers. At present, there are few defect libraries and theoretical methods for image analysis and status detection of distribution network equipment, and the image detection function in the actual application of unmanned systems needs to be improved.

3 | DEVELOPMENT TRENDS OF INTELLIGENT PERCEPTION OF DISTRIBUTION NETWORK

Aiming at the current situation of distribution network intelligent perception, the prospect of distribution network intelligent perception is proposed from the common technology, perception equipment, and advanced application levels. As shown in Figure 2, all aspects of distribution network field are deployed to monitor the real-time operation status of related equipment in the system, providing effective data support for the daily tasks such as operation and maintenance of the system and overhaul, and ensuring the stable operation of distribution network.

3.1 | Development trends of basic technologies

Combined with the characteristics of intelligent perception in distribution network, basic technologies such as sensing, communication, energy acquisition, and power chip will be developed for intelligent perception.

3.1.1 | Development trends of sensing technologies

Sensing technology is the basis of intelligent perception in distribution network. At present, the sensor data of distribution network are mainly electrical quantities such as voltage and current of distribution terminals and user meters, and non-electrical quantities such as images, temperature, and sound of state detection equipment, involving all scenarios such as distribution, metering, and inspection. As shown in Figure 3, under the new sensitive materials and sensing principles such as magnetism, light, sound, quantum sensing, it can break through the key technologies of autonomous and controllable sensors for typical sensing scenarios of distribution networks.

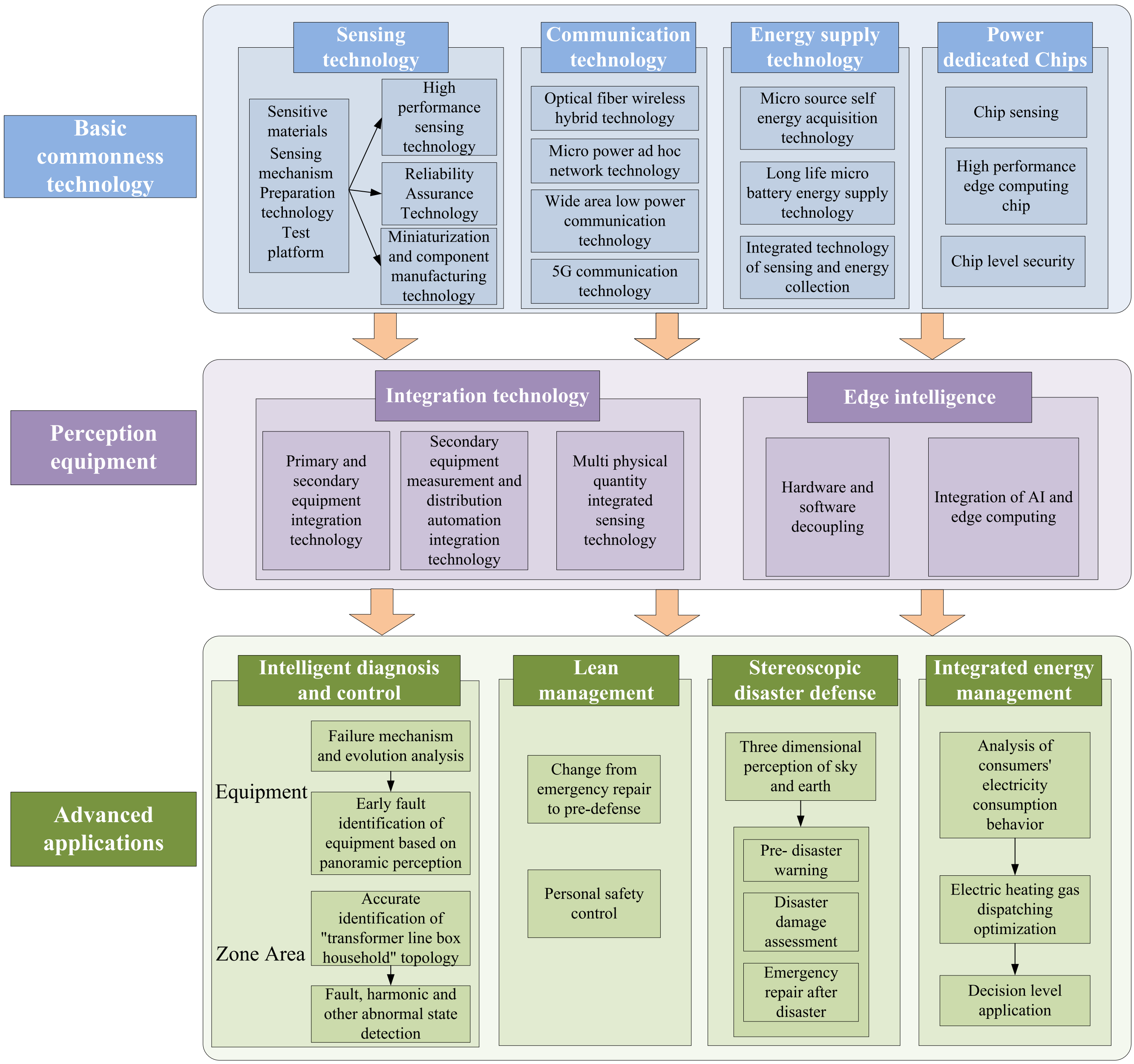

FIGURE 2 Development trends of intelligent perception of distribution network

This can solve the technical problems and promote the development of electric power sensing in the direction of high precision, high reliability, low power consumption, low cost, networking, intelligence, and miniaturisation, so as to meet the urgent needs of comprehensive perception of digital grid.

Sensing performance improvement under new sensing principles

The most important among the electrical parameters sensed by distribution network is the real-time voltage and current information of key nodes and equipment. Voltage and current signals have broadband time-frequency domain characteristics [38]. In addition to power frequency and direct current (DC) signals, it also includes a large number of medium and low frequency, medium and high-frequency transient signals and high-frequency transient signals, etc. Higher requirements are proposed for the range, accuracy, and bandwidth of sensors in different application scenarios of distribution network.

At present, various types of voltage and current sensors have been widely used in distribution networks, such as current transformer, potential transformer, Rogowski coils, Hall current sensors, etc. However, due to the influence of energy, installation, cost, etc., the existing sensor performance still cannot meet the requirements of high precision and high sensitivity, which is the main restricting factor for the self-distribution and metering functions. Sensors based on giant magnetoresistance effect (GMR) and tunnelling magnetoresistance effect can realize broadband and high-precision

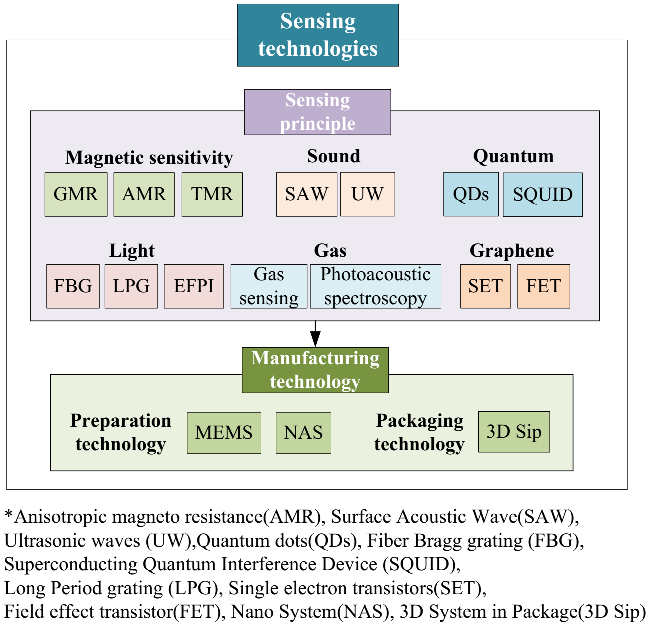

FIGURE 3 Sensing technologies. GMR, giant magnetoresistance effect; MEMS, micro‐electro‐mechanical system; TMR, tunnelling magnetoresistance effect

magnetic field measurement. They can be used to monitor AC and DC currents in distribution networks [39]. Their frequency bands range from DC to 10 MHz, with accuracy in mA level. The voltage sensor based on the electro‐optical effect and the inverse piezoelectric effect can achieve high‐precision, wide‐range electric field measurement, and can be suitable for direct measurement of distribution line voltage.

In terms of non‐electrical parameters' sensors, new sensing principles such as magnetic sensitivity [40], fibre grating [41], surface acoustic wave [42], quantum [43] and graphene sensing [44] will be promoted. It will overcome the technical problems of miniaturisation, integration, and multi‐parameter intelligent sensing. The smart micro sensors such as AC and DC current, weak magnetic field, space electric field, vibration and voiceprint need to be vigorously developed for new application scenarios to improve sensor performance.

Reliability in complex working conditions and environments

Due to the wide coverage of distribution network equipment and the complex environment, working reliability and stability in complex electromagnetic and climatic environments are the basis for the normal operation of the sensor. Although the testing terminals connected to the network have been strictly tested, the existing testing standards cannot simulate extreme operating conditions such as long‐term high temperature, high humidity, and strong electromagnetic interference, resulting in a weak resistance of sensors against extreme operating conditions and weak environmental conditions, and has a short lifespan. At present, State Grid Corporation has established a 'high severe cold, high humidity and heat, high salt spray, high dry heat, high altitude' intelligent measurement equipment joint laboratory, which can be applied to sensor reliability evaluation in extreme environments.

Therefore, according to the operating environment of distribution network equipment, the failure mechanism and failure mode of the sensor under extreme conditions such as lightning strike, operation, and short circuit should be explored. The operating limit electromagnetic interference conditions should be determined, and the multi‐dimensional stress superimposition effect of climate and environmental factors on the sensor should be analysed. The scope and degree of application of sensors in typical climatic environments should be studied, and a sensor reliability index system based on comprehensive typical electromagnetic and climatic environmental characteristics should be established, which will be the development trend of sensor reliability evaluation. This will guide the electromagnetic compatibility design and testing of sensors and sensing components.

Manufacturing technology of miniaturisation and component integration

Due to the size, installation method and cost of distribution network sensing device, the mature partial discharge and temperature monitoring technologies in the main network have not been widely used in distribution network. With the development of Micro‐Electro‐Mechanical System (MEMS) technology, sensors will be developed in the direction of miniaturisation, passivity, and integration to promote real‐time sensing of electrical and non‐electrical quantities in distribution network. Therefore, in the future, we will carry out the autonomy and localization of MEMS, nano and other microprocessing technologies. The system‐level (SIP) packaging and other Miniaturised manufacturing technology will be developed.

The technology of sensor miniaturisation will enrich the existing sensing methods of distribution network. In terms of electrical quantity detection, voltage and current sensors such as magnetoelectric effect sensors and printed circuit board type Rogowski coils have high‐precision, high‐bandwidth performance and characteristics, and they are of small size and low power consumption, making them suitable for FTU/DTU, TTU, fault indicator and electricity meters. In terms of non‐electric quantity detection, temperature sensors and displacement sensors based on surface acoustic wave, optical fibre and other sensing methods have the characteristics of passive wireless, low cost, and easy installation. They can be installed in power distribution lines and power distribution rooms with limited space. They are suitable for real‐time sensing of temperature, stress and other non‐electrical quantities of equipment such as distribution transformers and cable joints.

Due to the large number and low cost of distribution network equipment, its manufacturing and production processes are more flexible than those of main network equipment. Moreover, due to the low cost of equipment of distribution network, the sensing methods will develop in the direction of high reliability and low cost. In the future, devices and sensor network systems will be developed for specific power application scenarios. On the basis of miniaturisation of sensors such as stress and temperature, and passive wireless, the design route of sensor components should be explored. It has broad application prospects to research on sensors with the same lifespan as primary equipment, and implant them into primary equipment of distribution network. These technologies can be widely used for distribution network primary equipment such as distribution transformers, switch cabinets, switchgears, etc. They will improve the degree of intelligence of primary equipment of distribution network.

3.1.2 | Development trends of communication technologies

The wired communication methods of distribution network mainly include EPON passive optical network, industrial Ethernet optical network, and power line carrier technology. Wireless communication methods include power wireless private networks and wireless public networks represented by long-term evolution (LTE) 230 MHz and LTE 1.8 GHz [45]. Different communication are needed in different perception scenarios. For example, the protection control requires the delay in millisecond level, and the measurement delay can be up to minute level. Therefore, according to the characteristics of multiple distribution network points and wide coverage, conventional communication technology will present the development trend of regional high-efficiency self-organising network, wired and wireless hybrid [46]. At the same time, the emerging 5G communications will also lead the in-depth integration of distribution network services and application innovation.

Wired and wireless hybrid communication technology suitable for DA

Distributed FA can realize full-line regional feeder protection. It has the advantages of being fast and simple, small maintenance of topology changes, etc., and is gradually being promoted and applied. The communication volume between the protection devices is large, and the communication channel capacity and time delay requirements are high. The ring-shaped redundant communication network is composed of industrial Ethernet switches and optical fibres, which has the advantages of large communication information, low attenuation, and strong anti-interference ability, and can meet the needs of distributed FA construction. However, the large number of distributed FA terminal equipment in distribution network and the scattered layout are limited by the current situation of distribution network communication facilities, and it is impossible to directly transplant the point-to-point optical fibre communication mode of the main network.

EPON passive optical network can flexibly choose suitable chain, star and other network structures according to the line structure of distribution network. It has good adaptability in the WAMS communication of distribution network. Its bandwidth is 1.25 Gbit/s [47]. The upstream data of each optical network unit adopts time division multiplexing technology to meet the requirements of power DA. The wireless method can use the public 4G network or private TD-LTE 1.8G power network, and its rate is 100 Mbps for downlink and 50 Mbps for uplink, which meets the requirements in terms of communication bandwidth. The synchronization error of time through the network is relatively large, and it has been studied to use the current change amount as the synchronization reference to meet the synchronization requirements. Therefore, the mixed mode of industrial Ethernet communication, EPON communication, and wireless communication will be the development trend of distributed FA.

Low-power wireless communication technology suitable for distribution network monitoring and operation and maintenance

Low-power wireless communication technologies that include NB-IoT, LoRa, Mesh, etc., have the characteristics of long distance, low power consumption, and high reliability [48]. For battery-powered, self-powered micro-power sensors, single-layer or multi-layer networking is adopted, and the micro-power wireless communication method is connected to the sink node to realize the transmission of sensor data to the network layer, which can be widely used in distribution network operation scenarios such as condition monitoring, operation and maintenance.

In the application of online state perception of distribution network, low-power wireless communication technology can be applied to the data link transmission of the distribution line sensing terminal, and the network transmission of various types of sensing terminals in the power distribution room. A typical scenario is that in mountainous or remote areas, the instability of the 2G/4G network often reduces the stability and reliability of communication. At the same time, the GPRS/4G data transmission requires higher power consumption, which increases the difficulty of transmitting the data information. LoRa has the characteristics of long transmission distance and low power consumption. By adopting methods such as transparent data transmission and fixed-point data transmission, different network structures can be realized, such as star structure, mesh structure, tree structure, etc., to meet the needs of monitoring the operation status of distribution lines.

Realizing the linkage of terminals and personnel through highly reliable communication technology will help improve the efficiency of operation and maintenance [49]. At present, 'mobile terminal + live inspection peripherals' individual operation equipment has been widely used. Mobile terminal and inspection equipment realized networking through WIFI. Operation and maintenance personnel view the data of the inspection device in real time. At the same time, drones and wearing recorders are also gradually applied to the job site, which can transmit pictures and videos in real time and operation and maintenance personnel can remotely inspect the operation process. Limited by the 4G power consumption and transmission bandwidth, there are problems of short battery life, transmission stalls and delays. The use of Mesh ad-hoc network technology can realize low-latency and high-bandwidth transmission between operation and maintenance personnel and on-site command platforms. It is less affected by trees and walls in the work scene, and has high reliability.

5G communication technology suitable for multiple business scenarios

5G communication technology will be widely used in power systems. The power grid company has introduced measures to support the development of the 5G industry, sorting out 54 types of typical business scenarios covering the entire link of the 'generation, transmission, distribution, and transformation' power grids [50]. Among them, 5G can enhance the intelligent perception performance of distribution network in typical scenarios such as distribution differential protection, power distribution status perception, and intelligent operation and maintenance.

In power distribution differential protection, 5G can control the network delay within 1 ms, fully meet the 10 ms requirement of distributed FA network delay, further improve the efficiency of protection isolation, and realize reliable and safe power supply. The power grid company has successfully implemented the world's first 5G timing communication terminal for trial commercial use on the differential protection line of distribution network.

In power distribution status perception, it is essential to comprehensively sense the voltage, power, phase angle and other parameters of the smart grid, which can help realize the lossless transmission of PMU time series data, and realize the real-time dynamic evaluation of the status of the power grid during operation. The 5G power slicing network can expand the capacity of the smart grid and support the integration of a large number of equipment and various energy sources such as local power plants, distributed power sources, and electric vehicles. The comprehensive collection of user information is conducive to the development of smart grid dispatching and accurate load control.

In the field of intelligent operation and maintenance, 5G is suitable for high-speed and high-bandwidth scenarios such as job site monitoring and drone inspections. For example, it realizes real-time transmission of image and video data of on-site to ensure the clarity and accuracy of communication images and videos. It supports the automatic and refined inspection of the drone and can use 5G technology to interact with the background terminal in real time to realize the automatic identification and fault diagnosis of the network equipment components, as well as its own precise navigation and positioning and pose control.

In the field of intelligent perception in distribution networks, 5G has broad application prospects but the overall situation is still in its infancy. There is no mature solution in terms of delay jitter, synchronization, security, continuous connection and other technologies. The application level involves external units such as telecom operators, equipment manufacturers, and standards bodies, and a unified application deployment and standard specifications have yet to be formed.

3.1.3 | Development trends of energy supply technologies

With the development of intelligent sensing sensors in distribution network towards low power consumption and miniaturisation, energy acquisition methods such as photovoltaics and induction have limitations in supporting multi-scenario applications, mass deployment, and reliability of miniature intelligent sensors [51]. Therefore, micro-derived energy extraction technology, long-life micro battery energy supply technology, and sensor energy integration technology will be the development direction of energy supply technology.

Micro-derived energy extraction technology

There is abundant electric field energy, vibration energy, environmental wind energy and wireless microwave energy in the power environment. Energy harvesting is achieved through environmental energy harvesting devices, and the micro-derived energy extraction technology has become a new way of power supply. The main difficulty faced by this method is the reliability of energy extraction. Due to the diversity and variability of the environment, there is the possibility of intermittent power supply [52]. Generally, the output power of the micro-energy harvester is small and discontinuous, and cannot be directly used by the sensor node, and cannot provide stable and continuous power. Some technologies are developing rapidly as environmental stray energy collection and management technology [53], friction nano generator technology [54], etc. These technologies can solve the energy acquisition problem of secondary equipment such as monitoring components, terminals or devices under complex environmental conditions [55]. It is still in the stage of theoretical research and will be applied to low-power distribution network sensing terminals in the future.

Long-life micro battery energy supply technology

Existing miniature batteries such as lithium-ion batteries and miniature supercapacitors have been extensively researched and applied. However, its low power density and short cycle life cannot meet the needs of micro smart sensors for fast charge and discharge and long-life usage. Therefore, micro batteries with high-rate discharge, high energy density, low power consumption, wide temperature range, and long standby will have the application prospects of mass deployment that are suitable for sensing terminals in power distribution lines and power distribution rooms. Aiming at lithium-ion batteries, pre-inserted lithium optimization technology, and positive and negative electrode material ratio optimization technology, it will break through the current technical bottlenecks in batteries and meet the application needs of micro smart sensors in multiple application scenarios of distribution network perception.

Integration technology of sensing and energy supply

The integration of sensing and energy supply technology can realize low power consumption and self-driving of sensing terminals [56]. The typical technologies include integrated current sensing and magnetic field energy extraction technology based on magnetoelectric materials. It uses magnetostrictive/piezoelectric composite materials as sensing and energy-absorbing elements. The GMRis used to measure the current of the distribution line, and the electromagnetic induction energy output of the magnetoelectric material is connected in series in an array arrangement to improve the efficiency of magnetoelectric energy conversion and realize the integration of online monitoring and energy acquisition of distribution lines.

3.1.4 | Development trends of power dedicated chips

Capability improvement of edge computing chips

In terms of chip structure, heterogeneous multi-core is the mainstream trend in today's multi-core processor design. The core idea is that there is only one or several general-purpose cores in the processor to complete the task scheduling function [57]. The main computing tasks (such as floating-point operations, signal processing, image processing, etc.) are completed by a dedicated high-performance computing core, which greatly improves the execution efficiency and performance of the processor.

The chip computing power will be improved through technologies such as vector instructions and intelligent slicing based on artificial intelligence algorithms [58]. For example, in distribution network inspection scenario, fixed cameras, drones, robots, wearable equipment and other image and video interactions require high computing power. By using the neural network model under the deep learning framework and the real-time machine learning algorithm for edge-side target recognition, the high-performance and low-power artificial intelligence computing unit can be implanted in the chips. It can meet the needs of on-site real-time judgement.

Chip-level security

Different services of the digital grid have different security requirements for information transmission. For example, information collection service terminals have limited resources and are vulnerable to DDoS attacks. Single device authentication will trigger a signalling storm, and group authentication needs to be supported [59]. However, distribution network automation terminal requires low latency in millimetre-level and high reliability, which requires lightweight security algorithms that can be processed at the edge. Therefore, in the face of the demand for collection and access of massive sensing data, secure access and encryption methods should be at the chip level. Reliable security protection for the entire link from chip, terminal node, convergence layer gateway node to background network service needs to be built.

Embedded secure computing hardware engine will become a chip-level security solution for digital grid information flow. Through the digital self-encrypting hardware accelerator and the secure transmission module of the dedicated interface, it can realize efficient information transmission and effectively reduce the risk of theft in the data transmission process of the power grid. At present, there have been studies on the use of autonomous security chips in power DA fields such as two-way identity authentication between power distribution master stations and power distribution terminals. In the future, the application of chip-level security technology will be expanded, and the construction of a complete distribution network-aware security protection system will be promoted.

3.2 | Development trends of intelligent perception equipment

3.2.1 | Integration technology of intelligent perception equipment

Integration technology of primary and secondary equipment

For various types of miniaturised physical devices such as circuit breakers, load switches, and isolating switches, embedded sensors and AI modules are configured on the power device body to complete information collection. Nearby computing and information interaction can make the power equipment itself have the 'smart' function. In hardware development, the primary and secondary device fusion technology is used to integrate the primary body equipment, micro sensors and secondary terminal equipment, so that the equipment can analyse its own status, health assessment and self-protection. Future technology needs to further solve problems such as mismatched life of primary and secondary components, and interference of secondary components by strong magnetic fields.

For secondary equipment, it can integrate measurement, control, protection, anti-error lockout, fault recording, communication, remote control, information processing and other functional modules into one module. It can solve the management problems of original primary and secondary equipment interface mismatch, poor compatibility and expandability, complicated wiring, difficult operation and maintenance, etc. At present, there are problems of safety, reliability, and efficient integration of primary and secondary fusion equipment. It requires to unify the interaction of all primary/secondary interfaces, measurement, and control information to achieve compatibility, easy scalability and interchangeability of equipment.

Multi-physical quantity integration of state-aware equipment

The existing distribution network online monitoring system has few applications, mainly through the installation of various status sensors on the equipment. There exist several problems, such as single function, high cost, inconvenient live installation and maintenance, low coverage and defect detection efficiency, making it difficult for large-scale application. The patrol route of the substation inspection robot is limited and the station position is low, so it cannot achieve all-round coverage. In addition, there are fewer items to be patrolled by robots, which are mainly visible light and infrared temperature measurement. Moreover, their functions mainly stay at the stage of on-site data collection and simple threshold judgement with low level of intelligence.

Multi-physical quantity integrated sensing technology, that integrates infrared, video, partial discharge, temperature, humidity, and sound in one module, can be applied to online status sensing of distribution network. As shown in Figure 4, the MTU integrates image recognition, infrared detection, partial discharge detection and other detection technologies, and can have edge computing functions to realize real-time monitoring of the status of the distribution station room and fault warning. The edge calculation algorithm based on embedded deep learning model is embedded in the MTUs. They have the calculation and analysis functions of state anomaly detection, foreign object intrusion image recognition, interference and defect identification. Through non-contact intelligent detection methods, the power equipment is subjected to a full range of 24-h safety detection, covering the fault diagnosis and prediction of power distribution lines, distribution transformers, cable joints, switch cabinets, motors, and cable interlayers. They can be used as a convergence node in the power distribution Internet of Things, which can gather other types of sensor information nearby in a wireless or wired manner, and upload data in accordance with the Internet of Things access protocol. The MTUs mainly adopt

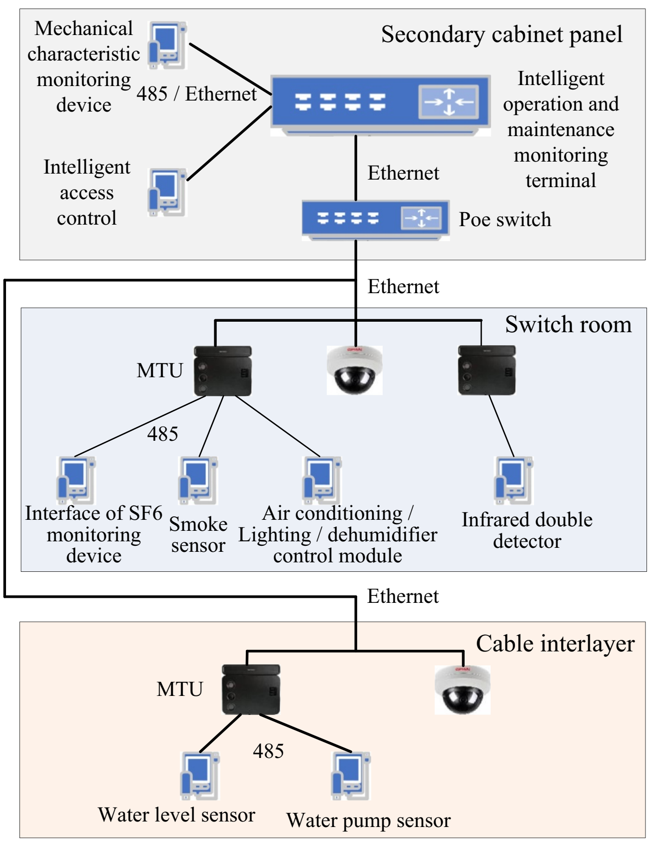

FIGURE 4 Application of integrated monitoring terminal unit (MTU)

the wireless access point name (APN) private network access mode. The special security chip of domestic SM series cryptographic algorithm is used to access the information intranet through the APN security access platform. The operation and maintenance personnel can remotely reach the equipment status and early warning information through the mobile terminal app or PC browser.

3.2.2 | Technology of edge intelligence

Decoupling the equipment software and hardware

The decoupling of terminal software and hardware can be realized based on an open hardware platform, and supported by a lightweight and high-performance operating system. The platform hardware and Software app need to be built to flexibly upgrade and expand the terminal business functions [60]. The key technologies involve multi-dimensional end-side-cloud collaborative intelligent processing technology, software-defined lightweight container technology, etc. The aim is to improve algorithm deployment flexibility and enhance the scalability of edge node embedded systems.

Combination of artificial intelligence and edge computing

According to the characteristics of the unmanned inspection of distribution network, more research should be conducted on the edge computing node operating system based on the combination of artificial intelligence and edge computing. This enables unmanned systems such as robots and UAVs to carry out autonomous and intelligent decision making based on inspection tasks, such as automatic recognition, autonomous navigation of flight paths, and precise control of poses.

3.3 | Development trends of intelligent perception advanced applications in distribution network

3.3.1 | Intelligent management and control of distribution network equipment and operating status

Failure mechanism analysis of distribution network equipment and early fault identification

Recently, there is insufficient research on the mechanism of high sensitivity and sensitivity of the weak signal of the equipment state failure characteristic parameters. The multi-parameter fusion sensing technology of electrical equipment cannot meet the needs of equipment defect diagnosis, resulting in insufficient knowledge of the multi-physical field information and its temporal and spatial evolution in the process of defect occurrence and development. As shown in Figure 5, under the development trends of high-precision and high-sensitivity sensing and equipment, the analysis of the panoramic information characteristics of distribution network equipment and the analysis of its temporal and spatial evolution law has a practical foundation. Through the failure mechanism of the key components in the power energy

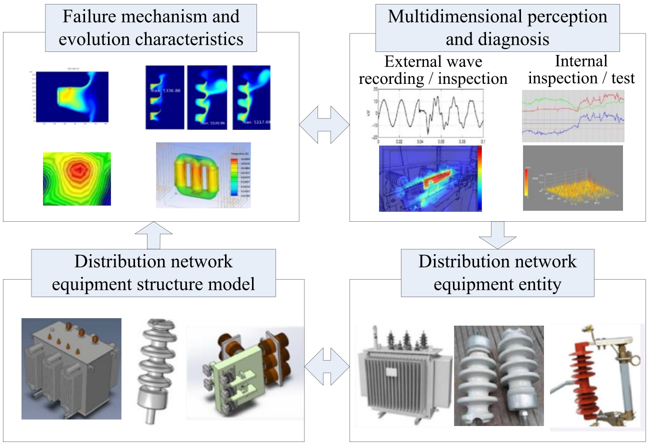

FIGURE 5 Framework of failure mechanism analysis and multidimensional diagnosis

equipment and the temporal and spatial evolution characteristics of the panoramic information during the failure process, the early warning of the equipment status can be realized.

It can explore the failure mechanism of key components in power energy equipment and the temporal and spatial evolution characteristics of panoramic information during the failure process through multi-level simulation modelling technology [61]. Distribution network equipment can be modelled and simulated from three dimensions of multi-field, multi-scale, and multi-region, and it needs to explore the complex mechanism between various physical fields and equipment state failure phenomena. The coupling relationship between the weak points of the equipment directly or indirectly connects to the boundary of the area. From the microscopic particles to the multi-scale evolution behaviour under the overall structure, the mapping relationship between the state of distribution network equipment and the electric field, magnetic field, temperature field, force field, light, trace gas, partial discharge and other panoramic information can be obtained, which be used as the theoretical basis for early warning of equipment status.

Through the internal and external multi-dimensional sensing methods of the equipment, the characteristics of panoramic perception information, equipment operating conditions and meteorological environment are integrated. Combined with multi-level simulation modelling technology, spatial-temporal multi-source information fusion technology, digital twin technology [62], etc., the abnormal operation status of the equipment can be diagnosed and warned. The diagnosis time can be put forward to the early stage [63]. For example, the distribution line monitoring device collects a large number of transient disturbance signals, which are caused by intermittent arc discharge and abnormal insulation of distribution network equipment. Existing protection and perception methods cannot accurately identify this fault. Multi-dimensional, high-precision perception of transient voltage and current signals, operating conditions, and environment through the propagation of the line can be collected [64]. Combining the mechanism of equipment insulation failure and analysing the damage degree of the arc to the equipment, it can realize the diagnosis and identification of the abnormality of distribution network equipment before the permanent trip [65]. Therefore, with the high-precision and panoramic development of sensing technology and equipment, early fault detection, location and identification of distribution network equipment have become the focus of future research.

Intelligent perception of operating status of the distribution area

In terms of topology recognition, the inaccuracy of the 'transformer-line-distribution box-user' relationship is the fundamental problem that restricts station topology recognition [66]. A miniaturised, plug-and-play current fingerprint module can be formed through high-precision current sensing and low-power wireless ad hoc network technology, which can be introduced into branch box meters and household meters to establish a network between smart meters and upper and lower devices. It can help realize the intelligent interconnection of the meter box side of the station area and automatic recognition of the station area topology.

In terms of abnormal state detection in the station area, with the increase of distributed energy and distributed power sources, the impact on station area faults and harmonics has gradually increased [67]. Through transient monitoring information and topology information, the core feature differences at different locations of the fault can be clarified. A database of electricity consumption information with the identification of fault types and continuous methods needs to be established. According to the functional requirements of the equipment deployment location, it can adaptively match fault perception to realize accurate judgement of typical faults and harmonic sources and graded protection of the end of the power grid. Moreover, it can realize situational awareness, protection and active management of the operating status of the station area, and improve the reliability of the station area's power supply and the quality of electricity service.

3.3.2 | Lean management of distribution network

The framework of lean management of distribution network is shown in Figure 6, including the linkage of operators, on site command hub and backstage command system.

The mode of operation and maintenance will transfer to 'pre-warning and active processing'

The existing distribution network operation and maintenance is still mainly based on traditional periodic inspections and fault repairs. Among them, distribution network overhead line is the focus of operation and maintenance management and control. More than 85% of the trip faults have short-term grounding and short-term discharge before they occur, and they can be restored by themselves without manual processing. Therefore, they have greater concealment. There is an urgent need to transform the operation and maintenance management mode and change the operation and maintenance management

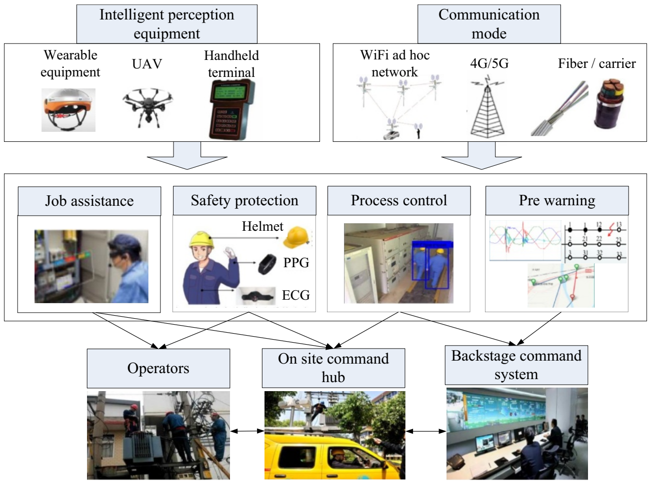

FIGURE 6 Framework of lean management of distribution network

and control mode from 'post-event emergency repair inspection' to 'pre-event early warning and active processing' to improve the operation and maintenance management and control capabilities and power supply service level.

In terms of operating status monitoring, due to the intermittent and strong randomness of transient waveforms under abnormal conditions, it should mine the abnormal status information of the line contained in the transient waveforms. A complete set of abnormal identification methods for distribution lines from abnormal section location, abnormal cause identification, abnormal trend analysis, etc. needs to be formed, and will be a key research direction for the management and control of distribution network failures. In terms of inspection, the scope of abnormal equipment is refined through the integration of manual and unmanned system inspections. The shooting and inspection of the operating terminal should be supported, and the line defect information needs to be pushed in real time, thus to form an on-site defect identification scheme. The rapid search of on-site defects need to be realized to reduce missed judgements and misjudgements caused by human factors such as lack of experience.

Multi-source heterogeneous data with different time scales and different structure types, such as resources, assets, operation, maintenance, experiment, and weather, will be systematically integrated. The internal relationship between equipment status indicators and the external environment in different modes needs to be studied. The impact of sudden and persistent harsh external environment on equipment health indicators should be analysed. Then, operating analysis models corresponding to different types of abnormalities can be established. The operation and maintenance decisions can be automatically generated based on equipment status and risks, and the management and control can be performed before fault trips.

Operation efficiency and personal safety control will be improved

In terms of improving operation efficiency, emerging intelligent technology is adopted to improve the individual ability of field operations. At the same time, the entire operation process is controlled to improve the quality and efficiency of power distribution operations. In terms of improving the ability and efficiency of individual personnel on the job site, intelligent technology with traditional power distribution operations is combined, and exoskeleton robots, smart wearables, and integrated and miniaturised instruments are used. At the same time, three-dimensional technology is used to construct a three-dimensional work site in real time, to achieve full coverage and a real-world roaming of the entire process. The people, equipment, signs and other objects in the work site are actively understood, and the work instructions to the non-sense evaluation are compared. In terms of operation result evaluation, a mobile command hub will be formed in the future, integrating equipment and management and control systems. The intelligent interactive methods are integrated such as image recognition and voice interaction to realize online automatic assessment of operation and maintenance quality. The on-site management and control of job quality can be realized to fully cover the area and form a closed loop of feedback from the platform, management personnel, and operators.

In terms of operation safety control, most of the electric power operation sites face complex situations such as multiple points, wide areas, and a complex team of operators. The research and development technology of intelligent safety equipment and the intelligent identification technology of on-site operation risk will enhance the safety guarantee capability [68]. In terms of safety equipment research and development, space electric field sensing technology can be used to develop smart helmets. When approaching the source of danger, it should promptly warn the operator to reduce the risk of electric shock. Under the regional wireless ad hoc network technology and wide area 5G communication technology, real-time transmission of pictures and videos through video monitoring terminals can be utilised. According to the person status, environment, and equipment status, the risk level of the work is automatically evaluated, and the work of the operator is guided to prevent the accident of personal injury and death caused by the operation error of and the accidental touching of the live equipment [69]. On-site operation risk identification is based on (1) environmental information such as temperature and humidity, altitude, oxygen concentration, toxic gas, etc. (2) staff body temperature, heart rate, blood oxygen and other physiological information. The risk level of the work can be automatically assessed to realize the real-time active warning of the hazard of the operator.

3.3.3 | Stereoscopic disaster defence

The faults caused by natural disasters in distribution network have the characteristics of group-occurring and clustering. The faults are related in time and space when natural disasters are spreading. Disaster prevention and emergency repair processes are interdependent with other facilities, such as transportation, communications, and water resources. Traditional power grid

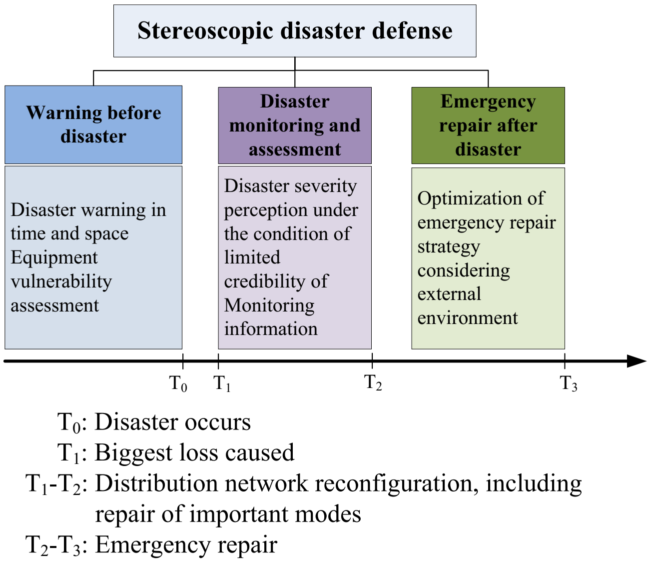

FIGURE 7 Framework of stereoscopic disaster defence

disaster emergency management research focuses on emergency response during the event or recovery after the event. With intelligent perception terminals and some techniques such as satellite weather monitoring and drone remote sensing, the stereoscopic disaster defence of distribution network will be carried out in Figure 7. It includes three aspects such as pre-warning before disaster, disaster monitoring and assessment, and emergency repair after disaster.

Pre-warning before disaster

In terms of pre-warning, disasters are still in their infancy during the time period $0{\sim}T_0$. Preventive measures can be taken in advance to reduce or slow down the severity of its impact or consequences. Regarding the natural disaster system of the power grid, most researchers focus on the design of power emergency management framework and empirical plan processing [70]. The perception information received from distribution terminals, weather monitoring terminals, and manual inspections should be collected comprehensively. The relationship between the failure rate of distribution network and the impact factors should be analysed according to the formation and propagation mechanism of disasters. According to the results of the evaluation, the weak links are identified and strengthened, so as to reduce the probability of failures. The operation stability of distribution network can be improved to avoid major losses caused by large-scale failures.

Disaster monitoring and loss assessment

On the basis of data collection, acquisition and analysis, disaster monitoring and loss assessment can be achieved to evaluate the possible or already suffered losses of distribution network during the time period $T_1{\sim}T_2$. Due to the destructive characteristics of natural disasters, the perception data are show limited and incredible. They are presented in the form of missing data, such as damage to secondary monitoring equipment and communication network damage, etc. Some technologies will be developed such as Petri network, pattern recognition and multiple hypothesis method. These will solve the problem of missing disaster data to achieve loss assessment.

Emergency repair after disaster

There are many difficulties in emergency repair of distribution network after disaster during the time period $T_2{\sim}T_3$. The labour and cooperation are widely divided among emergency repair resources. Moreover, the external environment such as meteorology and geography are complicated, which will have a continuous and dynamic impact on emergency repair. With the development of mathematical modelling and optimization algorithms [71], as well as people's increasing attention to the disaster resistance of distribution network, the best emergency repair strategy should be formulated to realize the reasonable dispatch of emergency repair resources after the disaster. Compared with the emergency repair under normal conditions, the external environment has obvious effects on the delay and hindrance during the emergency repair under disaster conditions. Therefore, it is necessary to consider three factors that the weather environment, emergency repair site environment, and infrastructure environment. It can fully reflect the impact of external conditions on emergency repairs, and also reflect the dynamics of external environmental impacts.

3.3.4 | Integrated energy management

With the trend of multi-platform and multi-service data sharing and integration through digital means, integrated energy management will be the important development of intelligent perception as shown in Figure 8.

Analysis of users' energy consumption behaviour

The energy consumption behaviour analysis has been widely researched. With the development of integrated perception of energy, heat and gas, the analysis of users' energy consumption behaviour will be achieved accurately [72]. It includes three aspects: energy behaviour characteristic analysis, energy behaviour pattern recognition, and energy behaviour understanding [33]. A database of typical load models for different regions, industries, different types of users can be established. The relationships between energy consumption parameters can be established through energy consumption information data, to realize more diversified load identification. User categories and non-invasive loads can be identified, to realize information adaptive classification and state quantitative identification of power supply system. Understanding the pattern of user power consumption is of great significance to power grid operation management such as demand side management and load forecasting. At the same time, it can improve the power service level according to the user's power demand.

Optimal scheduling of integrated energy

Existing studies have proposed that the energy Internet, and energy hubs are all manifestations of integrated energy

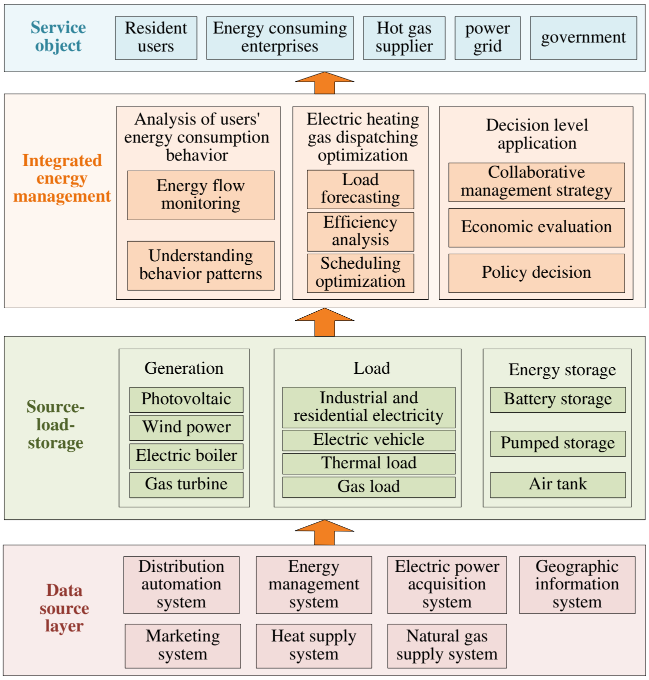

FIGURE 8 Framework of integrated energy management

systems. They are integrated energy systems with unified planning and dispatching of various types of energy such as electricity, gas, heat, and cold [73]. New energy resources represented by wind power and photovoltaics have been increasing in distribution network, so as the important demand-side resources represented by electric vehicles. The volatility of renewable energy output and the randomness of user load make the energy optimization management problem full of challenges. The complexity of optimised operation of the supply and demand of distribution network are increased. With the improvement of electricity consumption information collection and metering equipment, the current perception methods should have wider data coverage. The perception methods should not be limited to electrical systems and be extended to heat supply system and natural gas system. At the same time, the depth of perception will be expanded with comprehensive energy system modelling, operation optimization and benefit evaluation. The dynamic mechanism, control law and optimization characteristics under the integration of various energy will be a key direction that requires further in-depth research in the future.

Comprehensive energy management decision-level application

Under the development trend of intelligent perception in distribution network, comprehensive energy data and models will be improved [33, 73]. It will effectively support comprehensive energy management decision-level applications such as distribution network operation planning and social services.

The user electricity consumption information and grid load information are collected and synchronized in real time. Combining the national economic growth rate, industrial structure adjustment, consumption level, industrial and residential electrification degree, electricity price policy, climate/temperature change and other external factors, it should predict the electricity load curve, load time and spatial distribution of each cycle. These can provide support for abnormal energy consumption monitoring, energy planning, coordinated and optimised operation of the park's integrated energy system.

4 | CONCLUSION

(1) The quick development of sensing technology, communication technology, and intelligent power equipment will strengthen the foundation of Intelligent perception of distribution network. It will bring huge opportunities for the improvement of the observability, controllability and intelligence of distribution network
(2) The basic technologies such as miniaturised sensing, high-speed communication, high-efficiency energy acquisition, high computing power and high security chips will provide support for high reliability design of intelligent perception equipment. This can reduce perception costs and improve deployment capabilities that will become the development trend of perception equipment
(3) In the future, perception data of distribution network will have more depth, width, precision and density. The value of data will expand the application boundary of DA, electric energy metering systems, operation and maintenance. It will promote advanced applications such as accurate situation perception, lean management, stereoscopic disaster defence, and integrated energy management. The development trends of intelligent perception will support the construction of new power system

ACKNOWLEDGEMENTS

This work is sponsored by the National Key Research and Development Program of China 'Modes and key supporting technologies for the sustainable development of smart grid based on TCP ISGAN of the International Energy Agency' (2019YFE0102900).

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Reference [1] to [73] in this paper.

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How to cite this article: Yan, Y., et al.: Application status and development trends for intelligent perception of distribution network. High Volt. 6(6), 938–954 (2021). https://doi.org/10.1049/hve2.12159