Preliminary Study on Smart Electric Energy Metering System Technology

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Abstract

This paper focuses on the intelligentization of online electrical energy metering systems, exploring their system architecture design and intelligent technology requirements. Addressing existing problems in current systems, such as low-level smart meter design and insufficient communication capabilities, it proposes the necessity of applying multi-faceted intelligent technologies and advanced metering communication technologies for renovation and upgrading. Simultaneously, by referencing intelligent control theory, smart meter gateways, intelligent solutions for high-voltage equipment, etc., it provides theoretical and practical support for the intelligent transformation of the system.

Full Text

Preliminary Study of Smart Electrical Energy Metering System Technology

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Abstract: This paper focuses on the intelligentization of online electrical energy metering systems, exploring their system architecture design and intelligent technology requirements. In response to existing problems such as low-level smart meter design and insufficient communication capabilities, the necessity of applying various intelligent technologies and advanced metering communication technologies for transformation and upgrading is proposed. Theories such as intelligent control theory, smart meter gateways, and intelligent solutions for high-voltage equipment are introduced to provide theoretical and practical support for the intelligent transformation of the system.

Keywords: Intelligent Metering; Power System

The State Grid Corporation issued the "Opinions on Comprehensively Promoting the Construction of Smart Metering Systems," indicating that the construction of smart metering systems may become the future development direction of the metering industry, requiring research and cultivation of new markets for smart metering products.

Given that smart metering systems represent an innovation in power engineering with massive research topics—including online electrical energy metering, remote meter reading/acquisition communication, system power aggregation, automated verification, field calibration, metrological traceability, metering instrument distribution, and inventory management—they can also be extended to reactive power compensation metering and control, grid line loss metering and energy conservation. It can be said that they involve comprehensive, vertical, and real-time control of the entire power metering domain, multiple categories of intelligent control theory, and require solving many technical challenges with greater difficulty.

After careful consideration, this paper focuses on the intelligentization of online electrical energy metering systems and preliminarily explores their system architecture design and intelligent technology requirements.

1. Reasons for Developing Intelligent Applications for Electrical Energy Metering Systems

Electrical energy metering devices in power grids provide measurement assurance for power trade settlement and assessment of grid economic and technical indicators, belonging to the category of national legal metrology.

The electrical energy metering system is the integrated name for the power user electricity information collection system and the grid gateway and power supply metering system, managed by grid marketing and dispatching departments respectively.

Composition of the metering system: It is expected that by 2016, provincial-level grids will achieve basic full coverage of electricity information collection systems, with the State Grid's total collection coverage rate reaching 95.5%, and 377.58 million smart meters installed . Among them, high-voltage three-phase metering devices include approximately 3 million sets for dedicated transformer users, 1.8 million sets for public transformer districts, 52,000 sets for grid gateways, and power supply metering (to be counted). Low-voltage three-phase metering devices are estimated at 31 million sets. Currently, the system's basic functions include: periodic remote meter reading and billing/settlement for users or power generation enterprises, remote prepayment, providing metering data for user load management and business expansion, and supporting multi-professional collection needs of the grid, including power quality assessment, fault alarm location, and grid line loss statistics.

Here, why does this paper propose the development of intelligent applications for electrical energy metering systems? Recently, the State Grid provincial metering center's "Four Lines and One Warehouse" comprehensive, vertical, and real-time control key technology research and application project passed technical appraisal, marking new achievements in the application of intelligent technologies in State Grid laboratories. However, research on the intelligentization of existing online metering systems remains a weak link, with only limited projects such as intelligent fault diagnosis technology for metering devices being developed, which is ill-adapted to the development of smart grids/energy internet. The main problems are:

1) Low-level intelligent design of smart meters, unable to meet two-way interaction, distributed power access, demand response, and other intelligent applications. The metering function design of single-phase smart meters is incomplete, with low accuracy, and cannot adapt to multi-professional collection needs of the grid.
2) The electricity information collection system still uses one-way, low-speed communication, with automatic meter reading success rates failing to meet the practical requirement of 100%.
3) In supporting multi-professional grid collection, smart meters have incomplete metering functions and have not adopted optimized collection function design.
4) Electrical energy metering devices adopt a combined design without implementing comprehensive error assessment, and traditional transformers are prone to saturation under overload/overvoltage conditions.
5) Particularly, the communication network is not designed for two-way, high-speed communication, making it difficult to implement intelligent functions for grid-user interaction.
6) The system functions of existing electrical energy metering systems have not been further developed, limiting the system's functional expansion capabilities.

In light of these problems, drawing on international and domestic experience with smart grids and smart metering, it is necessary to apply various intelligent technologies and advanced metering communication technologies to transform and upgrade online electrical energy metering systems.

2. Research and Application of Specialized Intelligent Control Technologies

The transformation and upgrading of electrical energy metering system intelligence must first study existing intelligent control theories and intelligent control processes for smart grids/smart metering as references.

1) Concept of Intelligent Control

From Beijing University of Posts and Telecommunications' "Intelligent Information Technology": Intelligent control is a type of automatic control that can independently drive intelligent machines to achieve their goals without human intervention. The key to intelligent control lies in the high-level control, whose task is to organize the actual environment or process, i.e., decision-making and planning.

2) Intelligent Control Theory: Optimal Control

In 2005, Tsinghua University proposed "Optimal Control: Power Hybrid Control Theory and Advanced Dispatching Automation Construction." Power hybrid control theory can be described in set theory language: from grid-measured operation data to event sets, then transformed into control commands and operation instructions, completed through calculations of logical functions and composite logical functions. The entire power system's state can be changed through time-discrete operation instructions. The result of operation instruction actions makes the event set become an empty set, indicating that the power system is operating in a satisfactory state at this time, achieving the goal of multi-index self-optimization operation.

3) Intelligent Core of Smart Meter Measurement Systems: Smart Meter Gateway

In 2013, the German Federal Office for Information Security (BSI), commissioned by the German Federal Ministry for Economic Affairs and Energy, formulated a new technical specification for smart meter measurement systems, proposing a smart measurement system centered on the smart meter gateway, based on advanced two-way communication networks, connecting measurement instrument networks, wide-area power markets, and demand sides to achieve their interaction, referred to as IMsys.

4) Intelligent Solution for High-Voltage Equipment: Intelligent Control Process Design

From China Electric Power Research Institute's "Intelligent Solutions and Technical Characteristics for High-Voltage Equipment" and "Design of Smart Power Transformer Information Flow Solutions": The intelligent control process for high-voltage equipment involves sensor output signals undergoing preliminary processing and data processing through IEDs (Intelligent Electronic Devices) to output raw data and formatted information. Intelligent components perform further professional analysis on raw data or formatted information to generate intelligent information, completing basic functions such as measurement, control, and monitoring. Metering, protection, waveform recording, and power quality monitoring can also serve as extended functions. The control module is also part of the basic functions of intelligent components, with control instructions originating from grid dispatching systems or control strategies formed based on the equipment's own measurement and monitoring information. Finally, through the station control layer network, control instructions are issued by the grid dispatching system or intelligent components to achieve optimized operation of the grid or high-voltage equipment.

5) Main Features of New-Generation Smart Substations: Integrated Equipment and Integrated Business Systems

The new-generation smart substation demonstration project features integrated intelligent equipment and integrated business systems, achieving a transformation from separate professional design to overall integrated design, and from primary equipment intelligence to intelligent primary equipment. It represents the integrated application of advanced and applicable technologies, including: integrated primary equipment, such as using integrated intelligent circuit breakers that combine electronic high-voltage transformers, disconnectors, and circuit breakers; and integrated secondary equipment, such as the Liaoning 220kV Hejia Smart Substation, the world's first smart substation to use XJ Centralized Protection, meaning traditional primary protection systems required one device for each of the three functions: measurement and control, metering, and protection. Now, equipment integration and functional softwareization remove the binding between functions and devices.

6) Key Technologies for Smart Electricity Utilization: Demand Response and Energy Management

From China Electric Power Research Institute's "Discussion on Technical Architecture for Flexible Interactive Smart Electricity Utilization":

- **Demand Response (DR):** DR refers to encouraging power users to actively change their consumption behavior and optimize electricity usage through certain price signals or incentive mechanisms, reducing or shifting electricity loads during certain periods to optimize supply-demand relationships while users receive certain compensation. The implementation of DR requires support from advanced measurement, marketing, information communication, and control technologies, as well as macro policies such as electricity pricing policies, incentive mechanisms, and energy policies. DR can be said to be a complex system-level problem.
- **Energy Management:** Power user energy management mainly relies on smart devices such as (advanced measurement terminals), smart sockets, and various sensors, as well as interconnected networks, to achieve real-time collection, transmission, and analysis management of user internal energy consumption, environment, equipment operation status, and new energy information, providing auxiliary means for energy efficiency evaluation and demand-side management.

3. Architecture Design of Smart Electrical Energy Metering Systems

This section addresses the transformation and upgrading of electrical energy metering systems according to smart grid/energy internet development requirements, applying intelligent control technologies and advanced metering communication technologies.

3.1 Description of Smart Electrical Energy Metering Systems

The smart electrical energy metering system is a system based on integrated metering business design and two-way high-speed communication networks, using advanced metering communication technology, information sharing, intelligent decision response, interaction, and gateways as primary means, with capabilities for metering system performance optimization and efficient utilization and operation of user-side energy.

3.2 Main Functions of Smart Electrical Energy Metering Systems

Main functions include original system functions and new expanded system functions.

First, significant improvement of original basic functions: remote meter reading with periodic remote meter reading and billing/settlement for users or power generation enterprises, achieving 100% automatic meter reading success rate; remote prepayment with a collection cycle of 0.5h, ensuring "close switch" instructions are delivered to the meter within 0.5h after users pay overdue fees to restore power after operating the load switch; and continued expansion of integrated collection applications for four meters: electricity, water, gas, and heat.

Second, optimization of metering system performance: comprehensive error calibration of electrical energy metering devices including smart meters, voltage and current transformers, and voltage transformer secondary circuits, performed on the high-voltage side to achieve a comprehensive error of $±$0.2%, estimated to be $±$0.5% lower than original comprehensive error calculation results; linear metering using electronic voltage/current transformer metering, greatly changing the non-linear state of traditional transformers under overcurrent/overvoltage conditions and improving the accuracy of electrical energy metering and power quality measurement; integrated design of high-voltage/low-voltage electronic transformers and smart meters to reduce comprehensive errors and prevent electricity theft; self-compensation function for lost data where smart meters themselves or the system master station perform self-compensation when smart meters lose electricity data due to interference or three-phase metering devices fail; harmonic energy consumption evaluation for three-phase users and distribution networks; and intelligent fault diagnosis where the system master station performs remote intelligent fault diagnosis and alarms for online metering devices.

Third, user electricity load management and control using intelligent terminals to achieve real-time decision-making or delayed correct control functions.

Fourth, optimization and expansion of multi-professional collection applications for the grid, including grid power quality monitoring, assessment, and alarm with intelligent control functions added as needed; three-phase active/reactive power balance monitoring, assessment, and alarm with intelligent control functions added as needed; line loss calculation and alarm; and intelligent fault diagnosis and location for distribution networks.

Fifth, deepening of big data applications for electrical energy metering systems and development of new data mining.

Sixth, continuous improvement of grid-user two-way interaction functions to achieve grid and social energy saving and emission reduction goals: continued development of grid-user electricity information and business interaction services; gradual development of user demand response with the introduction of new electricity pricing policies or incentive mechanisms, including demand-side management and distributed power grid connection and control; expansion of user energy management and interaction services allowing large internal power equipment and air conditioning systems to participate in grid peak shaving and reactive power balance in real time; and adaptation to user needs for data, voice, video, and other Internet services.

3.3 Intelligent Technology Application Development Projects

First, construction of two-way, high-speed communication networks: 2016 State Grid metering key work requirements include research on the architecture of a new-generation electricity information collection system. The authors recommend unified specifications requiring 100% automatic meter reading success rate during the collection cycle and total system collection time. Specific collection cycles include: 24h for monthly meter reading and billing and monthly grid line loss calculation; 3h for some provincial grids to calculate daily grid line loss; 0.5h for user remote prepayment; and 15min for low-voltage grid fault early warning, alarm, and self-healing, user demand response, and online grid power quality monitoring and alarm. Total collection time for all users in provincial grids should be 10 million users per hour.

Key research areas include: broadband power line carrier communication application technology to solve local communication technology bottlenecks; broadband carrier concentrator design scheme considering both achieving 100% automatic meter reading success rate within 15min and significantly increasing the number of automatic meter readings; research on factors affecting expanded application of broadband power line carrier communication, including quantifying impacts on underground cables and public transformer district capacitor reactive power compensation devices, measurement and suppression methods for broadband carrier communication interference, and development of testing and suppression measures for interference emitted by broadband carrier communication itself, followed by organizing formulation of broadband power line carrier communication channel technical specifications; gradual phasing out of existing narrowband carrier communication modules and replacement with broadband carrier communication modules; use of dual-mode communication as a supplement to broadband carrier communication; and research on 4G remote wireless public network communication application technology and testing to solve user-side remote communication technology bottlenecks.

Regarding the system master station: within the grid, the electricity information collection system master station is already networked with the grid dispatching system and power marketing system, achieving unified calculation and assessment of grid "quantity, price, fee, loss" indicators, and can also develop grid-user interaction functions. The system master station's functions must add smart electrical energy metering system functions beyond the original master station functions of the electricity information collection system.

Additional research areas include: adopting two-way communication data transmission protocols and advanced password authentication from smart meters through collectors and concentrators to the system master station; dedicated transformer users and public transformer districts' intelligent terminals adopting two-way high-speed remote communication modules, expanded memory capacity, and advanced application programs to achieve autonomous decision response, remote software upgrades, provide exchange data information in multiple formats, and adapt to the expansion of more functions; and proposing electricity information collection technical solutions based on the Internet, telecommunications networks, and broadcasting television networks to achieve integration of data, voice, video, and other services, saving investment and operating costs and providing users with more convenient and modern lifestyles.

Second, optimization design of smart electrical energy metering system performance: For smart meters, new metering function items include three-phase smart meters with four-quadrant non-sinusoidal full power calculation functions and single-phase smart meters with sinusoidal full power calculation functions for implementing self-compensation of lost data, along with output information needed for the system master station to perform self-compensation of lost data caused by metering device faults. Smart meters should have expanded calculation and memory capacity with expandable display items, two-way high-speed communication modules, large memory capacity, advanced application programs to achieve autonomous decision response, remote software upgrades, and provide exchange data information in multiple formats to adapt to the expansion of more functional requirements. Note that if accessing multiple interactive functions from different devices/meters, gateway designs or products using multiple communication methods need to be adopted or additionally accessed.

Accuracy classes should be: grid gateway main meter metering uses 0.1S class three-phase smart meters; single-phase smart meter accuracy classes are upgraded to 0.2, 0.5, 1, and 2 classes for residential users with different monthly electricity consumption. Electronic voltage transformer accuracy classes are 0.1, 0.2, and 0.5 classes; electronic current transformer accuracy classes are 0.1S, 0.2S, and 0.5S classes. Electronic transformer capacity must match the power supply capacity requirements of smart meters, intelligent terminals, and power quality monitoring terminals.

Integrated design of electronic transformers and smart meters, as previously described, should control comprehensive error within $\pm$0.2% and provide interfaces for outputting information to intelligent terminals and power quality monitoring terminals. For high-voltage electrical energy metrological traceability, the China National Institute of Metrology has established 10kV, 1000A, 0.02 class three-phase high-voltage electrical energy measurement standard devices, which have been assessed and certified.

Third, system master station functions: Beyond the original master station functions of the electricity information collection system, the system master station must add smart electrical energy metering system functions including: compensation for data loss caused by faults in high-voltage three-phase metering devices of dedicated transformer users and public transformer districts using the system master station's four-quadrant non-sinusoidal full power calculation function; harmonic energy consumption evaluation for three-phase users and distribution networks including difference between fundamental and harmonic active energy metering, difference between sinusoidal and non-sinusoidal power factor calculations, and distribution testing of harmonic energy consumption in distribution transformers, power lines, and users; deepening of system big data applications and development of new data mining including full power calculations for metering points with incomplete smart meter metering functions, calculation of simultaneous coefficient of electricity load in public transformer districts to provide basis for distribution transformer capacity selection, online intelligent fault diagnosis/intelligent anti-electricity theft behavior for high-voltage three-phase metering devices, and monitoring and status assessment of operating energy meter and transformer metering performance; and multi-professional collection applications and expansion for the grid including online monitoring, assessment, and alarm of grid power quality with intelligent control functions, monitoring and assessment of three-phase active/reactive power balance at grid transmission nodes, grid line loss calculation based on full power, intelligent fault diagnosis and location for distribution networks, 10kV high-voltage integrated monitoring and control terminals, and networking with online intelligent monitoring systems for distribution transformers with integrated design of distribution transformers and measurement transformers.

Fourth, implementation of grid-user interaction functions: The smart meter gateway serves as a key device for grid-user interaction functions using data transmission protocols with multiple communication methods. To simplify communication networks and reduce duplicate investment, the authors do not recommend using intelligent interactive terminals to achieve two-way interaction. Technical development areas include: communication modules for user power equipment electricity information collection; user electricity information summary terminals; user internal communication networks; statistical electricity meters + energy saving monitoring systems + low-voltage maximum load monitoring and control systems; and two-way interactive communication networks and connection schemes between users and power supply departments.

International and domestic experience in smart grids and smart metering can provide beneficial references for the intelligentization of electrical energy metering systems. For example, the application of intelligent control theory in electrical energy metering systems and the application of some advanced intelligent technologies and products can accelerate the intelligentization process of electrical energy metering systems.

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