Research on the Evolution of Domestic Multi-functional Electric Energy Meter Technology

Authors: Zhang Zhen

Date: 2024-02-13T00:00:00+00:00

Abstract

This paper provides an in-depth exploration of the technical evolution of domestic multi-function electricity meters. With the rapid development of the domestic electric power market and continuous technological innovation, domestic multi-function electricity meters have undergone a transformation from simple billing to complex multi-functionality, and from single applications to broad domains. This transformation has not only propelled the rapid development of electricity meter technology, but also satisfied the growing electric power demands and management requirements. The article elaborates on four aspects: the concept of multi-function meters, the operating principles and algorithms of electricity meters employing digital multipliers, the origin and evolution of multi-function electricity meter standards, and the origin and evolution of domestic multi-function electricity meter products. Although domestically independently manufactured multi-function meters have achieved remarkable achievements, reliability and key process technologies remain to be enhanced. Furthermore, the development of communication technologies has also provided new opportunities for the advancement of electricity meter technology. The application of new technologies provides more convenient and efficient methods for data transmission and remote management of electricity meters. Domestic multi-function electricity meters have achieved significant accomplishments in technical evolution and application expansion, yet still face certain challenges and opportunities. In the future, with the continuous development of the electric power market and the advancement of smart grid construction, domestic multi-function electricity meters need to continue strengthening technological innovation and product development, enhancing product reliability and competitiveness, to meet higher application demands and market requirements.

Full Text

Abstract

This paper provides an in-depth examination of the technical evolution of domestic multi-function electric energy meters. With the rapid development of China' s power market and continuous technological innovation, domestic multi-function energy meters have undergone a transformation from simple billing to complex multi-functionality, and from single applications to broad domains. This evolution has not only driven rapid advancement in energy meter technology but also met growing power demands and management requirements. The article elaborates on four aspects: the concept of multi-function meters, the working principles and algorithms of digital multiplier-based meters, the origin and evolution of multi-function meter standards, and the origin and evolution of domestic multi-function meter products. Although domestically produced multi-function meters have achieved impressive performance results, improvements are still needed in reliability and key process technologies. Additionally, the development of communication technologies presents new opportunities for advancing energy meter technology. The application of new technologies provides more convenient and efficient methods for data transmission and remote management of energy meters. Domestic multi-function electric energy meters have made remarkable achievements in technical evolution and application expansion, yet still face certain challenges and opportunities. In the future, with the continuous development of the power market and the advancement of smart grid construction, domestic multi-function energy meters must continue to strengthen technological innovation and product research and development, improve product reliability and competitiveness, and meet higher application demands and market requirements.

Keywords: multi-function meter, analog multiplier, data processing unit

1. Concept of Multi-Function Meters

The concept of multi-function meters first appeared in the author's 1995 reading of the March issue of *Modernization of Electric Energy Measurement—Technical Report on the Current Status and Prospects of Electric Energy Measurement Technology in East China Power Grid*, Part II: "Improving Time-of-Use Measurement Technology and Steadily Developing Multi-Function Meters." The report stated: "The development of electronic technology has created a foundation for multi-function energy meters. In addition to time-of-use measurement, multi-function energy meters generally include demand measurement, load control, and load survey representative daily load curve functions, simplifying metering at user measurement points and facilitating data collection. Attention should be paid to promoting their development."

The report' s drafting process began in 1992 when the East China Power Industry Administration Technical Committee formed a research group comprising

14 experts from the East China Power Administration and its provincial power grids. By 1993, the sub-topic materials were gradually completed. In 1994, Zeng Naihong from the East China Power Industry Administration supplemented and wrote the materials, which were printed as a draft after review and ultimately formed the final report. This commentary notes that the former Ministry of Energy' s Power Department and the East China Power Industry Administration played a pioneering and guiding role in the initiation and development of domestic multi-function meters. Their achievements in promoting the development of domestic high-end energy meters include: first, releasing the first regional power grid electric energy measurement modernization technical report and proposing development and application topics for domestic multi-function meters; and second, organizing the drafting of the first domestic mechanical industry standard and power industry standard for multi-function meters, providing a basis for the development and application of domestic multi-function meter products.

2. Working Principle and Algorithm of Digital Multiplier-Based Energy Meters

The main content of this section is excerpted from the China Electric Power Research Institute's *Key Technologies for Dynamic Electric Energy Measurement in New Power Systems* and has been edited accordingly.

2.1 Working Principle

Active Energy Measurement Method: The process involves AC voltage sampling via an ADC circuit and AC current sampling via an ADC and high-pass filter (HPF) circuit, followed by parallel processing through a digital multiplier, low-pass filter (LPF), correction, integration, digital frequency conversion, pulse output, and finally active energy measurement.

Reactive Energy Measurement Method: Sharing the same parallel ADC circuits for voltage and current sampling with HPF, the signal then passes through a Hilbert filter, digital multiplier, LPF, correction, integration, digital frequency conversion, pulse output, and finally reactive energy measurement.

2.2 Digital Multiplier Power Algorithms

Time Domain: Dot product and numerical integration algorithms; Walsh overlapping algorithms; weighted average algorithms; window function convolution algorithms.

Frequency Domain: (Windowed interpolation) DFT algorithms; FFT algorithms.

Time-Frequency Domain: Wavelet transforms; S-transforms; modern spectral estimation and intelligent algorithms.

These algorithms can calculate electrical parameters including active power/energy, reactive power/energy, apparent power/energy, voltage and current RMS values, and fundamental frequency.

Typical Energy Meter Integration Algorithm Case Study: This content is excerpted from Wasion Group' s 2010 paper *Application of Composite Newton-Cotes Integration Algorithm in Electric Energy Measurement*. Wasion' s DTSD341-MA1 model, a 0.1S-class high-accuracy settlement gateway energy meter, employs the composite Newton-Cotes high-order integration algorithm. For signals containing harmonics up to the nth order, accurate calculation of signal electrical quantities, power, and RMS values requires sampling more than 3 points for the nth harmonic, meaning the signal sampling frequency must ensure more than 3n points per fundamental period. To improve calculation accuracy of the dot product algorithm for any determined input signal, high-order integration algorithms can be utilized. The Newton-Cotes algorithm is a practical and easily digitized numerical integration method, with nth-order Newton-Cotes algorithms having at least nth-degree algebraic precision.

3. Origin and Evolution of Multi-Function Energy Meter Standards

The technical requirements for multi-function meters in standards reflect the development level of domestic multi-function meters in different periods across four categories: meter definition, meter type, accuracy, and multi-function capabilities.

3.1 Reference Standard: Q/GDW 1354-2013

Released in March 2013, the State Grid standard Q/GDW 1354-2013 *Smart Electric Energy Meter Functional Specification* represents a relatively complete and forward-looking functional benchmark for comparison across different standards. Its functions are divided into two major categories: first, data/information/software output functions, including general output functions for multi-function meters and smart meters, and dedicated output functions for smart meters; and second, internal data/information/software formation and processing functions.

Key Provisions: The smart meter is defined as consisting of measurement units, data processing units, and communication units, with functions including electric energy measurement, information storage and processing, real-time monitoring, automatic control, and information interaction. The meter type is static, with accuracy classes of 0.2S, 0.5S, 1, and 2 for active energy measurement. The basic functions comprise 30 items with 119 detailed rules, including: four types of energy measurement (active and reactive total energy, active phase energy, combined active and reactive energy, programmable combined reactive energy, and time-of-use active and reactive energy); clock circuits and time-setting methods; five categories of event records (22 detailed rules covering power supply abnormalities, grid operation abnormalities, meter operation records, anti-theft functions, and event reporting/recording); five communication methods (RS485, infrared, carrier, public network, and micropower wireless); constant magnetic field monitoring; and energy meter software comparison functions.

However, this standard has some shortcomings: limited provisions for smart meter intelligence such as automatic control and information interaction functions; no requirements for bidirectional communication modules; no gateway application introduction; no mention of fundamental active energy or harmonic active energy measurement; and no reference to IR46 international metrological recommendations for active energy meters.

3.2 1995: JB/T 7656-95

In March 1995, China' s first mechanical industry standard JB/T 7656-95 *Multi-Function Electric Energy Meter* was released. It defined multi-function meters as comprising measurement units and data processing units capable of performing multiple billing methods, load management, and remote data transmission. Meter types were divided into mechanical-electronic and electronic multi-function meters. Accuracy classes were 0.2, 0.5, and 1.0 for active energy, and 2.0 for reactive energy. The standard included 12 basic function items with 30 detailed rules, covering energy measurement functions for specified time intervals, peak/valley/flat period active and reactive energy measurement, demand measurement, load curve recording, and apparent energy, iron loss, and copper loss calculation. The standard reflected the design level of domestic multi-function meters in the 1995 era, when induction meters still dominated the market, electronic meters were in batch use, and multi-function meters were in limited trial stages. It specified three types of multipliers: induction meters using rotating magnetic field principles, electronic meters with analog multipliers using time-division multipliers, and electronic meters with digital multipliers using dot product and numerical integration algorithms. Reactive energy measurement likely only used sine wave 90° phase-shifting circuits. Compared to Q/GDW 1354-2013, JB/T 7656-95 had significantly fewer general output function items and detailed rules, with no provisions for combined active/reactive energy measurement, programmable combined reactive energy, clock circuits, event records, five communication methods, anti-theft functions, or software comparison functions.

3.3 1997: DL/T 614-1997

In May 1997, the power industry standard DL/T 614-1997 *Multi-Function Electric Energy Meter* was released. It defined multi-function meters as comprising measurement and data processing units with two or more functions including time-of-use measurement and demand measurement, capable of displaying, storing, and outputting data. Meter types included electromechanical and electronic multi-function meters, with accuracy classes of 0.2, 0.5, 1, 2, and 3. The standard supplemented some new technical requirements based on JB/T 7656-95, but with only a two-year gap, the additions were limited. It introduced functional quantity requirements, added a 3rd accuracy class for reactive energy measurement, and included event record functions with three detailed rules. However, it still lacked provisions for combined active/reactive energy measurement, programmable combined reactive energy, clock circuit requirements, three communication methods (carrier, public network, micropower wireless), anti-magnetic interference theft prevention, and software comparison functions.

3.4 2007: GB/T 17215.301-2007

In October 2007, China' s first national standard GB/T 17215.301-2007 *Special Requirements for Multi-Function Electric Energy Meters* was released. It defined multi-function meters as comprising a single measurement mechanism, data processing unit, communication interface, and other functional components enclosed in one case, capable of measuring and displaying active and reactive energy with two or more functions including time-of-use measurement and maximum demand measurement. The meter type was static, with accuracy classes of 0.2S, 0.5S, 1, and 2. The standard included 12 basic function items with 36 detailed rules, adding event record detailed rules (9 items) and data communication technical requirements and protocols compared to previous standards. However, it still omitted combined active/reactive energy measurement, programmable combined reactive energy, clock circuit requirements, three communication methods, anti-magnetic interference theft prevention, and software comparison functions.

3.5 2007: DL/T 614-2007

In December 2007, the power industry standard DL/T 614-2007 *Multi-Function Electric Energy Meter* was released, maintaining the same definition as DL/T 614-1997 but specifying static meter types with accuracy classes of 0.2S, 0.5S, 1, and 2. The standard included 16 basic function items with 51 detailed rules, covering energy measurement, demand measurement, event records, communication interfaces and requirements, grid operation parameter monitoring, and pulse output. The internal data/information/software formation and processing functions were relatively complete, including requirements that meter software should not be upgradeable after factory release. However, it still lacked provisions for combined active/reactive energy measurement, programmable combined reactive energy, clock circuit requirements, three communication methods, anti-magnetic interference theft prevention, and software comparison functions. The extended functions mentioned harmonic voltage and current monitoring and fiber optic, Bluetooth, and wireless communication applications.

3.6 2009: Q/GDW 354-2009

In September 2009, the State Grid standard Q/GDW 354-2009 *Smart Electric Energy Meter Functional Specification* was released as China' s first State Grid standard for smart meters. It defined smart meters identically to Q/GDW 1354-2013, with static meter types and accuracy classes of 0.2S, 0.5S, 1, and 2. The standard included 25 basic function items with 85 detailed rules, introducing combined active and reactive energy measurement, clock circuit requirements, increased event record detailed rules, carrier and public network communication methods, tariff functions, load recording, tiered pricing, power-off meter reading, and security authentication. Compared to subsequent Q/GDW 1354-2013, the 2009 standard lagged in not mentioning programmable combined reactive energy measurement, micropower wireless communication, anti-magnetic interference theft prevention, software comparison functions, load switch misoperation detection, intelligent functions, or fundamental and harmonic active energy measurement.

3.7 2020: State Grid Standard (2020 Edition)

In August 2020, the State Grid standard *General Technical Specification for Smart Electric Energy Meters (2020 Edition) - Part 4: Smart Electric Energy Meter Functional Specification* was released for the new-generation smart meters. The 2020 edition smart meter is based on the 2013 State Grid standard smart meter, incorporating key requirements from the IR46 international metrological recommendation for active energy meters. It defines smart meters identically to Q/GDW 1354-2013, with static meter types and accuracy classes of B, C, and D for active energy measurement, and 2 for reactive energy measurement. The functional specification retains 76% of the functions from Q/GDW 1354-2013, with the most significant change being the accuracy class representation. Active energy measurement accuracy now adopts the IR46 representation method (A, B, C, D grades), while reactive energy measurement still uses the IEC standard representation, complicating accuracy testing for both active and reactive power. The standard adds detailed rules for event records (26 items) and grid operation parameter monitoring (7 items) but removes load recording and security authentication functions. However, it still does not propose new functions for intelligent meter projects or fundamental/harmonic active energy measurement development and application.

3.8 Latest Standard: Q/GDW 12180-2021

In January 2022, State Grid released Q/GDW 12180-2021 *Functional and Software Specification for Smart IoT Electric Energy Meters*. However, in 2022—the second year of State Grid' s smart IoT meter bidding—the first batch accounted for only 2.1% of the total equipment volume. Controversies emerged regarding smart IoT meters, primarily concerning high meter prices, optional rather than mandatory extended functions, and the impracticality of the embedded general operating system' s first-time adoption, while some special requirements for energy meters necessitate the development of embedded dedicated operating systems. Given these circumstances, this paper will temporarily refrain from discussing the State Grid Q/GDW 12180-2021 standard.

4. Origin and Evolution of Domestic Multi-Function Energy Meter Products

From 1992 to 2021, domestic multi-function meters evolved through five generations of product technology: mechanical-electronic multi-function meters, analog multiplier-based multi-function meters, digital multiplier-based multi-function meters (four categories), smart meters, and new-generation smart meters . Evaluation of multi-function meter technical performance focuses on four aspects: meter structure, new measurement technologies, accuracy, and multi-function/intelligent capabilities.

4.1 1992: Mechanical-Electronic Multi-Function Meter

In 1992, Shanghai Energy Meter Factory first launched the independently designed DSD8 model, a 0.5-class, mechanical-electronic three-phase three-wire multi-function meter. The meter structure consisted of an induction base meter, infrared photoelectric sensors, and an electronic multi-function recorder. It employed a power multiplier based on rotating magnetic field principles, offering functions including active total energy measurement, time-of-use energy measurement, interval or sliding-window maximum demand, magnetic adsorption infrared communication, self-test functions, and strong anti-interference capability. As the first generation of domestic multi-function meters, mechanical-electronic multi-function meters achieved multi-functionality based on active energy measurement. However, without fundamental reactive energy measurement technology, their multi-function development was limited.

4.2 1994: Digital Multiplier-Based Electronic Multi-Function Meter

In August 1994, Wasion Group first developed the DSSD331/DTSD341 model, a 0.5S-class electronic three-phase three-wire/four-wire multi-function meter using digital multipliers. The all-electronic multi-function meter structure comprised current sensors (CT), voltage sensors (PT), analog-to-digital converters (A/D), microcomputer dedicated chips, and LED displays. The digital multiplier performed various judgment processing and operations on digitized instantaneous current and voltage values within the microcomputer dedicated chip. Functions included forward/reverse active energy, inductive/capacitive reactive and four-quadrant reactive energy measurement, time-of-use active and reactive energy measurement, active and reactive maximum demand, grid active power, reactive power, voltage, current, power factor and frequency monitoring, load curve recording, two independent simultaneously operating RS485 interfaces, adsorption infrared communication, four open-contact pulse auxiliary terminal outputs, eight categories of event records, self-diagnosis and fault alarm functions, and voltage/current harmonic analysis up to the 21st harmonic. This digital multiplier-based multi-function meter represents the first category of the third-generation domestic multi-function meters using microcomputer chips. Through periodic waveform sampling, it enabled multi-function calculations including grid voltage, current, phase angle, active power, reactive power, apparent power, frequency, and harmonic content. Initially applied only to lower-class multi-function meters, improved sampling rates and calculation precision later enabled application to 0.1S-class grid gateway multi-function meters and standard energy meters. Today, digital multiplier-based multi-function meters dominate the domestic market due to their easy multi-function implementation, low cost, and short product development cycles. However, the A/D sampling software is non-real-time, presenting significant defects for non-periodic, unstable signals and scenarios with high harmonic content, where accurate active power calculation is impossible. Moreover, even with identical hardware, actual quality and performance levels may vary significantly between manufacturers due to the inability to conduct unified standard assessments of software capabilities.

4.3 1995: Time-Division Multiplier-Based Multi-Function Meter

In December 1995, Ningguang Electric Factory launched the DSSF22A-X/DTSF22A-X model, a 1-class electronic three-phase three-wire/four-wire intelligent multi-function meter using time-division multiplier integrated circuits. The multi-function meter structure employed dedicated energy meter integrated circuits, non-volatile memory, dedicated electric cards, and large-screen LCD displays. The analog multiplier used a small-scale measurement dedicated integrated circuit designed by the 771st Institute of China Aerospace Research Institute in 1991, employing time-division multipliers and dual-integration V/F conversion. It offered complete digital compensation including phase compensation without external components, and achieved variable-range processing during measurement for wider measurement ranges. Functions included precise measurement of active energy, reactive energy, active demand, reactive demand, power factor, and prepaid four-rate metering, overload and pre-set energy alarm and automatic power-off, phase loss alarm recording, automatic meter reading, card insertion/removal operations for information transmission between user meters and power supply department sales management systems, and various software and hardware anti-interference measures. Time-division multipliers hold an extremely important position in active energy measurement technology. The internationally classic (German) C12-type standard power converter with 0.005% measurement accuracy is used as a national measurement working standard for standard energy meter verification at the China National Institute of Metrology. Particularly when voltage and current signal waveforms are distorted, time-division multiplier harmonic power measurements match theoretical calculation results. However, time-division multipliers are only applied to active power measurement, and as multi-function meters, reactive energy measurement and other functions are important components requiring supplementary alternative phase-shifting circuits or A/D sampling solutions, which complicates the product. Consequently, multi-function meters using time-division multipliers currently hold a small market share.

4.4 2002: All-Digital Static Multi-Function Meter

In 2002, Nanjing Blue Star Power Meter Research Institute launched a 0.5S-class all-digital static multi-function meter. The meter structure comprised the all-digital CS5460A measurement chip (integrating A/D, voltage reference, operational amplifier, DSP, and digital interface), digital signal operations, digital filtering, digital quantity correction, and digital calibration units, requiring no physical adjustment components. The CS5460A chip employed new-generation analog-to-digital conversion technology and DSP digital signal processors. Functions included active and reactive energy measurement, phase energy measurement, voltage and current RMS and instantaneous values, power, power factor, non-linear compensation for instrument transformers, and super lithium battery backup for the clock with over 20 years storage life. Nanjing Blue Star' s all-digital multi-function meter represents the second category of third-generation domestic multi-function meters using digital measurement chips, featuring significantly improved measurement accuracy, anti-interference capability, and reliability. Established around 1980, Nanjing Blue Star primarily engaged in power meters, data acquisition devices, and software development, marketing, and import-export operations. Between 2002-2008, Blue Star' s all-digital electronic multi-function meter OEM products sold well, mainly supplying short-term OEM needs for large induction meter enterprises transitioning to multi-function meters and emerging electronic meter enterprises with insufficient multi-function meter development capabilities.

4.5 2002: Harmonic Measurement Multi-Function Meter

In 2002, Wasion Group first developed a 0.2S/0.5S-class electronic multi-function meter with harmonic measurement functions in China. The multi-function meter structure employed the internationally popular high-end energy meter design scheme: measurement DSP + management MCU hardware architecture. The harmonic analysis and measurement principle involved sampling and digital processing of each phase' s current and voltage by 16-bit A/D and DSP high-speed processors. Through corresponding digital calculations, the DSP performed real-time 256-point FFT transform processing on current and voltage signals to provide measurement values for amplitude and phase of 2nd-49th current and voltage harmonic components, with harmonic amplitude accuracy of 2% and phase accuracy of $±$1-2°. The DSP completed electrical parameter measurement, energy accumulation, harmonic analysis, and calculation of fundamental and harmonic energy. Measurement data was exchanged with the management MCU through high-speed interfaces, while the management section used a 16-bit MCU to complete display, data statistics, storage, communication, energy meter function selection, and initialization data setting. Functions included measurement of active and reactive energy total and time-of-use energy, combined reactive energy measurement, cross-month settlement, maximum demand calculation, voltage, current, and power measurement, and three optional harmonic energy measurement modes:

Mode 1 (fundamental-based) where total active energy equals fundamental active energy with 0.5S-class active energy measurement; Mode 2 (digital multiplier-based) where total active energy equals the sum of fundamental and harmonic active energy with 0.2S-class active energy measurement; and Mode 3 (FFT-based) where total active energy equals the absolute sum of fundamental and harmonic active energy with 0.5S-class active energy measurement. Additional features included transformer loss compensation, correction and compensation for external PT and CT ratio and phase errors, two independent RS485 interfaces, one adsorption infrared and far-infrared interface, load recording, event records, test output, alarm functions, and energy meter self-diagnosis and recovery functions. This represents the third category of third-generation domestic multi-function meters using the high-end (measurement DSP + management MCU) scheme.

4.6 2010: 0.1S-Class High-Accuracy Settlement Gateway Meter

In 2010, Wasion Group launched the DTSD341-MA1V1.0 model, a 0.1S-class high-accuracy settlement gateway multi-function meter. The gateway meter structure primarily comprised I/V conversion circuits (CT), V/V conversion circuits (resistive voltage division) entering analog-to-digital converters (A/D) with independent voltage references, then to measurement DSP. Key components were selected from internationally high-reliability brands, including German VAC high-permeability current transformers, American VISHAY high-precision cylindrical resistors, American 18-channel 24-bit high-precision A/D converters (12.8k sampling rate), American ADI high-performance external voltage reference chips and high-speed DSP measurement chips, and multi-layer high-performance PCBs with analog-digital separation. The overall measurement scheme featured high accuracy, high stability, high reliability, and long-life characteristics. High-precision design employed Newton-Cotes high-order integration algorithms, fast power flow resolution technology, and hardware phase matching technology to achieve high-accuracy measurement under dynamic loads. Factory active energy measurement accuracy was controlled within $±$0.04%, with reactive energy measurement at 0.5S class. The design made negligible the effects of ambient temperature, power factor, frequency, and load current rise/fall variation on measurement accuracy, with measurement accuracy within 0.1% over a 15-year service life cycle. Functions included forward active energy and four-quadrant reactive energy measurement (reverse measurement for reference only), two reactive energy measurement combinations configurable from four-quadrant reactive energy, time-of-use active and reactive energy, time-of-use active and reactive maximum demand calculation, up to 12 rates with two main and auxiliary time periods, dual clock backup, six types of data load curve recording with 20M byte capacity, dual RS485 interfaces, adsorption/far-infrared communication interfaces, one 100M adaptive Ethernet interface supporting UDP/TCP remote meter reading (supporting DL/T 645-2007 or user-defined protocols), rich grid event records, dual backup data storage with self-check and error correction functions, four open-contact energy pulses and LED energy pulse outputs, and large-screen wide-view LCD display. In December 2010, the Hunan Provincial Science and Technology Department organized a project appraisal meeting for "Key Technology Research and Application of 0.1S-Class Gateway Energy Meters" at Wasion Science Park. The appraisal concluded: "This achievement has multiple independent intellectual property rights, with key technologies reaching international advanced levels. It is recommended to develop standardized products and achieve industrialization as soon as possible." Wasion' s 0.1S-class high-accuracy settlement gateway multi-function meter filled the gap in domestic high-end energy meter products, exceeding the highest 0.2S class in the 2011 IEC energy meter standard. Currently, 0.1S-class gateway meters have been operating stably and reliably for over 10 years at regional grid gateways, provincial grid gateways, power plant grid-connection points, and frequently varying load electrified railway metering points. They have also passed EU MID certification and DLMS certification, gaining application in numerous countries.

4.7 2013: State Grid Standard Smart Meter

In 2013, State Grid launched the 2013 edition State Grid standard smart meter, the second smart meter model following the 2009 edition. Smart meter design and production are the responsibility of meter enterprises, while standard formulation, network access testing, product bidding, and acceptance are handled by grid metering and materials departments. The smart meter structure design follows Q/GDW 1356-2013 *Three-Phase Smart Electric Energy Meter Type Specification* and Q/GDW 1355-2013 *Single-Phase Smart Electric Energy Meter Type Specification*, including meter parameter determination, display and indicator lights, power-off display, external structure and installation dimensions, and material and process requirements. Technical design follows Q/GDW 1827-2013 *Three-Phase Smart Electric Energy Meter Technical Specification* and Q/GDW 1364-2013 *Single-Phase Smart Electric Energy Meter Technical Specification*, covering specifications, environmental conditions, mechanical and structural requirements, accuracy requirements, electrical requirements, insulation performance, electromagnetic compatibility, reliability, data security, software requirements, packaging, and communication module interchangeability requirements.

Currently, dedicated energy measurement chips include four categories: three-phase energy measurement chips, three-phase multi-function measurement chips, single-phase energy measurement chips, and single-phase energy meter SOC chips. Domestic manufacturers Shanghai Jingquan, Shanghai Belling, Fudan Microelectronics, and Shenzhen Chipsea occupy the majority of the domestic market, while foreign manufacturers ADI, TDK, Atemel, and Cirrus Logic occupy portions of the domestic market. Typical cases include Shanghai Belling' s BL6513C three-phase active power measurement chip based on digital signal processors with 3000:1 input dynamic range, non-linear error less than 0.1%, and 25mW static power consumption; Shanghai Jingquan' s ATT7022E/26E/28E series high-precision, multi-function three-phase energy measurement chips based on digital signal processors, integrating multi-channel second-order Sigma-Delta ADC, reference voltage, digital signal processing circuits, and built-in temperature sensors with 5000:1 input dynamic range and non-linear error less than 0.1%; and ADI' s ADE7878, ADE7868, ADE7858, and ADE7854 high-precision energy measurement ICs providing 0.2% accuracy for active and reactive energy measurement within a 3000:1 dynamic range, with 0.1% accuracy for reactive and active power measurement, including one chip with fundamental energy measurement capability.

The 2013 edition State Grid standard smart meter, following Q/GDW 1354-2013 *Smart Electric Energy Meter Functional Specification* and Q/GDW 1365-2013 *Smart Electric Energy Meter Information Exchange Security Authentication Technical Specification*, possesses relatively complete functions. After 1-3 years of operation, the 2009 edition smart meters exhibited numerous faults, reflecting serious product quality issues. Consequently, State Grid' s Marketing Department issued notices on rectifying and strengthening smart meter quality management and organized the formulation of technical specifications for major smart meter components (13 items), leading to the 2013 edition standard. The 2013 edition added new requirements including constant magnetic field protection, power frequency magnetic field anti-creep, high-temperature extreme working effects, communication module interface load capacity, communication module interchangeability, and energy meter software comparison functions, improving metering stability, reliability, anti-theft capability, and communication module interoperability, thereby significantly reducing meter failure rates. However, it did not propose new functions for intelligent meter projects or fundamental/harmonic active energy measurement development and application.

4.8 2020: New-Generation Smart Meter

In 2020, State Grid launched the 2020 edition State Grid standard smart meter—the new-generation smart meter—developed based on the 2013 edition and incorporating key requirements from the IR46 international metrological recommendation for active energy meters. The structural design follows State Grid standards *General Technical Specification for Three-Phase Smart Electric Energy Meters (2020 Edition): Part 3, Three-Phase Smart Electric Energy Meter Type Specification* and *General Technical Specification for Single-Phase Smart Electric Energy Meters (2020 Edition): Part 3, Single-Phase Smart Electric Energy Meter Type Specification*, including specifications, display and indicator lights, power-off display, external structure and installation dimensions, and material and process requirements, with current specifications expressed using minimum current Imin, transition current Itr, and maximum current Imax.

Technical design follows State Grid standards *General Technical Specification for Three-Phase Smart Electric Energy Meters (2020 Edition): Part 2, Three-Phase Smart Electric Energy Meter Technical Specification* and *General Technical Specification for Single-Phase Smart Electric Energy Meters (2020 Edition):*

Part 2, Single-Phase Smart Electric Energy Meter Technical Specification, covering specifications, environmental conditions, mechanical and structural requirements, accuracy requirements, electrical performance, insulation performance, reliability, data security, software requirements, packaging, and communication module interchangeability.

Key differences between IR46 and IEC energy meter standards include: accuracy representation methods (maximum permissible error, basic maximum permissible error, maximum permissible error shift); error traceability (data change processes from initial intrinsic error, intrinsic error, faults to significant faults should be traceable); accuracy classes expressed as A, B, C, D grades covering reference quantities, influence quantities, and interference quantity variation ranges; current working range representation using starting current Ist, minimum current Imin, transition current Itr, and maximum current Imax, with accuracy calculation methods from Ist to Imin; accuracy composition including basic maximum permissible error, influence quantity permissible error, and interference permissible effects, introducing interference quantities, interference levels, permissible effects, and energy meter error offset limits; comprehensive error estimation; and metrological characteristic protection through hardware and software separation.

The 2020 edition smart meter product possesses more complete functions according to the State Grid smart meter (2020 edition) functional specification. This represents the second category of third-generation domestic multi-function meters using digital measurement chips, demonstrating the application and demonstration of IR46 standards in domestic smart meters with focus on IR46 metrological accuracy and metrological performance protection requirements. In recent years, IR46 standards have become important foundational content for formulating domestic smart meter standards and national energy meter metrological verification regulations. However, IR46 standards have limitations, currently only covering active energy meter international metrological recommendations, while multi-function meter reactive energy measurement testing must still follow IEC energy meter standards, creating complexity.

Reviewing the origin and evolution of domestic multi-function meters (smart meters and new-generation smart meters) reveals profound changes in the domestic multi-function meter industry over 30 years: product types evolved from 1992 mechanical-electronic multi-function meters through electronic multi-function meters and smart meters to 2020 new-generation smart meters; design functions expanded from JB/T 7656-95 *Multi-Function Electric Energy Meter* standard with 12 basic function items and 30 detailed rules to Q/GDW 1354-2013 *Smart Electric Energy Meter Functional Specification* with 30 basic function items and 119 detailed rules; accuracy improved from 1992' s 1-class active energy measurement to 2010' s 0.1S class using digital multipliers; and the 2020 edition State Grid smart meter first applied key IR46 requirements in domestic energy meters.

Looking back at this development process, the industry should remember these units for their pioneering and guiding achievements: East China Power Industry Administration for releasing the first domestic technical report on electric energy measurement modernization and organizing the drafting of the first mechanical and power industry standards; Jiangxi Provincial Electric Power Test and Research Institute for first developing time-division multiplier-based electronic standard energy meters in 1973; Ningguang Electric Factory for first launching time-division multiplier integrated circuit-based electronic multi-function meters; Wasion Group for first launching digital multiplier-based multi-function meters in 1994, first developing 0.2S-class harmonic measurement electronic multi-function meters in 2002, and first launching 0.1S-class high-accuracy settlement gateway energy meters in 2010; and China Electric Power Research Institute for leading the development of the 2013 State Grid standard smart meter in cooperation with Wasion, Linyang, and other meter enterprises.

References

[1] Wang Changqing (Advisor: Tong Weiming). Research on Smart Meters for Advanced Metering Infrastructure in Smart Grids. *Harbin Institute of Technology Master' s Thesis*, 2011-06-01.

[2] Wang Jingzhe. Several Conditions Where Voltage Loss Timers Do Not Require Configuration. *Industry and Technology Forum*, 2011-05-30.

[3] Li Ming; Li Chunzhang; Jiang Yang; Zhu Zhongwen. Diagnosis and Countermeasures for Radio Frequency Radiation Immunity Tests of Multi-Function Energy Meters. *Measurement and Control Technology*, 2010-07-18.

[4] Lu Ying (Advisor: Wu Guozhong). Design Research and Application of Energy Meters Based on MSP430. *Zhejiang University Master' s Thesis*, 2010-05-01.

[5] Yue Yaobin; Meng Xiangzhong; Bai Xingzhen. Design of Communication Software for Distributed Substation Time-of-Use Energy Measurement Management Systems. *Microcomputer Applications*, 2006-07-15.

[6] Yue Hu; Guo Wanzhu; Liu Zhuo. Debugging of Concentrators in Power User Electric Energy Data Acquisition Systems. *Industrial Metrology*, 2011-09-15.

Note: Figure translations are in progress. See original paper for figures.