

Research and Development of Three-Phase Wide-band Smart Meters

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Abstract

Since 2021, the electricity meter industry has faced multiple challenges including slow market growth, reduced technical demand, talent loss, and insufficient revenue. The current downturn in the electricity meter industry is particularly evident in insufficient demand for new product technologies, loss of development talent, and operating revenues that cannot meet enterprise development needs. To address these issues, this article proposes the importance of promoting the development and application of new domestic smart meter measurement technologies, specifically noting the need to adapt to electrical energy measurement and monitoring demands arising from new energy grid integration and complex grid loads. To this end, the article proposes a new project for developing and applying three-phase wideband smart meters that have undergone actual power grid waveform testing and validation, aiming to drive the development of new technologies and markets in the electricity meter industry. Additionally, the article mentions that the 0.005-class three-phase wideband energy standard meter has been included in the National Key R&D Program, providing metrological traceability assurance for the development and application of three-phase wideband energy meters. Moreover, the article analyzes the impact of new energy grid integration on traditional power grid operating states, including wideband oscillations, overvoltage, and wideband harmonic currents, and points out the current lack of online measurement and monitoring smart meters for these abnormal conditions. Therefore, developing three-phase wideband energy meters is of significant importance for solving these problems.

Full Text

Research on the Development of Three-Phase Broadband Smart Meters

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Abstract: Since 2021, the meter industry has faced multiple challenges including sluggish market growth, reduced demand for new technologies, talent drain, and insufficient revenue. In response, this paper emphasizes the importance of advancing the development and application of new domestic smart metering technologies, particularly to address the demands of electric energy measurement and monitoring arising from renewable energy grid integration and complex grid loads. To this end, this paper proposes a new project for developing and applying three-phase broadband smart meters that have undergone testing and validation against actual grid waveforms, aiming to drive technological and market development in the meter industry. The inclusion of 0.005-class three-phase broadband energy standard meters in the national key R&D program provides metrological traceability assurance for this development. The paper also analyzes how renewable energy integration impacts traditional grid operation, causing broadband oscillations, overvoltage, and broadband harmonic currents, while noting the current lack of online metering and monitoring smart meters for these anomalies. Therefore, developing three-phase broadband energy meters is of great significance.

Keywords: three-phase broadband smart meters; broadband energy trade settlement pricing; shock loads

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1. Introduction: Industry Challenges and New Opportunities

Since 2021, the meter industry has experienced a downturn characterized by minimal market growth, lack of demand for new product technologies, loss of development talent, and annual revenues insufficient for enterprise development. Following the State Grid smart meter (2020 edition), the industry urgently needs to promote the development and application of new domestic smart metering technologies to expand market opportunities.

Currently, under the national policy of sinusoidal wave energy pricing, the path forward for new meter development must adapt to the construction of new power systems by State Grid and China Southern Power Grid. The integration of renewable energy, combined with harmonic-generating loads, creates bidirectional, time-varying complex waveform load currents that demand new metering and monitoring capabilities. After reviewing smart meter dynamic metering technology trends from the past two years, this paper proposes a new project for developing and applying three-phase broadband smart meters validated against actual grid waveforms, aiming to advance both technology and market growth in the meter industry.

The national metrology authority has included the 0.005-class three-phase broadband energy standard meter in the “Development of Internationally Equivalent High-Precision Metrology Instruments and Standards (Phase I)” project, explicitly to ensure fair and equitable energy trade settlement. This indicates consensus among national authorities on future broadband energy pricing policies and is significant for promoting three-phase broadband energy meter development. First, it provides metrological traceability for three-phase broadband energy meters. Second, it offers technical support for online metering and monitoring of broadband oscillations, overvoltage, and harmonic pollution in high-voltage grids caused by renewable energy integration. It also provides credible metering data for State Grid and China Southern Power Grid to propose new broadband energy trade settlement pricing policies to the government.

2. National R&D Project: Metrological Traceability Assurance

According to online information, the 0.005-class three-phase broadband energy standard meter was first included in the 2022 national key R&D plan “Development of Internationally Equivalent High-Precision Metrology Instruments and Standards (Phase I),” providing metrological traceability assurance for three-phase broadband energy meter development and application.

This project, organized by the national metrology authority and implemented by the Ministry of Science and Technology, has the following specifications for the 0.005-class three-phase broadband energy standard meter: frequency range 45 Hz-1 kHz, voltage 30-500 V, current 10 mA-120 A, and power/energy standard uncertainty of $1.0 \cdot 10^{-4}$ to $2.5 \cdot 10^{-5}$. The project execution period is 3-4 years, led by Hunan Institute of Metrology and Testing with participation from 10 organizations including China National Institute of Metrology, China Electric Power Research Institute (EPRI), Beijing Oriental Institute of Metrology and Testing, and Tianheng Measurement & Control.

Currently, the nation has not yet introduced new broadband energy trade settlement pricing policies. However, during new power system construction, frequent metering issues arise from renewable energy integration combined with harmonic-generating loads. Online metering and monitoring are needed at high-voltage grids, medium/low voltage distribution transformer areas (approximately 4 million areas), and harmonic-generating users (about 3 million high-voltage three-phase users and 7 million low-voltage three-phase users) to accumulate grid operation state data and issue 超标 alarms.

3. Impact of Renewable Energy Integration on Grid Operation

Renewable energy integration has disrupted traditional grid operation states, with different voltage levels exhibiting distinct operational anomalies. Currently, there is a lack of smart meters capable of online metering and monitoring for these anomalies.

High-Voltage Grid Issues:

In April 2021, China EPRI's "Analysis and Control of Large-Scale Renewable Energy Base Grid Integration Characteristics" reported that from 2015-2017, the Xinjiang Hami wind power base frequently experienced sub/super-synchronous oscillations with frequency ranges of 3 Hz-100 Hz-1000 Hz. These broadband oscillations are caused by grid integration of high-voltage renewable energy through power electronic devices involving speed control, phase-locked loops, current loops, and LC filters in dispatch control systems. Additionally, N-1 short-circuit faults in ultra-high voltage projects like the Qingyu DC line caused severe overvoltage at sending-end photovoltaics, reaching nearly 1.5 times rated voltage for durations ≤ 15 ms.

Medium/Low-Voltage Grid Issues:

Distributed renewable energy loads in medium/low-voltage grids exhibit bidirectional, time-varying, non-stationary characteristics, compounded by harmonic pollution from harmonic-generating users. According to China EPRI's October 2022 report "Key Technologies for Dynamic Energy Metering in New Power Systems" (hereinafter "Document A"), medium-voltage public node voltage spectra show high content near 2.5 kHz and 3 kHz, while low-voltage grid nodes show high content near 2.5 kHz. On the supply side, photovoltaic inverters exhibit harmonics near switching frequencies of 16 kHz and 18 kHz. On the consumption side, actual grid waveforms show time-varying, complex characteristics with multiple superimposed features: severe waveform distortion (31% THD for LED lights, 70% for inverter air conditioners, 39% for EV DC chargers), high crest factors (4.71 for air purifiers, 3.37 for laptops), and broad frequency spectrum distribution (>21st harmonic for air purifiers).

4. Technical Performance Requirements for Three-Phase Broadband Energy Meters

In 2002, Wasion first developed the 0.2S-class electronic DTSD341-9A/B/C series three-phase multifunction meters with fundamental and harmonic energy metering analysis functions, providing experience for designing three-phase broadband energy meter performance.

Design Features of DTSD341-9A/B/C Series:

The series employs two algorithms for active power: integration and Fourier transform, with high sampling rates (256 points/cycle) and fundamental/harmonic active energy metering capabilities. The series includes three types:

- **9A Type:** Uses digital multiplier for full-wave active metering: $P =$ accumulation of $(P_1 + P_h)$, where P_h is the h-th harmonic active power ($h=2\cdots n$). Accuracy: 0.2S class for active, 2 class for reactive. Features harmonic analysis, providing harmonic active energy and flow direction. Suitable for high-accuracy grid gateway metering.
- **9B Type:** Uses fundamental active metering based on sinusoidal waves: $P = P_1$. Accuracy: 0.5S class for active, 2 class for reactive. Suitable for

linear load metering.

- **9C Type:** Offers two metering modes: (1) Full-wave active metering using digital multiplier (Type A), and (2) Harmonic active metering based on Fourier transform: $P = \text{sum of } (P_1 + |P_h|)$, where $|P_h|$ is the absolute value of h-th harmonic active power. Accuracy: 0.5S class for active, 2 class for reactive. Features harmonic analysis, alarm for grid harmonic distortion, and load recording of harmonic amplitudes and phase angles for the first 10 harmonics. Suitable for harmonic-generating users like chemical plants, steel rolling mills, and electrified railways.

Enhanced Requirements for Three-Phase Broadband Energy Meters:

Drawing from this experience, three-phase broadband energy meters require higher performance specifications to accommodate bidirectional, time-varying complex waveforms from distributed/centralized renewable energy integration combined with harmonic-generating loads. Key requirements include:

- Wide dynamic current range with precise power mathematical expressions
- High-speed sampling (256 points/cycle)
- Improved Fourier transform accuracy
- High-order integration or other high-precision algorithms
- Fundamental active accuracy to Class D (0.2% error from I_{tr} to I_{max})
- Harmonic active metering at Class 1 or 2
- Bidirectional load current metering capability
- Harmonic active analysis providing fundamental/harmonic active energy and flow direction
- Alarm for harmonic distortion with recording of 1-21st harmonic voltage/current amplitudes and phase angles
- Power quality monitoring including broadband oscillation, overvoltage, voltage unbalance, harmonic distortion rate, and DC injection
- High-speed sampling and communication interfaces for actual grid waveforms

5. Challenges in Modeling and Power Algorithms for Bidirectional Time-Varying Complex Waveforms

China EPRI's Dynamic Energy Metering Evaluation System:

China EPRI has pioneered a dynamic energy metering evaluation system based on actual grid waveforms. The development path includes: lossless recording and analysis of actual grid waveforms, value traceability and transfer, wide dynamic range, and establishing a simulation test system based on actual waveforms.

The test system configuration includes: (1) Pacific Power's UPC-32E arbitrary waveform generator with AMX voltage amplifier and transconductance amplifier (capable of 99-segment waveform editing for dynamic test waveforms), and (2) Yokogawa DL850 ultra-high-speed recorder (100 MS/s, 16-bit sampling) for simulating various load impacts on meter error and data acquisition functions.

Key analytical methods include: (1) one-dimensional feature analysis using statistical measures (best, mean, median, variance, skewness, crest factor, harmonic content), and (2) time-frequency joint domain analysis (JTFA) using Cohen' s distribution model to establish time-frequency joint functions as data sources for subsequent dynamic waveform generation. Additionally, a homologous analog-digital technology platform outputs arbitrary analog and digital signals for high-accuracy dynamic waveform reproduction.

Experience from Impact Load Energy Meter Design:

A January 20, 2021 study on “Key Technologies for New Energy Meters for Impact Loads” provides valuable insights. The impact load model uses dynamic OOK (On-Off-Keying) signals (M1=1, M2=2) to establish a shock load current model, where M1 and M2 represent the number of 50 Hz sinusoidal current cycles during on/off periods. Testing shows conventional meters exhibit -12.86% dynamic metering error versus -0.05% steady-state error, proving periodic pulse transmission unsuitable for impact loads.

The impact load meter employs: 24-bit high-precision A/D (160 samples/cycle) for wide current input range without gain switching, dedicated phase compensation filters for rapid instantaneous power calculation, and zero-flux current transformers with 10 kHz bandwidth and 10 mA-25 A dynamic range. The energy calculation uses direct accumulation of instantaneous power pulses, triggering pulses when accumulated value exceeds threshold, with IIR low-pass filtering to remove 2ω components.

Development Implications:

These experiences suggest three-phase broadband energy meter development should: adopt 24-bit A/D sampling, use zero-flux CTs for wide dynamic range, and consider the OOK modeling method for dynamic load current waveforms (though laboratory-based rather than from actual grids). Given the nationwide distribution of renewable energy, developing these meters requires extensive actual grid waveform collection and modeling. It is recommended that State Grid plan and deploy provincial-level dynamic energy metering test systems based on actual grid waveforms, while industry authorities lead efforts to localize or independently develop high-end test instruments.

6. General Technical Specifications for Three-Phase Broadband Energy Meters

Since State Grid' s “Smart Meter (2020 Edition)” standard applies to sinusoidal wave energy meters, the general technical specifications for three-phase broadband energy meters should build upon this foundation, referencing IEEE 1459-2010 power model calculation methods and supplementing requirements based on dynamic load metering characteristics:

1. **Scope:** Applicable for 50 Hz and $h=2\sim n$ harmonics (including interharmonics) for measuring fundamental active energy, specified $h=2\sim n$ harmonic forward/reverse active energy sums, fundamental apparent energy,

and full-wave (UI) apparent energy.

2. **Terms and Definitions:** Supplement definitions for fundamental apparent energy, full-wave apparent energy, fundamental power factor, and full-wave power factor.
3. **Wide Dynamic Current Range:** From starting current I_{st} to minimum current I_{min} , transition current I_{tr} , and maximum current I_{max} . Compared to static sinusoidal meter standards, I_{st} should be reduced by 50% and I_{max} doubled.
4. **Accuracy Requirements:**
 - High-speed sampling: 256 points/cycle
 - Improved Fourier transform accuracy
 - High-precision algorithms for fundamental active/apparent power, harmonic active power, and full-wave apparent power
 - Synthesis algorithm and error test methods for h=2~n harmonic active power
 - Validation testing against actual three-phase load current waveforms
5. **Power Quality Monitoring:** Supplement broadband oscillation and overvoltage monitoring for high-voltage grids.
6. **Electrical Requirements:** Supplement specifications for power consumption, short-term overcurrent effects, self-heating, AC voltage tests, EMC tests, and test methods.
7. **Output Interfaces:** Supplement high-speed sampling and communication interfaces for actual grid waveforms.

Note: The GB/T 17215.302-2013 standard “Static Harmonic Active Energy Meters” only applies limited harmonic voltage/current influence testing for static sinusoidal meters.

7. Conclusion

This paper proposes the development and application of three-phase broadband smart meters validated against actual grid waveforms as an initial exploration to meet new metering and monitoring demands from renewable energy development and harmonic pollution mitigation.

Why This is Preliminary:

First, large-scale renewable energy development has only begun in the past two years, and future development toward new power systems may introduce new metering challenges. Second, China EPRI’s pioneering dynamic energy metering evaluation system will guide domestic development, prompting provincial grids to build test systems—a process requiring long-term effort for localizing high-end instruments. Third, while this project aims to promote new broadband energy pricing policies, success is uncertain. Fourth, whether State Grid and China

Southern Power Grid will accept, approve, and implement this project remains unpredictable.

Market Prospects:

In the near term, the market for three-phase broadband energy meters primarily includes distribution transformer areas, high-voltage harmonic-generating users, and large-capacity low-voltage three-phase users—totaling approximately 14 million users, representing about 12 billion RMB in meter investment. If the nation introduces broadband energy pricing policies, the market could expand to an additional 35 million large-capacity low-voltage three-phase users.

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