Performance Evaluation and Quality Test Methods for Multi-function Electric Energy Meters

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Abstract

A comprehensive and systematic performance evaluation and quality test methodology for multifunctional electricity meters is proposed. Through comparative studies of relevant domestic and international standards and the technical specifications of advanced meters, this methodology comprehensively considers multiple aspects including accuracy, stability, reliability, and intelligence level of the meters, providing robust support for quality enhancement and technological innovation in the electricity meter industry.

Full Text

Quality Test Method for Performance Evaluation of Multi-Functional Watt-Hour Meters

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Abstract: This paper proposes a comprehensive and systematic quality test methodology for evaluating the performance of multi-functional watt-hour meters. Through comparative studies of relevant domestic and international standards and the technical specifications of advanced meters, this methodology comprehensively considers multiple aspects including meter accuracy, stability, reliability, and intelligence level, providing robust support for quality improvement and technological innovation in the energy meter industry.

Keywords: Multi-function meter; Performance evaluation; Quality test

Introduction

After fifteen years of development, domestic multi-function watt-hour meters have reached an annual production scale of 1.2 million units, with active energy measurement accuracy ranging from Class 0.2S to Class 1, and continuously evolving functions and communication protocols. However, in the transition toward a quality-centric era, the industry faces challenges in technological innovation and independent intellectual property rights. These issues are closely related to lagging and incomplete multi-function meter standards, as well as a lack of research on differentiated product performance evaluation (quality) testing methods.

Multi-function meter standards are typically divided into reference standards and enterprise standards. Reference standards refer to IEC standards, national standards, electric power and machinery industry standards, and national metrology verification regulations—broad technical regulations that guide industrial development. Enterprise standards adopt the technical requirements and test methods specified in reference standards as fundamental design documents to plan product quality levels. For a long time, due to the guidance of reference standards, enterprise standards have lacked independent innovation; the divergent requirements from grid metering application departments have increased the burden of product design improvements; and low-price competition has led to uncontrolled product quality. Compared with international brand products, there remains a significant gap in the quality of domestic multi-function meters, with imported meters dominating main grid gateway metering positions, and even the development of new-generation mid-to-low-end multi-function meters facing considerable difficulties.

This paper consists of three parts: differentiated design analysis of imported grid gateway multi-function watt-hour meters, a practical review of current reference standards, and an exploration of product performance evaluation (quality) test methods. Its purpose is to provide positioning ideas, framework design, and exploration methods for typical product indicators when formulating enterprise standards for new domestic multi-function watt-hour meters.

1. Differentiated Design of Imported Grid Gateway Watt-Hour Meters

Currently, enabling domestic Class 0.2S multi-function meters to assume a dominant position in grid gateway metering has become an aspiration for the energy meter industry. A comprehensive study of the differentiated design of imported grid gateway watt-hour meters forms the foundation for evaluating the practicality of current reference standards and discussing/formulating enterprise standards for new multi-function meters.

Differentiated design primarily refers to: which indicators in these imported grid gateway meters exceed IEC standards; functions and indicators not covered by IEC standards; the highest values of the same indicator among similar imported meters; technical differences and gaps compared with domestic Class 0.2S multi-function meters; and how to adapt to global meter market application demands and new developments in metering technology.

The technical specifications summarized below are compiled from samples of eight models of imported Class 0.2S grid gateway watt-hour meters:

1.1 Metering Chips

Two categories are employed: (1) Proprietary metering chips from meter manufacturers, including AC sampling power algorithm-based multiplier chips and time-division multiplier chips (the latter being a specific imported product); and (2) General-purpose chip combinations with proprietary algorithms, featuring 14-bit to 18-bit A/D converters for voltage/current circuits, 32-bit CPUs, and maximum sampling rates of 256 points per cycle.

1.2 Energy Metering Accuracy

Active energy metering maintains two levels of performance: (a) The error curve from 0.05%In to Imax serves as a horizontal reference, and (b) actual errors are controlled within $±$0.05%. Reactive energy metering accuracy reaches $±$0.2%, while apparent energy metering achieves $±$0.3%. Apparent energy employs two algorithms: vector method and arithmetic method, with four-quadrant apparent energy measurement capability. Qh metering accuracy is $±$0.3%. Over a 30-year effective lifespan, these meters maintain stable accuracy without requiring any periodic verification.

1.3 Harmonic Energy Metering

Two metering modes are implemented: (1) Separate measurement of fundamental and harmonic energy, and (2) measurement of total harmonic energy and its percentage of total active energy.

1.4 Typical Meter Constants

For 3$\times 100V, 3\times$5A configurations, constants are C=20000 imp/kWh and kvarh.

1.5 Anti-Interference Capability and Reliability

Features include specially designed metering circuits and main components, dedicated anti-interference measures, sequential timing design for voltage circuit loss-of-voltage and recovery scenarios, and storage of all metering data in two different locations within a non-volatile EEPROM as original and backup copies. Electromagnetic compatibility undergoes more rigorous testing than IEC and ANSI standards, including high-voltage impulse influence, fast transient and oscillatory transient tests, power ramp tests under fast transients, radio frequency interference tests at 31MHz, 154MHz, and 454MHz, irregular power cycling tests, low-voltage continuation tests, IEEE C37.90.1-1989 protective relay and relay system surge withstand capability tests, and ANSI C62.41 surge immunity tests.

1.6 Starting Power

Starting active power is less than 0.05% of rated active power, while starting reactive power is less than 0.1% of rated reactive power.

1.7 Voltage Application Range

Adaptive voltage input ranges from 45V to 290V (phase voltage). For specified voltage ranges, the measurement range is 70-115% of reference voltage, with an allowable range of 65-130%.

1.8 Time Reference

A typical real-time clock (RTC) uses a 20MHz crystal oscillator with synchronization sources including internal crystal oscillator, power system frequency ($±$10 PPM), external ASCII receiver (1ms precision), IRIG-B GPS receiver (1ms precision), and support for master station and acquisition terminal time synchronization.

1.9 Demand Calculation

Demand calculation categories include maximum demand, minimum demand, current demand, previous demand, target demand, cumulative demand, continuous cumulative demand, and thermal demand, with demand periods synchronized to the meter' s internal clock.

1.10 Voltage-Hour, Current-Hour, Frequency-Hour, and Power Factor-Hour Metering

These advanced metering capabilities are standard features.

1.11 Accurate and Rapid Measurement and Recording of Instantaneous Quantities

Measurement accuracy includes voltage, phase current, neutral current, frequency ($±$0.01 Hz for 47-63Hz), and power factor. The shortest measurement and recording period is 10ms, refreshed once per second, with maximum and minimum values recorded at 1ms time resolution. Instantaneous apparent power measurement distinguishes between vector VA (excluding harmonic influence) and arithmetic VA (including harmonic influence).

1.12 Voltage and Current Unbalance

Measurement includes zero-sequence, negative-sequence, and positive-sequence components for both voltage and current.

1.13 Power Quality Monitoring

Capabilities include harmonic measurement from 2nd to 63rd order with 1% accuracy, single-order resolution up to 50th harmonic including amplitude and phase angle, voltage tolerance curves (CBEMA/ITIC), power supply reliability of 99.9999999% (representing only 2 cycles of fault time per year), recording of voltage sags, swells, and disturbances, and capture of instantaneous current changes.

1.14 Loss Compensation for Transformers and Power Lines

Features include voltage-squared-hour and current-squared-hour recording for loss compensation.

1.15 Dynamic Error Correction for Instrument Transformers

This advanced functionality enables real-time error correction.

1.16 Data and Event Recording

Non-volatile memory capacity reaches 10MB, supporting load profile recording and data logging functions.

1.17 Communication Functions

Communication interfaces include serial ports (RS232/RS485 at 115200 bps), infrared interface (19200 bps), built-in modem (33600 bps), Ethernet (10/100 MHz), IRIG-B interface, and 20mA current loop. High-speed communication methods encompass frame relay, optical fiber, wireless, wired, telephone network, Ethernet, and microwave networks. Major protocols include IEC 62056 series, IEC 870-5-102, DNP3.0, Modbus RTU, and TCP/IP. A protocol conversion RTU unit with CPU enables direct communication with SCADA systems or other local RTUs. Internet connectivity supports WEB browser data access and automatic email transmission for alarm information or periodic system status updates.

1.18 Output and Input Functions

Pulse, analog, and digital status inputs/outputs are implemented through independent, complete I/O modules communicating via Lonworks protocol over twisted pair. Output pulse specifications include programmable pulse widths from 5-250ms with polarity control. LED pulse output operates below 40Hz with 8ms pulse width. A master-slave meter network architecture allows multiple meters to form a network via fiber optic, with one master meter functioning as a data collector.

1.19 Display Modes

Display capabilities include vector diagrams, harmonic bar charts [Figure 6: see original paper], and LED backlighting with 0-120 minute adjustable duration.

1.20 Self-Diagnostics

Two diagnostic modes are implemented: (1) Power-on self-test with periodic memory testing, and (2) Continuous monitoring of hardware, software, and recorded data during operation, with abnormal events communicated via upload, emergency alarms, and fault code display.

1.21 Hardware Circuitry

Modular design features pluggable communication modules with backplane-based inter-module communication, enabling field modification and functional expansion during the meter's service life. Supercapacitors provide backup power for over 20 days during outages.

1.22 Support Software

Compatibility includes ITRON MV-90 system integration, meter programming software, communication protocol editors, and meter data file software.

1.23 Meter Casing

Casing materials include anti-static glass fiber reinforced plastic and flame-retardant polycarbonate (recyclable after service life). Casing types include socket-mounted, rack-mounted, panel-mounted, DIN standard, and Type A base configurations.

2. Practical Review of Current Reference Standards

2.1 IEC Relevant Standards

Currently, IEC has not established dedicated standards for multi-function meters. Relevant standards include IEC 62052-11 (general requirements for static watt-hour meters covering terminology, standard electricity values, mechanical requirements, climatic conditions, and electrical requirements including EMC) and IEC 62053-21/22/23 (specific requirements for Class 1 and 2 active energy/Class 0.2S and 0.5S active energy/Class 2 and 3 reactive energy static meters).

Key provisions include: - For multi-energy meters containing additional functional elements (maximum demand indicators, electronic tariff registers, time switches, ripple control receivers, data communication interfaces), relevant standards for these elements also apply. - Test levels are set at minimum values to ensure inherent functionality under nominal working conditions; other levels may be negotiated between user and manufacturer for special applications. - Active energy metering accuracy applies for cosϕ=0.25(L)-1-0.5(C); reactive energy metering for sinϕ=0.25(L/C)-1. - IEC 62053-23 covers reactive energy metering under sinusoidal conditions. - Meter test equipment references IEC 60736:1982. - Reliability requirements follow IEC 62059 series standards.

Critical Issues Identified:

1. **Error Limit Relaxation:** When cosϕ(sinϕ)\$ $1, IEC standards relax error limits inconsistently, stricter$ versus other power factors varies.
2. **Low Power Factor Definition:** For cosϕ<0.25, should error limits be defined by enterprise standards?
3. **Zero Power Factor:** How are error definitions and calculation methods determined at cosϕ=0?
4. **Switching Power Supply:** What types are commonly used in meters? How are power consumption peaks captured?

5. **Temperature Coefficient:** Should be measured across the entire working range.
6. **External Magnetic Fields:** How should test equipment generating constant external magnetic fields be designed?
7. **Harmonic Influence:** IEC test circuits cover harmonics from DC to 21st order but state Fourier analysis is incomplete, while international practice uses 63rd order analysis. What harmonic analysis technology should be adopted? How should reference meters be traceable under odd and subharmonic conditions?
8. **Voltage Ranges:** Standard meters require traceability across specified, extended, and limit working ranges, plus maximum voltage during ground faults.
9. **Test Outputs:** IEC 62053-31 for electrical test outputs requires waveform compliance testing, including rise time verification using Tr=0.2 s standard receiving diodes and optical radiation intensity signal testing.
10. **EMC Requirements:** During electrostatic discharge, radiated electromagnetic field, and surge immunity tests, temporary function/performance degradation is acceptable. During fast transient burst tests, temporary degradation is acceptable but accuracy must remain within specified limits (verifiable by counting or other methods). During RF conducted disturbance and damped oscillatory wave tests, equipment must not malfunction and error changes must remain within limits.
11. **Reactive Meter Power Consumption:** Should Class 2 and 3 reactive meters both have 5VA current circuit consumption?
12. **Three-Phase Reactive Meter Testing:** If test methods and meters are affected differently by voltage/current unbalance, reference voltage must be adjusted to perfect symmetry. What reactive metering principles are commonly used? How do sinusoidal reactive meters respond to voltage unbalance?

2.2 GB/T17215.301-200X

As China' s first national standard for multi-function meter special requirements, it establishes technical specifications based on advanced international standards. However, it lacks supplementary technical requirements for IEC standard application issues, has different views on demand accuracy, and requires subsequent validation methods for apparent energy metering accuracy, event recording, and extended functions.

2.3 National Metrology Verification Regulation: JJG 596-1999

Focused on legal metrology verification to ensure measurement accuracy and value consistency, JJG 596-1999 provides basic verification content including technical requirements for meters under test, basic verification conditions, requirements for verification equipment, verification methods, wiring diagrams, data rounding methods, and verification result processing. It applies to AC active energy meters (both standard and installed meters), uses Ib to represent test current without distinguishing direct-connection or transformer-connected meters, and specifies methods for determining basic error, verifying register readings, and determining permissible errors and standard deviation estimates S(%) for verification equipment.

2.4 Power Industry Standard: DL/T 614-2007

DL/T 614-2007 specifies technical elements for ordering, acceptance, and use of multi-function meters in the power industry, standardizing function configurations. It improves demand accuracy calculation methods, proposes consistency assessment for meter errors, and includes protocol compliance testing for DL/T 645-2007 with data transmission line anti-interference tests. It also references IEEE 1459-2000 for power measurement definitions under sinusoidal, non-sinusoidal, balanced, and unbalanced conditions.

2.5 Comprehensive Analysis

IEC standards focus on type testing for static meters under sinusoidal, stable load conditions, emphasizing energy metering accuracy and test methods. While crucial for domestic meter development, they lag behind the metering performance of imported Class 0.2S grid gateway meters. The analysis reveals three layers of issues: (1) New requirements and methods in IEC revisions need tracking and adoption; (2) Original IEC requirements need clarification and improvement; (3) Gaps exist between IEC standards and current product design technologies, requiring supplementary technical requirements and test methods.

GB/T17215.301-200X, JJG 596-1999, and DL/T 614-2007 each have specific positioning but require updates to address modern grid developments, including harmonic energy metering, power quality monitoring, and advanced metering technologies.

3. Performance Evaluation (Quality) Test Methods for Multi-Function Meters

Performance evaluation (quality) testing primarily aims to identify quality differences and adaptability to physical condition changes.

3.1 Basic Test Methods

Conducted according to IEC standards, national standards, industry standards, and national metrology verification regulations, basic tests comprise nine categories: accuracy, climatic conditions, electrical requirements, EMC, function compliance, programming requirements, mechanical and component requirements, data security and software, and average lifetime—totaling approximately 62 test items.

3.2 Additional Test Methods

Building upon basic methods, additional tests expand scope through: - **Extended Accuracy Testing:** Expanding current range testing from fixed points to 0.5IQ-1.2Imax, phase angle range from cosϕ(sinϕ)\$ \$0.25 to 0-360°, error distribution statistics, experimental standard deviation calculation, and four-quadrant error asymmetry analysis. - **Critical Testing:** Including critical phase angle tests, critical voltage tests, and creep tests. - **Influence Quantity Testing:** Assessing meter operating conditions and error changes during influence quantity tests (voltage unbalance, ground fault, EMC) and calculating total variation caused by influence quantity changes (ambient temperature, voltage range, frequency variation). - **Physical Condition Simulation:** Including impact load tests, demand testing under dynamic loads, and harmonic response capabilities of voltage, current, and power. - **Enhanced Severity:** Increasing test severity for accuracy, EMC, and communication interface tests. - **Algorithm Verification:** Including harmonic active power calculation, apparent power and power factor calculation, and uncertainty calculations for various test methods. - **New Testing Technologies:** Encompassing power quality measurement function correctness, rapid measurement and recording correctness, electrical/optical test outputs, electromagnetic environment testing under reference conditions, communication protocol compliance testing, timing sequence testing during voltage circuit faults, and storage capacity testing. - **New Test Items:** Including operational reliability testing, event recording correctness, extended function accuracy, and lifetime verification test methods.

3.3 Application of Performance Evaluation Test Methods

1. **For User-Facing Class 0.2S-1 Meters:** From the approximately 105 test items described, select appropriate basic and additional tests for each of the nine categories specified in IEC and national standards, and compile detailed quality test implementation rules.

2. **For Grid Gateway Meters:** Based on product characteristics (energy metering accuracy, error stability/repeatability/consistency, reliability, dynamic load response, real-time measurement/recording, communication functions, and grid operation requirements), select suitable tests from the seven categories and compile performance evaluation test implementation rules.

3. **Metrological Traceability for Special Quantities:** Test result credibility ultimately depends on metrological traceability. Available traceability sources include:

    - **Power Frequency Harmonic Power Standard (NIM):** Covers 45-65Hz fundamental frequency, up to 60th harmonic, with analysis uncertainty of harmonic voltage <30 V/V (k=2), harmonic current <36 A/A (k=2), and harmonic power <42 W/VA (k=2).
    - **Power Quality Calibration Device (CEPRI):** Calibrates AC voltage RMS, harmonic content, and other power quality parameters.
    - **Power Frequency Sinusoidal Power Standard (NIM):** Supports low power factor metering ($\cos\phi$=0-0.25) and reactive power ($\sin\phi$=0-1).

For tests lacking traceability, analytical uncertainty and supporting test data should be provided.

4. **Comprehensive Evaluation:** The comprehensive evaluation method for multi-function meter performance assessment requires further research. Currently, it is recommended that individual performance evaluation results be ranked rather than graded.

Conclusion

Drawing from international brand product design and manufacturing experience, multi-function meter quality assurance depends on design, materials, and processes—including careful component supplier selection with rigorous testing, proprietary metering chips, special circuit board design and testing, complete test flow systems, rigorous critical testing, prototype testing, pre-shipment stability testing, and full lifecycle quality control. The performance evaluation (quality) test methods described herein focus on product comparison, selection, and acceptance testing/analysis, and can also serve as references for new product design finalization and prototype testing.

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