Applications of Smart Meter and Instrument Cloud Fusion Technology

Authors: Zhang Chunhui, Zhang Zhen, Zhang Zhen

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Abstract

This text primarily introduces the development and application of a smart meter remote online detection system employing high-precision computing based on the "instrument cloud." Initially, it reviews the evolutionary trajectory of conventional smart meter remote online detection system technologies, along with their inherent limitations and challenges. Subsequently, it elaborates on the genesis of this research initiative, encompassing the proposition of instrument virtualization technology within the "instrument cloud" framework, investigations into instrument virtualization under cloud computing environments, and the specific requirements and challenges posed by the State Grid Corporation. The discussion emphasizes the development project of the smart meter remote online detection system that leverages "instrument cloud" high-precision computing, detailing the fundamental principles and practical applications of instrument virtualization technology in cloud computing contexts, as well as the system's competitive advantages and market prospects. The development of this system is anticipated to mitigate the constraints and challenges associated with traditional smart meter remote online detection systems, enhance both measurement accuracy and the precision of intelligent diagnostics, concurrently reduce overall system costs, and thereby promote broader deployment and application of the technology.

Full Text

Preamble

The Application of Smart Meter and "Instrument Cloud" Integration Technology

ZHANG Chunhui[1], **ZHANG Zhen**[2]
(1. State Grid Shandong Electric Power Company, Jinan, Shandong 250001, China;

2. Huaneng Jinan Huangtai Power Generation Co., Ltd., Jinan, Shandong 250100, China)

Abstract: This paper introduces the development and application of a remote online detection system for smart meters utilizing high-precision computing on the "Instrument Cloud." First, it reviews the evolution of traditional smart meter remote online detection technologies and identifies their limitations and challenges. Then, it presents the motivation for this research, including the proposal of instrument virtualization technology in the "Instrument Cloud" environment, research on instrument virtualization under cloud computing, and the needs and challenges faced by State Grid. The paper focuses on the development project of a smart meter remote online detection system employing high-precision Instrument Cloud computing, covering the principles and applications of instrument virtualization in cloud environments, along with the system's advantages and market prospects. This development will help overcome the limitations of traditional systems, improve measurement accuracy and intelligent diagnostic precision, reduce system costs, and facilitate widespread adoption.

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1. Traditional Smart Meter Remote Online Detection System Development

The development trajectory of traditional smart meter remote online detection systems includes: - **2002:** Jilin Electric Power Research Institute published "Development of a Multi-channel Three-phase Energy Meter Remote Computer Detection System." - **2004-2014:** Subsequent publications or product announcements from Central China Grid Technical Center (2004), Xiamen Airlines (2005), Shanghai Electric Power Metering and Measurement Management Institute (2007), Yunnan Electric Power Test Research Institute (2007), Henan Star High-tech Company (2008), North China Electric Power Research Institute and North China Grid Company (2009), Taiyuan UTOPIC Company (2010), Zhengzhou Sanhui Electric Company (2010), and Zhengzhou Ruineng Company (2014).

These traditional systems shared common characteristics: each required a standard energy meter and computing system, complicating the secondary circuits of instrument transformers. Due to high investment costs, deployment was limited to select grid gateway metering points and a small number of 110kV and above high-voltage substations. Current remote online detection technology primarily compares measurement results between on-site standard meters and tested smart meters, but the calibration and maintenance of these standard metering devices has become a new challenge. Furthermore, the master stations of energy metering automation systems (or electricity information collection systems) have not fully utilized their potential for centralized data analysis and processing.

2. Origin of This Research

In February 2017, scholars from Shenzhen Power Supply Bureau and Tsinghua University published "Electronic Energy Meter Remote Online Detection System Based on 'Measurement Instrument Cloud,' " proposing a new approach: performing high-precision data calculation and processing in an "Instrument Cloud" environment to replace standard energy meters and computing systems. This approach significantly reduces secondary circuit modification workload and system costs, facilitating broader adoption. The paper also presented an implementation scheme for newly configured high-speed data acquisition terminals, though it only briefly introduced the "Instrument Cloud" concept without detailing the next-generation system design.

Earlier, in August 2014, Tsinghua University scholars published "Research on Instrument Virtualization in Cloud Computing Environment," proposing the physical architecture of instrument virtualization systems and generalized "Instrument Cloud" operational procedures, but without addressing smart meter remote online detection specifically. Recently, State Grid News reported on the launch of the "State Grid Cloud" platform and the migration of provincial grid business systems to cloud applications.

State Grid Requirements: Since 2010, State Grid has installed approximately 38 million three-phase smart meters. Beginning in 2018, these meters entered an 8-year periodic replacement cycle. Consequently, in early 2017, State Grid issued "Guidance on Metering Work in 2017" (State Grid Marketing [2017] No. 105), which first proposed "comprehensively promoting smart meter condition-based detection and replacement." The guidance emphasized: (1) fundamental metering work—comprehensive full-event data collection to improve online monitoring and intelligent diagnostic accuracy; and (2) condition detection—first completing supporting function deployment in MDS and marketing business systems, then following the principle of "master station evaluation and planning first, then on-site detection," to conduct condition detection for Class I, II, and III user metering devices.

Since State Grid' s metering departments have not widely adopted traditional remote online detection systems, three-phase smart meter condition detection relies solely on on-site inspection and partial assessment methods. Continuous 24-hour assessment of three-phase smart meter accuracy across wide load ranges presents a significant technical challenge. Therefore, research and development of a new-generation smart meter remote online detection system that meets State Grid' s requirements for comprehensive condition-based detection and replacement is both timely and necessary.

After synthesizing these developments and concretizing the next-generation system, the authors prepared "New Thinking for Meter Development: Application of Smart Meter and Instrument Cloud Integration Technology." This paper focuses on the development project of the Instrument Cloud-based high-precision computing remote online detection system, discusses extended application development projects for smart meter-Instrument Cloud integration technology, and evaluates market prospects for reference.

2. Development Project for Smart Meter Remote Online Detection System Using Instrument Cloud High-Precision Computing

2.1 Instrument Virtualization Technology in Cloud Computing Environment

This section primarily excerpts from "Research on Instrument Virtualization Technology in Cloud Computing Environment" :

"Instrument virtualization technology is the foundation for achieving instrument program control and remote measurement. Many instrument functions originally performed by hardware can now be accomplished through software algorithms, significantly reducing instrument development and usage costs."

Cloud computing's Infrastructure-as-a-Service (IaaS) model: "The basic concept of IaaS is to virtualize fundamental IT hardware resources—including CPUs, memory, storage devices, and network equipment—through a Virtual Machine Monitor (VMH), then allocate them on-demand to upper-layer Virtual Machines (VMs). From the user' s perspective, each VM instance is equivalent to a custom computer or server with networking capabilities."

"Currently, the most widely used technology in cloud computing is hardware-level virtualization, as it offers the highest efficiency. In hardware-level virtualization, VMs share the same instruction set as physical hardware, and the vast majority of VM instructions can execute directly on the hardware."

"A new instrument virtualization model simulates remote instruments as local hardware devices of the cloud platform, directly connecting them to the VMH. It merely informs the VMH that an instrument has been connected to the cloud, without providing any specific information or functions related to instrument operation."

IaaS-based Remote Measurement Architecture:
Instrument → (Bus Connection) → Instrument Provider → (Network Connection) → Instrument Virtualization: CPU/Memory/Hard Drive → Virtual Machine Monitor (VMH) → Virtual Machine (VM): One-to-one connection with instrument virtualization and its CPU/memory/hard drive, operating system, measurement program.

2.2 Design Outline of the Instrument Cloud-Based High-Precision Computing System

This section primarily references "Electronic Energy Meter Remote Online Detection System Based on Measurement Instrument Cloud" and "Research on

Instrument Virtualization in Cloud Computing Environment," combined with the authors' practical metering experience.

System Architecture Components:

1. **User (YH):** Equipped with tested energy meters and newly configured high-speed data acquisition terminals.
   The new data acquisition terminal samples on-site voltage and current data at 4,000 Hz. "The terminal consists of four parts: a high-precision data acquisition unit, meter communication module, 4G wireless communication module, and central control unit." The central control unit's most critical function is ensuring strict time consistency between sampled data uploaded to the Instrument Cloud and the energy metering pulses of the tested smart meter—this is essential for detection accuracy. The central control unit can use the Precision Time Protocol IEEE1588 to synchronize time between the data acquisition terminal and the tested smart meter.
   Terminal development: To reduce costs, load control terminals from existing energy metering automation systems (or electricity information collection systems) can be appropriately modified to acquire data. If on-site conditions are unsuitable, standalone products can be designed.

2. **Energy Metering Automation System Master Station (ZZ):** The central control system.

3. **Instrument Owner (IS):** Owner of local instruments (or local working computers).

4. **Instrument Agent (IA):** Deployed on the host computer of local instruments (or local working computers) or implemented through dedicated hardware. The IA's basic function is to push local instrument access information to the Instrument Cloud's Instrument Resource Management System (IRM) via the network, along with auxiliary information to help users (YH) or instrument owners (IS) identify local instruments.
   The IA remotely virtualizes connected local instruments as resource nodes, with their status information stored on the Instrument Cloud's Storage Controller (IM).

5. **Instrument Cloud Platform Components:**

   - **Instrument Resource Management System (IRM):** Processes access information pushed by Instrument Agents (IA)

   - **Cloud Controller (CC):** Provides user interfaces for querying and calling authorized instrument resources

   - **Storage Controller (IM):** Provides instrument resource registration and management functions in the cloud

- **Cluster Controller (CLC):** Contains Node Controllers (NC)
- **Node Controller (NC):** Contains VMs including application programs, operating systems, and instrument drivers

Communication Architecture:
- Instrument Resource Management System (IRM), Cloud Controller (CC), and Storage Controller (IM) connect via 4G wireless public network or power private network to: Instrument Agent (IA), User (YH), Instrument Owner (IS), and Energy Metering Automation System Master Station (ZZ)
- Cluster Controller (CLC) connects via shared private network to Node Controllers (NC)
- Node Controller (NC) establishes virtual connections with Instrument Agent (IA)

System Operation Requirements and Procedures:

Pre-operation Preparation:
The Energy Metering Automation System Master Station (ZZ) must provide the Instrument Agent (IA) with: parameters of tested smart meters, various calculation methods, result processing requirements, and measures to ensure detection correctness, based on on-site detection requirements. ZZ must also apply to the Cloud Controller (CC) for technical conditions to use authorized local instruments.

User (YH) Requirements:
After receiving the detection command from the master station (ZZ), the system must first synchronize metering time between the tested smart meter and the newly configured data acquisition terminal. Then, the terminal uploads sampled on-site voltage/current data and the tested meter' s energy metering output information via 4G wireless public network or power private network to the Instrument Agent (IA) requested by ZZ for data/information calculation and processing. Users must also send remote online detection start/stop times to ZZ.

Operational Procedure:
1. The system master station (ZZ) "can query and call authorized local instrument resources through the user interface provided by the Cloud Controller (CC). When ZZ needs to use a particular authorized instrument, it submits an application to CC."
2. "CC then sends a resource call command to the Storage Controller (IM), which pushes the instrument resource node' s access information through the Cluster Controller (CLC) to the node where ZZ' s requested VM resides. Finally, the Node Controller (NC) containing the VMH establishes a virtual connection with the local instrument and sends a hardware access notification to the user' s running VM, which displays a 'new hardware found' message and prompts for driver installation."
3. The master station (ZZ) sends all pre-operation requirements to the VM

of the confirmed local instrument node, which executes the detection program for the user' s tested smart meter according to ZZ' s requirements and returns results to ZZ.
4. After ZZ finishes using the local instrument, the resource can be reclaimed by IM. If it' s a shared resource, other users may apply for it. All instrument resource scheduling and management functions are implemented in IM.

2.3 Instrument Cloud Platform Construction

State Grid Cloud Overview:
On April 27, 2017, "State Grid Cloud" was officially released, with its integrated platform going online simultaneously. State Grid Cloud comprises Enterprise Management Cloud, Public Service Cloud, and Production Control Cloud. The Public Service Cloud covers external network areas, supporting power marketing, customer service, e-commerce, and other businesses. It is deployed across three centralized data centers and 27 provincial company data centers. In 2016, pilot construction of Enterprise Management Cloud and Public Service Cloud was launched at headquarters and units including Beijing, Jibei, Tianjin, Shanghai, Zhejiang, Jiangsu, Fujian, Heilongjiang, and Shaanxi Electric Power, deploying cloud platform components and migrating 12 types of applications including synchronous line loss analysis to the cloud.

Reference Case: Jibei Electric Power' s marketing audit system migration to State Grid Cloud
"The State Grid Cloud operating system can automatically match and select the most suitable resources according to the marketing audit system' s requirements. Jibei Electric Power deployed the marketing audit system through the cloud OS 'application management' module with one-click deployment, completing deployment of 5 application instances in seconds and distributing them across 3 physical hosts. The cloud OS also supports resource state transformation, converting physical machines into virtual machines."

Recommended Technical Route for Instrument Cloud Platform:
Given State Grid Cloud' s significant advantages—powerful parallel, distributed, and cross-domain computing capabilities, automatic resource matching based on business system requirements, and support for physical-to-virtual machine conversion—combined with the ease of migrating electricity information collection systems and users to the cloud, the authors recommend prioritizing State Grid Cloud as the foundation for Instrument Cloud platform construction and next-generation system deployment. Implementation steps include:

1. Develop standardized operation and application software for the Instrument Cloud-based high-precision computing smart meter remote online detection system that meets State Grid Public Service Cloud requirements.

2. Through agreement with interested provincial grid data centers, develop

corresponding modules in the State Grid Public Service Cloud operating system using provincial grid cloud components to deploy the new system.

3. Pilot the next-generation system in cooperation with interested provincial grid data centers before broader promotion.

Note: The Instrument Cloud platform construction approach using cooperative development with cloud service providers requires further verification and discussion.

2.4 Metrological Traceability Discussion

Per JJG 1001 regulations, calibration is defined as "a set of operations performed under specified conditions to determine the indication error of a measuring instrument."

- The three-phase active power values calculated by Instrument Cloud high-precision computing can be field-tested using high-accuracy three-phase standard energy meters in the user' s on-site environment. For a 0.2S class tested smart meter, the metering error of three-phase active power calculated by the Instrument Cloud should not exceed 0.05%. On-site calibration can use three-phase standard meters with 0.01 or 0.02 class accuracy, achieving actual metering errors not exceeding 0.012%.
- Currently, no corresponding metrological calibration specifications exist for field calibration of three-phase active power calculated by Instrument Cloud. As an initial step, the authors recommend establishing a local [measuring instrument] verification regulation: develop a metrological calibration specification for three-phase active power data calculated by Instrument Cloud high-precision computing, led by provincial metrology institutes through consultation, then submit for approval and publication by provincial metrology administrative departments as a statutory technical document for verification.

Further discussion on metrological traceability for the next-generation system will depend on project progress.

2.5 Application Prospects

- **High-voltage substations:** State Grid has approximately 10,000 substations at 110kV and above. Over the past 5 years, about 400 substations (4%) have adopted traditional remote online detection systems, with total investment of ¥120 million (¥300,000 per substation). The Instrument Cloud-based system, requiring no standard meters or computing systems and minimal secondary circuit modifications, offers significantly reduced investment for widespread deployment. If adopted at 60% of 110kV+ substations at ¥100,000 per substation, total investment would be ¥600 million.

- **Large industrial users:** The new system can be extended to large industrial users with monthly consumption $ $1 million kWh or transformer capacity $ $2,000kVA, representing about 10% of State Grid' s large industrial users (50,000 households). At ¥10,000 per household, investment would total ¥500 million.

3. Extended Application Development Projects for Smart Meter-Instrument Cloud Integration

Leveraging State Grid Cloud as the foundation and supported by advanced application software at electricity information collection system master stations, smart meter-Instrument Cloud integration technology can develop a series of new grid metering, control, and compensation products with broad market prospects.

3.1 Three-Phase Smart Meters with Condition Monitoring Functionality

This involves upgrading existing three-phase smart meters to output high-speed on-site voltage/current sampling data via 4G wireless public network or power private network to the Instrument Cloud. Supported by the electricity information collection system master station, the Instrument Cloud calculates three-phase active power with high precision, enabling 24-hour condition monitoring of operating three-phase smart meters without requiring periodic on-site inspections.

Market potential: State Grid has 480,000 large industrial users. Deploying new 0.2S class meters at ¥3,000 each requires ¥1.4 billion investment. Among general industrial users, the top 10% by capacity (1.28 million households) could use new 0.5S class meters at ¥2,000 each, requiring ¥2.5 billion. Total investment reaches ¥3.9 billion.

3.2 High-End Three-Phase Smart Meters for Harmonic Source Users

These meters feature non-sinusoidal full power (active, reactive, distortion, and apparent power) calculation capabilities. The meter outputs high-speed voltage/current data, with non-sinusoidal full power calculation software provided by the electricity information collection system master station. The Instrument Cloud performs high-precision calculations and returns results to the meter for storage and processing.

Field tests by a provincial power metering center on 60 large industrial harmonic source users showed voltage harmonic content generally within 5%, while 60% had severely excessive current harmonics.

Primary applications: Testing low power factor caused by non-sinusoidal distortion power, assessing energy consumption growth rates due to non-sinusoidal waves, and providing field metering data for pricing authorities to develop economic sanctions for grid harmonic pollution control.

Market potential: Deploying these high-end meters at 20% of State Grid' s large industrial users (100,000 households) at ¥4,000 each requires ¥400 million investment.

3.3 Power Quality Monitoring and Intelligent Compensation

State Grid's high-voltage substations, public transformer stations (~4 million stations), and dedicated transformer users (~1.5 million households) require increasing deployment of power quality monitoring, intelligent control/compensation equipment, reactive power balance monitoring/intelligent compensation devices, and three-phase load balance monitoring/compensation measures as smart distribution networks advance. These can be implemented by upgrading existing on-site dedicated/integrated terminals or configuring new data acquisition terminals to output high-speed voltage/current sampling data. The Instrument Cloud performs high-precision calculations under support from relevant master station software systems and returns results to corresponding terminals to achieve these distribution and consumption business functions.

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Author Biographies

ZHANG Chunhui, male (1938-), engaged in electric energy metering technology research.

Corresponding Author: ZHANG Zhen, male (1977-), engaged in electric energy metering technology research. Email: 721047546@qq.com

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