

Research on the evolution of smart meter technology

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Abstract

Smart meters are not merely devices for measuring electricity consumption, but also core components of the smart grid that enable efficient monitoring, prediction, and management of power usage. An examination of smart meter technology evolution reveals that this transformation did not occur instantaneously; rather, it has undergone an extensive evolution from initial mechanical meters to electronic meters, and subsequently to highly intelligent meters. Technological breakthroughs at each stage have laid the foundation for the current form of smart meters. During the era of mechanical watt-hour meters, electric energy measurement depended primarily on the rotation and counting of mechanical components. The accuracy and stability of this method were subject to mechanical wear, environmental interference, and other factors, making it difficult to meet the growing demands of power management. With the rapid advancement of electronic technology, electronic electricity meters emerged. These devices utilize electronic technology to sample and process current and voltage signals, substantially improving measurement accuracy and stability. Additionally, electronic electricity meters enabled remote meter reading and data processing capabilities, significantly facilitating power management. However, they still exhibited limitations, including the complexity of data processing and constraints in communication capacity. These challenges drove the development of smart meters, which integrate advanced technologies such as the Internet of Things, big data, and cloud computing to enable real-time monitoring, analysis, and prediction of power consumption.

Full Text

Preamble

Abstract: The smart meter is not only a device for measuring electricity consumption but also a core component of the smart grid, enabling efficient monitoring, prediction, and management of power usage. An examination of

smart meter technology evolution reveals that this transformation did not occur overnight. It has undergone a long journey from initial mechanical meters to electronic meters and now to highly intelligent meters.

Technological breakthroughs at each stage have laid the foundation for the modern smart meter. In the era of mechanical watt-hour meters, energy measurement relied primarily on the rotation and counting of mechanical structures. This method's accuracy and stability were affected by mechanical wear, environmental interference, and other factors, making it difficult to meet growing power management demands. With the rapid development of electronic technology, electronic electricity meters emerged. These devices use electronic technology to sample and process current and voltage, greatly improving measurement accuracy and stability. Simultaneously, electronic meters enabled remote meter reading and data processing, bringing significant convenience to power management. However, limitations remained, such as complex data processing and limited communication capacity. These challenges drove the creation of smart meters. Smart meters integrate advanced technologies such as the Internet of Things, big data, and cloud computing to realize real-time monitoring, analysis, and prediction of power usage. They can not only accurately measure electricity consumption but also provide personalized recommendations and energy-saving solutions based on user behavior and demand.

Throughout this evolution, communication technology has played a vital role. From initial wired communication to the integration of wireless public networks, wireless private networks, power line carrier, and other communication modes, smart meters have achieved real-time communication and data sharing with grid management systems. This has made power management more intelligent and efficient while providing users with more convenient and personalized electricity experiences. However, smart meter technology development also faces challenges. Ensuring data security and privacy protection is an urgent problem to solve. Meanwhile, as the smart grid continues to develop, smart meters need to be more closely connected and coordinated with other devices to achieve more efficient and reliable power management.

Looking ahead, smart meter technology will continue to innovate and break through. With further development of the Internet of Things, big data, artificial intelligence, and other technologies, smart meters will have more powerful functions and performance, providing a more solid foundation for the intelligence and efficiency of the power industry. Simultaneously, we must also address challenges related to data security, technical standards, and cost, actively seeking solutions to promote the sustainable development, application, and promotion of smart meter technology.

Keywords: smart meter; technology evolution; power grid

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0 Preface

In April 2009, Hangzhou Haixing Company delivered the international report “Application and Development Trend of Smart Meter” at the domestic electricity meter industry conference. In May 2009, the State Grid Corporation released the “Strong Smart Grid” development plan (2009-2020) at the International Conference on UHV Technology in Beijing. Against this background, State Grid issued China’s first smart meter series enterprise standard in August 2009, launching an 11-year journey of research, development, large-scale application, and construction of electricity information collection systems on the user side.

From 2009 to 2019, State Grid’s total bidding volume for smart meters reached approximately 621 million units, with a total investment of 129.1 billion yuan. The bidding product from 2009 to mid-2013 was the 2009 version standard smart meter, which was replaced by the 2013 version after mid-2013. By the end of 2019, State Grid had developed two generations of smart meters comprising four models: the 2009 version (first generation, first paragraph), the 2013 version (first generation, second paragraph), the “dual-core” smart meter based on the IR 46 concept from the 2016 design scheme (new generation, first paragraph), and the multi-core modular smart meter from the 2019 technical requirements (new generation, second paragraph).

By the end of 2018, State Grid had installed and applied primarily the 2009 and 2013 versions of its standard smart meters, with a total of 458 million smart meters in operation in its power supply business area, covering 99.87% of users and representing a total investment of 99.8 billion yuan. The 2013 standard smart meters accounted for approximately 331 million units (72.2% of the total), while the 2009 standard smart meters accounted for about 127 million units (27.7%). As electricity meters are legal measuring instruments for electricity consumption settlement and assessment of power grid technical and economic indicators, State Grid aimed to achieve, for the first time in its power grid system, unified management of electric energy metering technology including function, type, technology, and testing (including software testing), as well as centralized and unified automatic verification of smart meters (10-40 million units) by provincial power grid research institutes to improve the quality level of smart meters across the entire network.

In August 2018, State Grid conducted a large-scale sampling inspection of smart meters (approximately 360,000 meters) across 26 provincial power grids over more than seven years, achieving a qualified rate of 99.64%, demonstrating ideal quality and deviation control for online operation. However, the statistical method for this sampling pass rate has been questioned online, as the failure replacement rate is typically very high during the initial stage of smart meter installation and operation, particularly for the 2009 version of State Grid standard smart meters.

This paper summarizes the development of State Grid smart meters (2009-2020) from the perspectives of development style, total operation amount, total bid-

ding amount, and development application goals. The author has followed the entire development process from 2010 to 2020, writing 17 special manuscripts compiled in the *Collection of Modern Electricity Meter Application Research*. In February 2009, the Marketing Department of State Grid held an expert seminar on “Power Meter Type, Function and Bidding Technical Specifications” at the China Electricity Research Institute, which the author attended. This paper therefore focuses on how the 2008 specifications were transformed into the 2009 version of the State Grid smart meter series enterprise standard, extracting design characteristics through collection and interpretation of standards, professional journals, and application reports, discussing controversial design and application issues, and proposing improvement suggestions.

1. Design Characteristics and Quality Evaluation of State Grid Smart Meters

1) Original 2009 Version of State Grid Standard Smart Meters -Design Features

The 2009 version provided the first definition of smart meters, though the “intelligence” function was not fully implemented, causing differing viewpoints. In terms of meter function, compared with the DL/T614-2007 multi-function electricity meter, the new standard proposed applications including hard clock circuits, programming passwords, cost control, event records, tiered electricity pricing, preliminary power outage meter reading, and ESAM module security certification.

Quality Evaluation: The 2009 edition was converted and supplemented from the 2008 “electricity meter type, function and bidding technical specification.” Due to the short conversion time, there was insufficient scientific and detailed demonstration and testing for newly proposed functions and technical requirements. Many original requirements were incomplete and unclear, leading to design and manufacturing quality issues. The incomplete and solidified power metering functions could not be selected according to provincial power grid needs, resulting in irregular meter operation. Some meter suppliers lacked experience in smart meter design and manufacturing, particularly in software design, component screening, and production processes, leading to high failure rates during initial operation. Consequently, in July 2012, the State Grid Marketing Department issued the “Notice on Further Strengthening the Quality Control of Smart Power Meters.”

Application Situation: From the end of 2009 to mid-2013, State Grid bid for 225 million smart meters of the 2009 version, with an investment of approximately 46.8 billion yuan. Currently, about 127 million of these standard smart meters remain in online operation, accounting for 27.7% of the total smart meters in operation. After mid-2013, the 2009 version no longer participated in

State Grid smart meter bidding.

2) 2013 Version of State Grid Standard Smart Meters -Design and Test Characteristics

Compared with the 2009 version, the 2013 version did not fully solidify the measurement function, which could not be selected according to demand—a defect of the new standard. However, the new standard introduced many innovative and practical requirements for metering performance and function expansion: theft prevention measures, selection of advanced metering chips, refined event records, measurement safety assurance, technical specifications for 15 major component categories, implementation of automatic verification of smart meters at the provincial level, and gradual configuration of HPLC and gateway requirements.

The 2013 version smart meter did not meet the requirements for application of the OIML IR 46 standard in China.

Application Situation: From mid-2013 to 2019, State Grid bid for 400 million copies of the 2013 standard smart meters, with an investment of approximately 83.2 billion yuan. Currently, about 331 million of these meters operate online, accounting for 72.7% of the total smart meters in operation. These meters were originally scheduled for replacement in 2019 with “dual-core” smart meters—the new generation smart meters (first paragraph). However, due to changes in State Grid’s development direction from January 2019 to January 2020, the 2013 version continues to operate on the grid. On April 19, 2020, online reports indicated that the first batch of electricity meters in 2020 (24.752 million units) with a total amount of 4.26 billion yuan would likely continue using the 2013 version of the State Grid standard smart meters.

3) 2016 State Grid Design Scheme: “Dual-Core” Smart Meter Based on IR 46 Concept -New Generation Smart Meter (First Paragraph)

State Grid’s “dual-core” smart meter design scheme based on the IR 46 concept represents the first application of OIML’s IR 46 standard in China. To meet the protection requirements of the IR 46 standard, the architecture adopts a “dual-core” structure with separate metering and management cores, changing the integrated architecture design of earlier smart meters.

Specific Design Technology: The dual-core smart meter employs dual MCU and dual memory schemes, proposes voltage and current sampling measurement or instantaneous value measurement, electrical energy data with time scale, more reliable real-time clock power design, HPLC communication mode, and online upgrade capability for management core software.

Design Scheme Review: The naming of “dual-core” smart meters is inappropriate, the design content is incomplete, and many items are missing. The term “dual-core” only indicates implementation of part of the IR 46 standard (measure-

ment and technical requirements), while the core requirements of measurement characteristics protection and measurement control are more important. The design scheme body includes six interface parts: phenomenological design, structural design, definition, metering core function requirements, management core function requirements, and communication protocol program upgrade. It lacks traditional smart meter design elements including function positioning, overall architecture design, hardware and software design and testing, reliability design and verification testing, process design and testing, and type testing specifications.

Project Survival Period: Only four years elapsed from project approval to prototype trial operation: - **Project Approval:** State Grid Marketing Department [2015] No.53 proposed “To carry out the international application research of IR 46 active power meter” in January 2015. - **Design Scheme:** In September 2016, State Grid issued the “Dual-core” Intelligent Power Meter Design Scheme based on IR 46 concept and organized publicity and implementation meetings for electricity meter enterprises. - **Prototype Launch:** In 2017, some domestic enterprises developed “dual-core” smart meters and sent them to the State Grid Measurement Center for inspection. - **Prototype Trial Operation:** In November 2018, the “dual-core” smart meter was first operated in the Zhejiang power grid. - **Transition Products:** In January 2019, State Grid proposed alternative meter positioning and expanded design for “dual-core” smart meters, which served as technology reserves for the new generation of smart meters (second paragraph).

4) 2019 Technical Requirements: New Generation Smart Meter with Multi-Core Modular Structure (Second Paragraph)

In June 2019, State Grid launched a prototype of a new generation smart meter (second type) whose performance and functions cover not only IR 46 standard implementation requirements but also alternative meter positioning and expansion function design requirements proposed in January 2019.

Design Features: This new generation smart meter (second paragraph) differs from previous designs by adopting a multi-core modular structure: - **Multi-Core Design:** Separation of metering and management cores; extension of electric energy metering from sine wave active and reactive measurement to fundamental wave active/reactive and harmonic active measurement; increase of active energy collection and freezing period from 15 minutes to 1 minute; software test requirements covering 10 legal-related and 7 non-legal-related software components; service life increased from 8 to 15 years. - **Modular Design:** Comprising metering core module, management core module, functional expansion module, and connection into a metering system. Three typical application scenarios are proposed: orderly charging of electric vehicles, intelligent analysis and application of residential power load characteristics, and “multi-meter integration” information collection.

Follow-up Development: The author proposes application topics requiring study after prototype launch, including formulation of series product standards covering all performance and functional design of the new generation three-phase smart meters, and new technology development projects (see Parts 3 and 1 of this paper).

Application Situation Changes: In January 2020, State Grid adjusted its development direction, drawing attention to the application trend of the new generation smart meter (second type). The author believes that the multi-core modular architecture subverts the traditional integrated architecture design of electronic/smart meters, representing a new leap in smart meter design. The extended function module design, proposed for the first time in China, can meet meter expansion function requirements on demand—highly desirable. However, the product design problem lies in the expansion function module. As noted above, in January 2019 State Grid proposed and promoted scenario application implementation of alternative meter positioning and expansion function design requirements. Therefore, according to State Grid's new development direction, the positioning and expansion function design of the new generation smart meters (second paragraph) need re-approval and selection to determine desirability after improvement.

New Demand Before Official Launch: In April 2020, the State Grid Marketing Department issued professional work points for intelligent electricity consumption in 2020, proposing to “actively promote optimization of energy use in public transformer areas, promote R&D of household intelligent appliances, and jointly develop intelligent IoT air conditioners, electric water heaters, etc., combined with new generation smart meters. Build a State Grid household smart energy use platform to realize interaction and intelligent control between home appliances and the power grid, improving household energy efficiency and reducing electricity costs.”

These professional work points explain that promoting public transformer area energy optimization through new generation smart meters enables R&D of intelligent IoT home appliances, collection and transmission of household smart energy platform information, and interaction and intelligent control between home appliances and the power grid. These new functions can be realized in the new generation smart meter (second type) expansion function module only by adding the metering module, connecting, sensing, and control module with indoor appliances using new indoor communication technology.

Comprehensive Development Process Evaluation (2009-2020)

Important Achievements in 11 Years of State Grid Smart Meter Development:

- **Full Coverage Achievement:** For the first time, basically full coverage of smart meters was achieved in the State Grid power supply business area. By the end of 2018, 458 million smart meters were in operation

with 99.87% user coverage, marking the second turning point in China's electricity meter development history where the main body of grid operation meters changed from induction + electronic meters to only smart meters, with induction meters fading from the domestic market. (Note: The first turning point was in 2005 when electronic meter output exceeded induction meters for the first time.)

- **Unified Quality Management:** For the first time, unified quality management of smart meters in the State Grid system was realized, accumulating experience in meter quality management at both ends and supervision. This includes unified product standards (2009 and 2013 editions), unified manufacturing quality supervision (documents on strengthening quality control, advanced metering chips, technical specifications for 15 major components, high-temperature aging processes), and unified meter testing (centralized, unified, automated verification of 10-40 million smart meters by provincial research institutes).
- **Multi-Functional Design:** The multi-functional design conforms to electricity price reform demands and greatly expands meter application scenarios. New functions beyond DL/T614 multi-function electricity meters include cost control, tiered pricing, active power collection, 1-minute freezing cycle, time-scale power collection, hard clock circuit and calibration, programming password application, blackout meter reading, AC/DC strong magnetic field theft prevention, management core software upgrade, voltage and current waveform data output, low-voltage grid power failure reporting, and ESAM module security certification.
- **Architecture Evolution:** The overall architecture transformed from the integrated design of traditional electronic meters to the multi-core modular integrated architecture of the new generation smart meter (second type). The separation design of metering and management core modules meets IR 46 requirements, while the extended function module implementation can meet changing functional requirements—highly practical and characteristic.
- **Operational Reliability:** The 2013 edition adopted many innovative designs addressing defects of the 2009 edition. After seven years of operational assessment, product quality is relatively stable and reliable. Since mid-2013, 331 million 2013 version standard smart meters have been installed, accounting for 72.2% of total operating smart meters. It is estimated that in 2020 and the following 2-3 years, the main metering products in State Grid smart meter bidding will continue to be the 2013 version.

Problems in Development and Application (2009-2020):

- **Frequent Development and Eagerness for Quick Success:** Smart meter development has been frequent, mainly considering function expansion demands, low prices, and large investment required for operational meter replacement. According to national legal metrological verification

periods, electronic electricity meters have an 8-year cycle, which can be interpreted as the operational life of new smart meters needing to exceed 8 years from the perspective of ensuring qualified measurement error.

- **Case 1: 2009 Edition Standard Smart Meter Project.** Due to high failure rates and irregular functional applications, this version no longer participated in State Grid bidding after mid-2013, with the shortest online operation period being only 3.5 years. In the first half of 2013, maximum online operation reached 225 million units with 46.8 billion yuan investment. Currently, online operation has dropped to 127 million units, with complete replacement estimated within three years.
- **Case 2: “Dual-Core” Smart Meter Project.** After only three years of 2013 version operation, State Grid eagerly released the IR 46-based dual-core design scheme in 2016, laying out development for electricity meter enterprises—driven by the need to apply OIML’ s IR 46 standard in China first. However, the author believes current IR 46 application in China has limitations: IR 46 is only a recommendation for active power meters, while international standards for reactive power and other meter types from OIML have no determined timeline; the IEC standard for IR 46 is still in formulation; and State Grid enterprise standards face challenges in implementing IR 46 requirements. As explained above, in January 2019 State Grid proposed alternative meter positioning and expanded function design requirements for dual-core smart meters, which would serve as technology reserves for the new generation. Therefore, the dual-core project lasted only four years before implementation.
- **Incorrect Initial Design Technology and Positioning of 2009 Version:**

First, the 2009 version only provided a definition of smart meters without fully implementing “smart” technology, leaving unclear how to realize functions for distribution network-user interaction. Internationally, there is no unified smart meter definition, but common application features include: GE (China) stated in 2009 that smart meters have two-way communication features and built-in advanced smart programs that can independently judge and respond to information without waiting for master station commands; Hangzhou Haixing noted smart meters serve as gateway applications with communication functions for water/gas meters and home display units; Germany formulated a new technical specification in 2013 where the smart meter gateway is the core intelligence module. The 2009 State Grid standard only had primary intelligent functions—two-way power metering and grid measurement automation information interaction—without bidirectional communication modes, communication gateway applications, or advanced interaction functions. State Grid’ s marketing/metering and distribution departments have long held different

views on whether smart meters should directly support advanced interactive functions. This relates directly to the positioning of State Grid's electricity consumption collection system, which initially positioned AMI as a remote automatic meter reading system (AMR) rather than advanced measurement infrastructure for two-way interactive communication and control.

Second, the metering function positioning was incorrect. The power metering function was incomplete and solidified, limiting other professional and provincial power grid requirements. Internationally, single-phase and three-phase smart meters offer single power and full power options selected according to power trade settlement, grid line loss calculation, reactive power monitoring, and harmonic pollution source monitoring. Full power metering includes active, reactive, and apparent power, with GE's kV2c three-phase smart meter even calculating distortion power factor. Canada's electricity trade settlement will use fundamental wave active power measurement from 2021. The 2009 State Grid standard limited single-phase smart meters to active power metering only, with three-phase meters including active and reactive functions that could not be changed. This limitation continued through the 2013 standard, dual-core design scheme, and new generation smart meter (second paragraph) technical requirements.

Third, the accuracy of single-phase smart meters was only Class 2, with factory error controlled within $\pm 0.6\%$, which is unreasonable. Internationally, single-phase smart meters are designed as Class 1, 0.5, and 0.2 for selection as needed. The author believes anti-theft measures for low-voltage grids should start from single-phase smart meter measurement: users with monthly consumption above 500kWh need Class 0.2 meters; above 200kWh need Class 0.5; above 100kWh need Class 1; below 100kWh use Class 2 or 1. For users above 200kWh, single-phase smart meters should design typical daily load curves, sending alarms when actual consumption differences exceed set limits.

- **New Generation Smart Meter (Second Paragraph) Design Issues:** This design covers IR 46 standard implementation requirements and alternative meter positioning with expanded functions proposed in January 2019. However, in January 2020, State Grid adjusted its development direction, requiring re-approval and selection of positioning and expanded function design. Improved local communication technologies supporting State Grid smart meter development include narrowband (fast), broadband (medium frequency) power line carrier technology, micro-power wireless communication, two-way communication, and gateway applications—topics requiring special discussion.

3. Expectations for the New Generation of State Grid Smart Meters

1) Finalization and Long-Term Trial Operation

The new generation of State Grid smart meters needs design finalization and improvement before large-scale trial operation in different environments for an extended period.

Reframe Design: - Re-approve and select alternative meter positioning and expanded function design for the new generation smart meters (second paragraph). - Supplement new demands, such as the 2020 smart electricity consumption key points proposing R&D of smart IoT home appliances, collection and transmission of household smart energy information, and interaction and control between home appliances and the power grid. These should be verified through function demonstration and included as expansion functions. - Carefully consider and re-evaluate the practical value and implementation difficulty of IR 46 standard application in active power metering.

Expand Argument and Improve Design: Given that the new generation smart meter (second type) completely changes the integrated architecture of early smart meters and proposes many future metering functions and expansion functions (including software testing), comprehensive performance and function argumentation must be organized by metering departments to provide basis for new meter standards before entering large-scale trial operation in different environments. This takes time but is safer.

Standard Formulation and New Technology Topics: Based on projects proposed by the author on November 19, 9, and published in this article, the following development projects for new generation smart meter series enterprise standards and new technologies are combined and refined: - Type, function, technical requirements, testing, and safety certification series standards for multi-core modular architecture new generation smart meters. - Algorithm and measurement application technical specifications for fundamental active measurement; active measurement and harmonic traceability. - Technical specifications for orderly charging and metering of electric vehicles. - Residential power load identification algorithm, assessment, and application technical specifications. - Software test requirements and application technical specifications for new generation smart meter software. - Reliability technology demonstration and testing for 15-year meter service life. - Supplement “intelligent” functional technology, including two-way communication and gateway technology, built-in advanced judgment and intelligent programs for independent response to realize advanced interaction between users and distribution networks, intelligent control of household and commercial appliances, user demand response, and future real-time pricing for real-time trading in power spot markets. - Open full power (active, reactive, apparent) metering function design for selection by other professional and provincial power grids according to needs. - Design multiple accuracy levels for single-phase smart meters based on users’ maximum

monthly consumption evaluation. - Deepen smart meter technology research, expand test scope and efficiency, and formulate improved technical specifications for meter software testing. - Greatly reduce replacement rates at initial installation and operation stages through improved product reliability design, testing, and demonstration. - Apply DL/T698.45 data communication protocol to revision of new generation smart meters.

Domestic High-End Electricity Meters: Domestic high-end electricity meters have not fully entered the status of main meters at the grid threshold.

2) Long-Term Planning for Re-Development

Reviewing 2009-2020, State Grid smart meter development has experienced a tortuous process with important achievements but also many problems requiring further research and forward-looking measurement.

Initial Design Defects: As China's most influential central enterprise, State Grid has the most authority on electricity meter operation quality at the grid threshold. The metering department should coordinate with the electricity meter industry to organize collaborative problems of domestic high-end electricity meters, mainly formulating metering technical specifications for high reliability, high stability, and long life; promoting design and production of domestic high-reliability components; conducting demonstration tests of meter reliability design; and accumulating long-term operation data to improve domestic high-end electricity meter design, striving for domestic high-end meters to enter the grid threshold status.

Forward-Looking Research: Carry out forward-looking research on electric energy metering technology, accelerate introduction of new international metering technology, and improve State Grid smart meter quality levels. The metering department should jointly conduct research with meter enterprises on sine wave full power energy metering, very low power factor measurement, fundamental load measurement, waveform measurement, and nonlinear direct 10-35kV high-voltage metering advanced applications to improve smart meter operation quality, reduce grid harmonic pollution and line loss, and provide measurement data for large user monitoring mechanisms. The measurement standardization administrative department should reform international meter standards and communication cooperation mechanisms, providing more opportunities for meter enterprises to participate in IEC and international meter communication projects, which will also help accelerate introduction of international measurement new technology.

International Development Trends: - IEC is developing standards for 0.1S static active energy meters; Landis+Gyr is also developing 0.1S and E860 series. - Full power measurement accuracy exceeds IEC's highest requirements: active power measurement error $< \pm 0.1 \pm 0.2 \pm 0.3\%$. - Internationally, 0.5S class fundamental wave reactive power measurement is being promoted. Canada will use fundamental wave active power measurement for electricity trade settle-

ment from 2021. - Power quality monitoring technology will become key for differentiated design and expanded function applications. - High measurement rate and communication: accurate and rapid instantaneous value measurement, high-speed recording and wave recording; multi-communication mode and protocol applications; practical measurement technology for transformer and power line loss calculation. - Wi-SUN wireless communication technology application: In March 2019, Landis+Gyr won the bid for Tokyo Electric Power Company's project deploying over 20 million smart meters using Wi-SUN mesh network communication meeting IEEE802.15.4 standards for energy management.

Compared with these international smart meter and communication technologies, China's new generation smart meter performance and communication technology design level has many gaps. Based on smart meter quality management experience, the metering department should make development plans according to new requirements for energy internet enterprise construction and international measurement communication technology.

4. Domestic Market Demand and Questions for New Generation Smart Meters

In early 2022, this paper summarized 151 manuscripts about domestic new generation smart power meter market and technology development around new power system construction. After analysis, five categories with important influence on meter industry development were extracted: domestic meter market, international meter market, new energy grid power quality monitoring and metering, electricity information acquisition system technology updates, and promotion of user-side power internet applications. These are outlined below with subsequent discussion points.

1) 2021 State Grid: New-Generation Smart Meter Bidding Amount Increased 28.2% Year-on-Year

In 2021, State Grid invited bids for new generation smart meters in two batches (30.402 million in the first batch and 36.334 million in the second batch), with a total bidding amount of 66.736 million units (total winning amount: 16.97 billion yuan), representing a 28.2% increase over 2020's total of 52.056 million units.

Growth Analysis: - 2021 was the first year of new generation smart meter grid application. 430 million smart meters (2009 and 2013 versions) not meeting IR 46 standards and new energy grid metering requirements need replacement. Over an eight-year replacement period, an average of 53.7 million new-generation smart meters are needed annually. - For annual new users, based on 3% of total users (510 million households) in State Grid's power supply area in 2020, 15 million new meters are needed. - New development of intelligent

IoT electricity meter function batch application. - Expanded application of high-accuracy settlement pass meters in domestic power grids. - For metering fault processing meters, calculated at 0.5% of total operating meters in 2020, 2.55 million new meters are needed.

For the first time, this paper focuses on rising meter prices. The estimated average unit price of new generation smart meters in 2021 is 254.28 yuan, 19.6% higher than 2020' s average of 212.6 yuan.

2022 Market Prospects: As the new generation smart meter market enters a steady and gradual period, with 376 million smart meters in operation (2009 and 2013 versions) requiring 53.7 million annual domestic updates, plus new market demand and new functions, the minimum demand for new generation smart meters in 2022 is expected to be 60 million units. The State Grid electricity meter market is eternal. However, State Grid limits the maximum number of electricity meter enterprises (about 6% of total bidding amount), far from meeting sustainable development needs. Therefore, in recent years, while continuing centralized bidding, enterprises are exploring diversified industries. In 2020, smart meter exports grew rapidly, providing experience for domestic smart meters to enter the international high-end electricity meter market in batches.

2) Promoting Localization of Power Grid Gateway Meters

Over the past 20 years, Weisheng has introduced new high-end metering technologies including 0.1S class active power measurement, nonlinear load measurement, and harmonic measurement. In 2010, Weisheng developed China' s first 0.1S class meter using digital multiplier technology, with functions including fundamental wave, harmonic measurement, satellite timing, and tide crossing, compatible with multiple communication protocols and language displays. The pass meter uses independent intellectual property multiplexing measurement algorithms (including high-order Newton-Cotes integral algorithm, active/reactive power measurement algorithm, difference algorithm, international compensation algorithm), selects high-performance components, and uses advanced production processes to ensure factory error $\leq \pm 0.04\%$ for active power measurement and $\leq \pm 0.1\%$ error during the 15-year life cycle for high stability and reliability. After testing against similar international power grid pass meters, domestic 0.1S class pass meters have reached advanced levels, breaking the import pass meter monopoly and promoting localization of high-accuracy settlement pass meters. Weisheng' s 0.1S class pass meters have been used for trans-regional power grid connection lines, inter-provincial connection lines, large power substations, and electrified railway traction stations, operating stably and reliably for many years.

3) Non-Interventional Load Identification Function Applied in Hunan Power Grid

In July 2021, Hunan Electric Power Company installed 543 smart IoT electricity meters in the first batch across five low-voltage platform areas in Changsha and Xiangtan, equipped with non-interventional load identification modules that obtain high-frequency sampling waveforms of voltage and current. Using electrical feature combination algorithms, the system can identify user electrical power consumption and periods. Based on traditional smart meters, the smart IoT electricity meter adds harmonic temperature measurement and measurement error self-monitoring functions, with service life increased from 10 to 16 years. The meter can predict hidden measurement dangers from heating and burning, solving metering blind spots for high-speed railway and high-harmonic pollution equipment connected to the grid to prevent various risks. In 2021, Hunan Electric Power promoted application of over 1,000 smart IoT electricity meters province-wide.

4) Jiangsu Electric Power: Multi-Core Modular Load Analysis Meter with Remote Software Upgrade

Under the existing electricity information collection system framework, upgrading new functions by replacing load analysis modules on-site is difficult for large-scale application. In the current domestic standard system, online software upgrade is not allowed. However, according to the IR 46 standard, only when the metering core and non-metering core are independent can function expansion and remote upgrade of the non-metering part ensure no impact on measurement performance, providing ideas for developing load analysis power meters with remote upgrade software.

The new electricity meter designs with metering core, universal function core, and special load analysis core. Through interaction with the electricity information collection system, normal metering core function and online update of household load identification function are achieved in the new remote system, including communication topology, matching algorithm, and load feature library remote upgrade process. The power meter multi-layer load analysis chip uses a tree classification algorithm based on Mahalanobis distance. Tests show single appliance identification accuracy can reach 95-98%, more than 70-90%, indicating that under the premise of not affecting measurement performance, remote upgrade load analysis software can accurately identify details of typical household appliances.

5. International Smart Meter Demand and Market Competition

1) International Electricity Meter Market Summary

The total population of 230 countries is about 7.5 billion, with 89% (6.675 billion) and total households of about 1.335 billion. Currently, there are about 1.7 billion electricity meters (industrial, commercial, residential). In 2020, about 963 million smart meters were installed, with a 59% penetration rate, indicating global demand of 737 million smart meters and a continuous growth trend.

The international smart meter market started in Europe and America. After 10 years of development, China currently accounts for 62% of global smart meters, followed by North America, Europe, Asia (excluding China), Latin America, the Middle East, and Africa. Internationally reputable smart meter companies with large export volumes include Landis+Gyr, Itron, General Electric, and Elster.

Domestic Smart Meter Exports: In 2020, Chinese electricity meter enterprises exported to 160 countries and regions, shipping about 59 million single and three-phase smart meters with total export value exceeding 1.3 billion US dollars (8.4 billion yuan), at an average price of 30.7 US dollars (200 yuan). Major exporting enterprises include Hangzhou Haixing, Weisheng, Shenzhen Technology, and Huali, with Haixing exporting 280 million US dollars (1.8 billion RMB) in 2020.

2) Century-Old International Electricity Meter Brand: Landis+Gyr High-Quality Smart Meter

- 1993: Produced ZU-type 0.2S class high-precision pass meter using time-split multiplier.
- 1995: Introduced ZB type 0.5S class stationary three-phase meter based on Hall multiplier (DFS).
- 1998: Shandong Power Grid imported Landis+Gyr's power grid electricity automatic charging system with ZU 0.2S pass meters and FAT data processors for power plants, and ZB 0.5S static meters with METCOM data processors for high-voltage substations.
- 2004: Developed new generation ZQ type 0.2S class high-precision settlement pass meter using digital multiplier technology.
- Early 2000s: Developed AMI and its command system (Grid Stream).
- 2016: Developed grid router with ability to connect to multiple communication platforms.
- 2019: Cooperated with Tokyo Electric Power Company to complete an AMI project installing over 20 million smart meters using Wi-SUN mesh network communication protocol meeting IEEE802.15.4 standards.
- September 28, 2021: Landis+Gyr AG reached a merger agreement with Luna Company (Turkey), acquiring 100% shares expected to complete by end of 2021. Luna is a leading Turkish meter supplier with annual revenue over \$60 million.

The ** period Zhen Zhang: Research on the evolution of smart meter technology
The acquisition of Luna will give Langir a significant share of the Turkish market, including AMI business opportunities that are not yet launched, as well as using Luna's vertical integration capabilities to boost sales in the surrounding areas and markets.

Currently, Luna products are exported to many countries in Africa, Asia, Europe (including Germany) and South America. 20,2021, "Transmission Distribution World" reported: Landis & Gyr, an American subsidiary of New Jersey Public Utilities (PSE & G) and Landis & Gyr Group (Langier Group) Technology Inc Signed a 10-year agreement.

Langier will provide 2.3 million smart meters to PSE & G, as well as related network infrastructure, software & services. All the meters are connected to the Langier Grid stream Connect AMI platform. PSE & G will complete the deployment of 2.3 million smart meters over the next four years.

The Langier Grid stream network is also used to support sensors for grid management and consumer interaction technology for power and gas services; Grid stream AMI adds grid edge intelligence to every metering and network device to improve efficiency and automation for utilities and consumers. - Focus on Langier is transforming In April 2017, suge reported by Switzerland:

Langier will transform from a professional metering supplier to a company providing customers with the industry's most advanced network and Internet of Things (IOT) solutions.

Langier, annual sales of \$1.6 billion, providing comprehensive smart grid solutions across more than 30 countries on 5 continents.

3) Promoting Overall Export of Domestic High-Quality Smart Meters and AMI/AMR Systems

Saudi Smart Meter Project: In April 2021, State Grid's Saudi smart meter project was officially completed, representing the first large-scale overseas export of China's electricity information collection system business. The general contractor was China Power Technology and Equipment Corporation (CLP Equipment Corporation). Signed on December 19, 2019, the project covered nine regions in western and southern Saudi Arabia, including main station systems, 5 million smart meters, concentrators, external circuit breakers, software development, scheme design, production, hardware supply, installation, commissioning, testing, equipment transportation, and storage.

In April 2019, Nanrui Group began key technical breakthroughs for the Saudi project, organizing AMI/AMR system integration and interconnection testing. In July 2019, Nanrui led provision of the overall AMI/AMR solution, winning the bid organized by Saudi Power Company and laying the foundation for CLP Equipment Company to win the project. Procurement was conducted in batches in China, with Linyang winning 330 million RMB, Ningbo Samsung winning

450 million RMB, Chint supplying over 100 million RMB in shell plastic circuit breakers, and Shenzhen completing 2.4 million smart meters within one year. Nanrui became the contractor for the power information collection system, responsible for project implementation.

Nanrui developed and exported a complete AMI/AMR system process according to local conditions, proposing overall solutions suitable for local special needs. In March 2020, owners requested adding narrowband Internet of Things (NB-IoT) communication mode, increasing application ratio from 5% to 50%. The large number of simultaneous NB-IoT access devices significantly impacted communication quality. After joint research, a smart meter reading scheme suitable for millions of NB-IoT devices was finally designed. The project is based on main station system architecture such as intelligent acquisition elastic architecture, massive data storage, and intelligent data analysis, capable of meeting communication connection management for 7.5 million smart meters, heterogeneous communication access, and 1 billion metering data storage and processing requirements. The terminal information communication adopts dual-mode and narrowband wireless communication schemes.

Shenzhen Technology's Chengdu Great Wall Development Company exported 2.58 million smart meters (15-year service life) to the Saudi project, accounting for the largest share. In recent years, Middle Eastern countries have large energy transformation demands, beginning large-scale smart meter deployment requiring advanced communication technology, dual-mode operation, and suitability for local environments. The company exports both finished products directly through Chengdu processing trade and semi-finished products for local assembly, building local intelligent production systems to expand export markets.

Weisheng: From Product Export to Overall Solution Output: - August 2021: Weisheng Brazil signed a smart meter contract with the Brazilian Electric Power Authority worth over 100 million yuan for more than one million meters, reflecting international brand recognition. - September 2021: Weisheng Mexico signed a contract with the Mexican Federal Electricity Commission to supply over 1 million smart meters worth over 260 million yuan, with delivery completed in subsequent months.

Weisheng's recent global market strategy has achieved considerable results based on sustainable market development. The company is gradually becoming a global supplier of overall solutions in the energy IoT and management field. In 2020, Weisheng's total operating amount reached 4 billion yuan (8% year-on-year growth), with overseas business accounting for 15%. After 20 years of internationalization, Weisheng's product field has expanded from power metering to water, gas, heat, and electrical products; business from energy metering to intelligent management; and business model from product export to overall management solutions and engineering services. Since 2014, Weisheng has operated in overseas markets, familiar with national conditions and market rules of Belt and Road countries, opening marketing channels through "localization" operations. Products are now sold to over 50 countries and regions, with factories

in Tanzania, Brazil, and Mexico.

Commentary: This article's title— “It is the right time to promote overall export of domestic high-quality smart meters and AMI/AMR!” —reflects that while the domestic State Grid electricity meter market is eternal, it has entered a stable period where demand can no longer meet sustainable development needs of electricity meter enterprises. Over the past decade, enterprises have achieved great success exploring smart meter exports, with China's electricity, water, and gas meter exports accounting for 50% of global market share. Export methods include product export, semi-finished product export for overseas assembly, and overseas factories or joint ventures (mainly in Asia and Africa). The Saudi smart meter project is a typical case of overall export of smart meters and electricity information collection systems (including main station systems), a first for China.

U.S. AMI Development: This section is extracted from *Introduction to Smart Grid* edited by Xu Xiaohui.

In August 2006, the Federal Energy Policy Commission defined AMI concept. AMI mainly includes home network systems, smart meters, communication networks connecting to power company data centers, meter data management systems, and data integration platforms. AMI is a fully configurable infrastructure integrated into current and future grid operations.

Smart Meter Functions: Green meters with demand response functions that reduce CO₂ emissions, save energy, and improve efficiency. Functions include programmable metering, time-sharing pricing, net metering for renewable energy, power failure notification and recovery, remote on/off, demand response services to prevent high electricity prices or peak load limits, pre-payment, power quality monitoring, anti-theft monitoring, and communication with other intelligent equipment.

Communication Facilities: Continuous information interaction between power companies, users, and controllable loads must use open two-way communication standards with high reliability. AMI must have local information concentrators to collect data from all smart meters and transmit to central servers through various media. The “last mile” downlink from concentrator to electricity meter is a technical bottleneck with no feasible solution due to large quantities, complex field environments, low communication media quality, and high cost pressure.

Home-Area Network: Main functions include real-time display of energy usage and price information, price feedback, energy consumption setting and peak control, automatic load adjustment, and user human control. Suitable communication methods include BPL, Home Plug, ZigBee, WiFi, and WiMax technologies.

Meter Data Management System (MDMS): A database with analysis functions that interacts with other information systems to verify, edit, and eval-

uate AMI data legitimacy.

Operation Gateway: Obtains AMI information required for functions by interacting with grid application layer systems (advanced distribution, advanced transmission operation, asset management).

AMI Support for Smart Grid Operations: (1) Enhances user participation initiative; (2) Enables real-time monitoring and control of distributed generation and energy storage; (3) Increases market activity by connecting users and grid for load adjustment or energy transfer based on price; (4) Smart meters with power quality monitoring modules enable rapid measurement, diagnosis, and adjustment; (5) Realizes distributed power grid operation models to reduce external attack impacts; (6) Assists grid fault self-healing; (7) Provides accurate and timely data to improve asset management and grid operation.

Landis+Gyr AMI Development: Described previously. On December 19, 2012, Landis+Gyr (Zhuhai) organized an AMI technology exchange meeting highlighting global AMI pilot situations: U.S. pilots using RF Mesh wireless network technology; European pilots adopting Prime-G3 narrowband (fast) power line carrier network technology; AMI software system: Grid Stream.

Requirements for Domestic High-Quality Smart Meter and AMI/AMR Development: - **High-Quality Smart Meter Standards:** Currently, China's smart meter prices are relatively low, reaching international medium quality but not yet entering international high-end markets in batches. There are no unified standards for high-quality smart meters. After performance testing of imported meters, index requirements can be summarized: (1) Factory error strictly controlled at 40% of meter grade (25%); (2) Impact volume index at 50% of standard requirements; (3) Flat meter error curve with linearity at 20% of meter grade; (4) Flat, generous style with low surface temperature rise; (5) Service life ensuring error does not exceed grade requirements; (6) Landis+Gyr's independently developed electric energy metering algorithm proprietary chip effectively improves meter reliability and safety.

- **AMI System Design:** The Saudi project's main station system is based on 10 years of domestic electricity information acquisition system design experience. However, most domestic electricity meter enterprises lack this experience, representing a shortcoming requiring increased investment in high-level software talent development. Future AMI system design should reference Landis+Gyr and Nanrui experiences, collecting global AMI function requirements with system flexibility for modification and supplementation.
- **IoT Application Design:** International and domestic IoT applications are in early stages. Local communication adopts HPLC, Wi-SUN, and narrowband wireless technologies, requiring adaptation to local residential density, communication requirements, climate environment, and media, with innovative design for user IoT applications. Wi-SUN communication

protocol is expected to become the core IoT protocol, as demonstrated in TEPCO's 20 million smart meter project using Wi-SUN home energy management communication standards. With end-to-end addressability, wide coverage, security, and high scalability, Wi-SUN will expand to smart homes.

Conclusion

In the near future, continuous scientific and technological progress will make life more convenient and efficient. As an important part of the smart grid, smart meters are constantly evolving and upgrading. With technology development, smart meter functions have continuously expanded. Modern intelligent electricity meters not only have basic electricity metering and remote meter reading functions but also realize load control, user information management, and power quality detection. Through smart meters, grid operators can comprehensively understand electricity consumption and provide more personalized services.

With continuous development of cloud computing, big data, and other technologies, smart meters have begun integrating with these technologies to form more intelligent and efficient power grid management systems. Through electricity consumption data collected by smart meters, grid operators can analyze, predict, and optimize electricity usage to improve grid supply efficiency and reliability. Meanwhile, with IoT technology, smart meters will focus more on user interaction and intelligent decision-making to achieve more personalized and intelligent electricity services. Security and reliability have become important technical trends as network security issues become increasingly prominent. Finally, green protection and sustainable development will be emphasized to promote transformation of energy utilization patterns.

In summary, with continuous technological progress and broadening application fields, smart meters will play increasingly important roles in smart grids, making greater contributions to improving energy utilization efficiency. Simultaneously, we must pay attention to smart meter technology safety and reliability to ensure user electricity and data security. In the future, smart meter technology will continue evolving and innovating, bringing more convenient, efficient, and sustainable electricity experiences.

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