Research on the Electricity Meter Testing Industry Based on Smart Grid Demonstration Project Design Concepts

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Abstract

This passage primarily describes the transformation of State Grid's investment strategy regarding smart meters and distribution networks, along with its implications for the metering industry. State Grid has shifted its investment priority from smart meters to new-generation smart substation demonstration projects and smart distribution network construction. The new-generation smart substations are characterized by integrated intelligent equipment and unified business systems, encompassing the integration of primary equipment, integration of secondary equipment, and functional integration between primary and secondary equipment. State Grid has also highlighted the urgency of distribution network development and outlined plans to accelerate the intelligent upgrading of distribution networks. Furthermore, the text addresses recent advancements in electronic meter testing technology, particularly the progress achieved by the National Institute of Metrology (NIM) in high-voltage three-phase energy metering standards, including high-voltage standard power sources and high/low-voltage multifunctional standard meters. These technological developments provide more accurate and efficient tools for electronic meter testing. In summary, the passage reflects the continuous evolution and upgrading of grid technology, which poses new challenges and opportunities for the metering industry. Traditional meter manufacturers must adapt to these changes, study and research modern grid measurement technologies, and develop new products suited to the rapid development of smart distribution networks.

Full Text

Introduction

In 2013, the third batch of centralized smart meter bidding by State Grid Corporation of China (SGCC) experienced a sudden decline, significantly impacting the meter, terminal, and testing equipment markets. This shift occurred because SGCC redirected its smart grid investment focus from smart meters to new-generation smart substation demonstration projects and smart distribution network construction.

Smart Grid Development Context

New-Generation Smart Substations

In December 2012, SGCC convened a kickoff meeting for new-generation smart substation demonstration projects. These projects are characterized by integrated intelligent equipment and unified business systems, representing a fundamental shift from discipline-specific design to holistic integrated design, and from primary equipment with intelligent features to truly intelligent primary equipment. Key integration features include:

Primary Equipment Integration: This involves adopting integrated intelligent circuit breakers that combine electronic high-voltage transformers, disconnectors, and circuit breakers into a single unit. **Secondary Equipment Integration:** The 220kV Hejia Smart Substation in Liaoning represents the world's first implementation of XJ centralized protection, where traditional designs required separate devices for protection, measurement & control, and metering functions. The new approach integrates hardware and implements functions through software, decoupling specific capabilities from dedicated physical devices. **Functional Integration Between Primary and Secondary Equipment:** The 500kV Lili Substation in Fujian pioneered the "primary equipment + intelligent terminal + sensor" model, utilizing multi-function Intelligent Electronic Devices (IEDs) for online monitoring of parameters such as moisture content, pressure, and density.

Smart Distribution Network Development

SGCC's 2013 mid-year work conference identified distribution network development as an urgent priority, advocating for scientifically constructed distribution networks based on international experience. Future distribution networks will accelerate their intelligent upgrading process through several key capabilities:

- **Enhanced Compatibility:** Ensuring seamless integration of green power sources and new electrical equipment to enable plug-and-play functionality for end customers.
- **Dynamic Network Architecture:** Evolving into a dynamic, efficient, and conveniently interactive super-architecture network that supports real-time information and power exchange, enabled by advanced communication technologies to achieve high-reliability, real-time communication between distribution networks and customers at all levels.
- **Self-Healing Capabilities:** Through real-time monitoring of power supply reliability, implementing fault warning, analysis, and decision-making

to achieve self-prevention and self-recovery, optimizing grid operation and ensuring reliable power supply.
- **Power Quality Optimization:** Employing advanced power electronics, nanomaterials, and low-power technologies to optimize power quality control and minimize grid losses.

SGCC's Q4 2013 work conference emphasized seizing opportunities from the emerging third industrial revolution, addressing the "weakness at both ends" of the grid (ultra-high voltage backbone and distribution networks), accommodating rapid development of renewable energy and distributed generation, and meeting increasing demands for friendly electricity consumption interaction. The conference proposed adapting to distributed power source integration by supporting plug-and-play functionality, promoting dedicated low-voltage circuit breakers and anti-islanding devices, advancing green intelligent electricity usage, actively guiding microgrid development, and researching bidirectional interactive intelligent equipment—Liu Zhenya specifically mentioned studying bidirectional interactive smart meters twice. The conference also advocated for differentiated distribution automation construction.

New Metering Work Topics for 2014

According to available information, SGCC's 2014 marketing (metering) work program introduced several new research topics: electricity consumption and energy efficiency monitoring management, new-generation smart substation energy metering technology, operating status assessment of energy metering devices, and pricing management and metering traceability for distributed power sources.

Implications for the Meter Testing Industry

These developments offer important insights for the meter testing industry's evolution. Beyond maintaining traditional meter testing markets, industry players should adopt design concepts from new-generation smart substation and smart distribution network demonstration projects—namely integrated intelligent equipment, unified business systems, and alignment with future distribution network intelligent upgrading processes. This encompasses secondary equipment integration, primary-secondary equipment functional integration, bidirectional interactive smart meters/devices, new-generation smart substation energy metering, plug-and-play functionality for distributed power sources and smart electrical equipment, power quality optimization control, grid loss minimization, electricity consumption efficiency monitoring, operating status assessment of metering devices, and high-reliability real-time communication technologies. Traditional meter enterprises must adapt by learning and researching modern grid measurement technology, subsequently developing distribution and consumption network operation measurement, online monitoring & control systems, and related products to meet the anticipated rapid development of smart distribution networks.

Latest Developments in Electronic Meter Testing Technology

High-Voltage Three-Phase Energy Metering Standards

The China Metrology Institute has developed a high-voltage three-phase energy metering standard system (10kV, 35kV, 110kV/1000A) with 0.02% accuracy.

High-Voltage Standard Power Source: This three-phase high-voltage high-current standard power source serves as the physical standard for high-voltage energy, essentially functioning as an equivalent standard power grid. The system employs an embedded industrial control computer as its core. The HVS1500 (A, B, C) three-phase six-channel harmonic signal generator is a digital signal generator whose waveform data is directly configured by the computer, which can adjust settings to lock the output voltage and current waveforms and their phase relationships through feedback. Output amplitudes are controlled via corresponding D/A converters. After amplification by HVP1500, voltage signals pass through three voltage transformers to obtain the required three-phase high voltage, while current signals pass through three current transformers. High-accuracy V/V and I/V converters transform these high-voltage and high-current signals into A/D-level voltages, which are then quantized by six A/D converters in terms of time and amplitude. The computer calculates and locks output voltage, current (including frequency, amplitude, waveform, and phase), and power (active and reactive) from fundamental definitions, forming a complete three-phase standard power source.

High/Low-Voltage Multi-Function Standard Meter: This critical component serves as the measurement section of the standard power source. Its six-channel standard I/V and V/V converters accurately transform input high-current and high-voltage signals into A/D-level signals for sampling and connection to an embedded computer. The computer calculates input voltage, current (frequency, amplitude, waveform, phase), harmonics, and power (active and reactive) from definitions, with power integration yielding energy to form a three-phase multi-function standard meter.

Following third-generation ATE concepts, the standard meter features two software applications—"Three-Phase Multi-Function Standard Meter" and "High-Voltage Three-Phase Multi-Function Standard"—combined with two sets of I/V, V/V, and other hardware to implement both low-voltage and high-voltage functions. The low-voltage version offers voltage ranges of 50V, 100V, 200V, 400V and current ranges of 0.1A-100A (basic range 5A/100V), while the high-voltage version provides voltage ranges of 10kV, 35kV, 110kV and current ranges of 1000A-10A.

Traceability: The high-voltage energy metering standard's traceability chain extends to the national energy reference (3$\times 10^{\{-5\}}) through the national three-phase energy standard (1\times 10$ {-

4})*andnationalhigh* − *voltageratiostandard*(2×10^{-5}$). Prior to traceability experiments, the standard meter is calibrated by the national energy standard laboratory, and standard voltage and current transformers are calibrated by the national high-voltage standard laboratory. The 10kV/1000A, 0.02-class three-phase high-voltage energy metering device has been certified by national metrology authorities, enabling direct metrological traceability for 10kV high-voltage meters domestically. Industry attention should also focus on whether 10kV, 0.05-class three-phase high-voltage meter calibration devices will undergo certification assessment.

Performance Evaluation in Metering Boxes

Zhengzhou Wante Electric Company has developed a performance evaluation test device for single-phase smart meters installed in metering boxes. The device complies with State Grid's new smart meter standards, July 2012 quality control management guidelines, Chongqing Electric Power Research Institute's technical specifications, distributed power source grid-connection metering requirements, and relevant national legal metrology regulations.

With 0.1 accuracy class, the device includes 44 conventional test items per IEC/national standards and 41 special performance evaluation test items conducted inside metering boxes. Special tests include long-term creep testing for meters under test, influence of adjacent meters under different loads on creep/start/basic error, impact of adjacent meters powering on during creep/start/basic error tests, effect of spacing distance from adjacent meters, influence of high-current busbars, and interaction between the meter under test and low-voltage circuit breakers.

Test results for ten single-phase smart meters from different manufacturers in a meter box revealed significant performance variations: - For the same meter under test across 0.01Ib to Imax at power factors of 0.5L-1.0, with 40A applied to adjacent meters, variation reached +0.47% at 0.5Ib/1.0, increasing with decreasing load current and lower power factor to +35.1% at 0.01Ib/0.5L. - At 0.05Ib/1.0 with 40A on adjacent meters, 90% of manufacturers' meters showed variations of $±$1% to $±$5%. - At 0.01Ib/0.5L with 40A on adjacent meters, all test meters exhibited variations of $±$3% to $±35±$0.5°), all test meters showed large errors, some exceeding 20%. - Current mutations at 0.5Ib and below produced large average errors, some exceeding 20%. - Voltage variation tests revealed some meters' errors increased with voltage, while others activated internal protection at high voltages. - Minimum operating voltages varied across manufacturers (100-125V), as did minimum communication operating voltages (100-125V).

Bidirectional Interactive Smart Meters and Testing Technology

At SGCC's Q4 2013 work conference, Liu Zhenya proposed researching bidirectional interactive smart meters. However, in October 2013, the China Electric Power Research Institute published an article stating that smart meters' primary functions are based on current domestic smart electricity usage practices and do not carry specific interactive business functions, whereas smart electricity interaction terminals can handle information exchange, intelligent analysis/control, and multiple interactive services. This discrepancy suggests that SGCC's 2014 annual work conference will make final decisions and unified deployments regarding smart distribution network construction and the development of smart electricity technologies, including bidirectional interactive smart meters and smart electricity interaction terminals.

Technical Improvement Requirements for Bidirectional Smart Meters: - Existing communication methods and rates cannot meet new requirements - Need to distinguish between normal reverse energy metering and abnormal reverse counting - Interfaces and communication protocols with smart home systems require development - Software must be verified for correctness, security, and consistency - New non-volatile ferroelectric memory is gradually being adopted for external storage - Solid-state relays may replace magnetic latching relays as they continue to improve - "Power outage information upload" function requires supercapacitors (5.5V, 1F) as backup power - Magnetic coupling elements may replace optocouplers for isolation

Research Perspectives: The Zhejiang Metrology Institute's preliminary exploration of smart meter concepts, standardization, and testing methods emphasizes that smart meters are no longer terminal products but intermediate links between users and distribution centers, maximizing resource efficiency through timely information exchange. The International Organization of Legal Metrology (OIML) defines smart meters as instruments with basic metering functions plus additional functions based on bidirectional communication. IR46 international recommendations regulate production and legal management aspects.

Testing should simulate actual usage environments to verify reliability, stability, and security of bidirectional communication functions. Software testing should cover documentation analysis, metering function verification, software feature confirmation, data flow analysis, and module testing. As residential loads increase, Rogowski coil advantages become more prominent. ARM Cortex-MCU series processors are being adopted. If detected energy data cannot be written to memory or the writing process fails, meter accuracy degrades. Smart meter software testing processes generally include software documentation analysis, metering function confirmation, software feature verification, data flow testing, and module testing.

Nanjing Grid's research on large consumer smart electricity interaction applications covers interactive information content, terminal equipment, and communication architecture. The China Electric Power Research Institute's October 2013 discussion on flexible interactive smart electricity technology architecture indicates that Shandong Provincial Science and Technology Department organized a project appraisal meeting in Jinan on October 29, 2013.

Online Monitoring and Laboratory Testing Systems

A substation online energy meter remote monitoring system and laboratory-based three-phase meter performance testing device under simulated field conditions are being developed to meet SGCC Marketing Department's 2014 requirements for operating status assessment technology research.

The remote monitoring system for substations (gateway, large consumer, line loss statistics) has a preliminary accuracy class of 0.05, comprising three combined 0.02-class single-phase standard meters and 0.02-class, 0.5A intermediate current transformers. Online meter performance data is transmitted via fiber optic networks to provincial/municipal power department remote centralized monitoring platforms.

The laboratory testing device has a preliminary accuracy class of 0.2, simulating field conditions including three-phase voltage, current, and phase angle asymmetry/imbalance; grid frequency deviation from rated range; excessive voltage/current harmonic content; strong electromagnetic field influence; and ambient temperature and humidity variations.

Research focuses on comparison methods and database design techniques for test data from both subsystems, referencing work by Chongqing Electric Power Research Institute and Chongqing University on fuzzy comprehensive assessment and testing strategies for energy metering devices.

High-End Smart Meter Testing

iMeter High-End Smart Meters: These devices enable high-density, high-precision dynamic characteristic monitoring of voltage and current, accurately recording substantial waveform information for local anomalies or faults in power supply systems. They sensitively identify and accurately judge potential, transient, and continuous local faults, enabling rapid diagnosis of accident sources, fault direction, and fault source location.

Imported High-End Meter Research: A collaborative project on comprehensive imported high-end meter performance research includes: - Technical standards analysis - Internal structure and performance dissection - Component research (thermistors, through-hole electrolytic capacitors, PUS cables, CTs, voltage sampling resistors, PCB layers, clock batteries, AD converters, voltage references, crystal oscillators, terminal blocks) - Production process stability measures (PCBA processing, layout, cleaning, coating, assembly) - Chassis structure analysis (PCBA mounting, terminal block copper bar positioning, base positioning columns, voltage terminal wire fixing, CT wire fixing, display board mounting) - Special testing methods including linearity tests from starting current to maximum load, multi-stress tests simulating field load environments, and reliability verification

Key stability issues affecting gateway meter accuracy include small-signal accuracy divergence, long-term drift after extended operation, and improving accuracy stability under temperature and humidity variations. Solutions involve careful European component supplier selection, rigorous internal component testing, and special circuit board materials.

Reference Products: Research covers high-end meters including Landis+Gyr's ZMQ202C.6, Iskraemeco's WQMT, Elster's A1800, Actaris's SL7000, Itron's Q1000, and Ningbo Sanxing's MK6E.

IR46 Compliance Testing

Development of three-phase electronic meter performance testing devices to meet OIML's IR46 legal metrology specifications should be considered proactively to prepare for future implementation requirements.

Low-Voltage Narrowband PLC Communication Testing

The development of field-use low-voltage narrowband carrier communication multi-frequency SNR testers represents a domestic market gap. Related developments include: - Chongqing Electric Power Research Institute's development of a carrier communication routing test device - Shenzhen Zhongchuang Electric's HE1001 power line network analyzer - Beijing University of Chemical Technology and Heilongjiang Electric Power Research Institute's design and application of low-voltage power line carrier channel impedance testing terminals - Nanjing Zhide's low-voltage carrier point-to-point communication test system

Distribution Transformer Intelligence Technology

SGCC Electric Power Research Institute's project proposes a B/S architecture-based intelligent monitoring system for distribution transformers, enabling unified monitoring, analysis, and processing of transformer electrical and non-electrical parameters. The distribution transformer terminal primarily measures operating parameters, performs energy metering, issues abnormal condition alarms, analyzes operating status, and supports maintenance decisions. To manage geographically dispersed transformers, the system employs dual-mode positioning technology supporting both BeiDou and GPS.

The integrated distribution transformer information platform comprises four modules: real-time status monitoring, fault early warning, loss and load power quality monitoring, and maintenance decision support. Key research questions include improving service life, developing universal seamless communication protocols for interaction among numerous intelligent transformers and software systems, and achieving more accurate fault diagnosis.

Statistical Meters and Load Monitoring

Statistical meters incorporate power load measurement, low-voltage power line protection, energy management, and local communication networking functions.

Their energy management capability involves measuring and evaluating energy consumption, then managing electrical loads to maintain or reduce user-defined peak power. These meters control low-voltage automatic circuit breaker tripping/closing and implement energy management through selective disconnection and timely reconnection of non-critical loads, requiring specialized software algorithms.

Under user-defined maximum power constraints, statistical meters employ real-time energy consumption monitoring and specially developed logic algorithms to control primary/secondary circuit switching via low-voltage automatic circuit breakers based on user-defined load priority rankings while ensuring normal system operation. Local communication networking is recommended using Qingdao Dongsoft's 4th-generation narrowband PLC (20kbps) chips, wireless sensor networks, or OFDM narrowband high-speed carrier communication. A reference product is ABB's Emax2, the world's first low-voltage circuit breaker integrating energy management and smart grid communication functions.

Power Transformer Testing Technology

Emerging areas in power transformer testing technology include: - Integrated design of distribution transformers and measurement transformers, adding current transformers to high/low-voltage leads using amorphous core materials, incorporating measurement windings inside high-voltage coils, and installing temperature sensors - Hunan Electric Power Company's development of transformer capacity tester calibration devices - China University of Mining and Technology's virtual instrument-based transformer testing platform - Guangzhou Zhiyuan's high-precision transformer loss tester - Wuhan Haomai's pre-commissioning transformer hexagon diagram testing - Chongqing University's error analysis of common energy loss calculation methods

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