Retrospect and Prospect of Harmonic Energy Metering Technology

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Abstract

This paper primarily presents the development and application of harmonic electric energy metering technology in China since the 21st century. With the increasing demand for harmonic electric energy metering in power grids, the promulgation of the world's first harmonic power definition standard IEEE 1459-2000 has propelled the development of harmonic electric energy metering technology. The text also addresses key factors in the application and development of this technology, including the expanding scope of harmonic pollution in power grids, user confusion regarding the selection of appropriate harmonic electric energy metering principles, and the introduction of novel harmonic electric energy metering technologies from international sources. Furthermore, the paper introduces domestically developed achievements in harmonic electric energy metering technology, such as 0.2S-class gateway three-phase electric energy meters, 0.2S-class three-phase harmonic active electric energy metering product series, three-phase fundamental active electric energy metering products, as well as the development of cutting-edge practical technologies including metering chips that utilize Hilbert digital filters and low-frequency filters for harmonic reactive power calculation. Overall, this paper provides a comprehensive overview of the development history, current application status, and future development directions of harmonic electric energy metering technology in China, along with related technological and product achievements.

Full Text

Review and Prospect of Harmonic Energy Metering Technology Development

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Abstract

Since the beginning of the 21st century, harmonic energy metering technology in China has developed rapidly, transitioning from theoretical debates on harmonic power definitions to practical implementation discussions. With the successive introduction of harmonic reactive energy metering chips and harmonic/fundamental active energy metering chips, along with field trials of imported and domestic three-phase harmonic meters and fundamental wave meters, energy metering technology has achieved a major leap from sinusoidal to non-sinusoidal waveform measurement. This paper reviews the development and application of harmonic energy metering technology in China since 2000. Driven by increasing grid demand for harmonic energy measurement and the promulgation of the world's first harmonic power definition standard IEEE 1459-2000, the technology has advanced significantly. Key factors influencing its application and development include expanding grid harmonic pollution, user confusion over which metering principle to adopt, and the introduction of international technologies. The paper also presents domestic achievements such as 0.2S-class gateway three-phase meters, 0.2S-class three-phase harmonic active energy metering series, three-phase fundamental active energy products, and cutting-edge developments like Hilbert digital filter and low-frequency filter chips for harmonic reactive power calculation. Overall, this article summarizes the evolution, current status, and future direction of China's harmonic energy metering technology, along with related technical and product achievements.

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Since the 21st century, China's harmonic energy metering technology has developed rapidly, shifting from theoretical disputes over harmonic power definitions to practical discussions. With the successive launch of harmonic reactive energy metering chips and harmonic/fundamental active energy metering chips, along with the grid trial operation of imported and domestic three-phase harmonic meters and fundamental wave meters, energy metering technology has achieved a major transition from sinusoidal to non-sinusoidal measurement.

Driving Factors for Harmonic Energy Metering Technology Application and Development

Grid harmonic pollution has become increasingly severe, with an expanding scope of contamination. Not only do traditional smelting enterprises, electrified railways, and industries using high-power rectification equipment exhibit prominent power quality issues, but enterprises and urban residential areas with small rectification equipment, computers, color TVs, and frequency-conversion appliances also frequently exhibit current harmonics exceeding 50%. This has created confusion among different users regarding which principle to adopt for harmonic energy metering instruments.

The promulgation of IEEE 1459-2000, the world's first harmonic power definition standard, marked a milestone. Harmonic power theory, including debates over definitions and properties, had persisted for decades, with new theories often sparking fresh controversies. IEEE 1459-2000 summarized these historical debates and responded to the practical needs of harmonic energy metering technology application and development.

International harmonic energy metering technologies have been introduced, including harmonic power metering standards, online harmonic energy meters, and high-performance integrated circuits. In recent years, imported high-accuracy standard meters and metrology institutions from multiple countries can provide test reports for harmonic active power and apparent power. This enables traceability for harmonic energy metering.

New approaches to expand power marketing in the grid have emerged. The question is how to leverage existing electricity billing policies and adopt new harmonic energy metering technologies to improve power marketing while preparing for the formulation of economic policies to suppress harmonic loads.

This paper will comprehensively review the introduction of harmonic energy metering technology, domestic independent development achievements, grid trial operation status, and provide explanations for the development of cutting-edge practical technologies.

1. Introduction of Technology and Domestic Development Achievements

As an initial stage, the introduction of harmonic energy metering technology and domestic independent development served as fundamental means to explore and understand the distribution and characteristics of power harmonic loads and to accumulate measurement data.

1.1 Harmonic Active Energy Metering

0.2S-Class Gateway Three-Phase Energy Meter (Imported): This meter features harmonic and fundamental active energy metering functions with a sampling rate of 256 points per cycle. Its internal modular structure combines multiple modules according to different logic configurations, utilizing A/D sampling measurement modules, FFT modules, harmonic power calculation modules, and integration modules to achieve fundamental and 2nd–63rd order harmonic energy metering.

0.2S-Class Three-Phase Harmonic Active Energy Metering Series (Domestic): With a sampling rate of 256 points per cycle using FFT transform technology, this series offers three application modes. The first mode is a 0.2S-class three-phase harmonic active energy meter based on digital multiplier principles, providing harmonic analysis functions and delivering both harmonic active energy and harmonic active power flow direction. The second mode is a 0.5S-class three-phase fundamental active energy meter based on sinusoidal power theory. The third mode calculates total active energy using the absolute sum of fundamental and each harmonic energy, offering harmonic analysis functions and providing harmonic active energy and power flow direction. It measures amplitude and initial phase of voltage and current harmonics from the 2nd to 49th order, with amplitude accuracy of 2% and phase accuracy of 2° for harmonics 2–21.

0.2S-Class Three-Phase Fundamental Active Energy Metering Product (Imported): This product achieves harmonic suppression capability of better than 30dB for 3rd harmonics, 60dB for 5th harmonics, and 90dB for 7th harmonics. It measures amplitude, initial phase, and power of phase-by-phase 2nd–50th harmonic voltage and current, as well as phase-by-phase and three-phase total forward, reverse, and four-quadrant fundamental active energy and maximum demand.

Three-Phase Harmonic/Fundamental Active Energy Metering Chip: This chip offers a load dynamic range of 1000:1 with active power linearity of 0.1%. It uses band-pass filters to separate fundamental and harmonic components. For fundamental energy metering, a low-pass filter provides over 30dB attenuation for harmonics above the 3rd order. For harmonic energy metering, a fundamental wave suppressor provides over 30dB attenuation of the fundamental component.

1.2 Harmonic Reactive Energy Metering

Three-Phase Harmonic Reactive Power Metering Method Using Hilbert Digital Filter (Patented Technology): This method employs an IIR-type Hilbert digital filter designed from half-band filters. Within the design frequency range of 40–960Hz, all same-order voltage and current harmonics are phase-shifted by 90° with maximum phase error not exceeding 0.025°. The relative error between the directly measured sum of fundamental and each harmonic reactive power and simulation results is 0.020%. This metering method offers advantages of lower order, reduced computation, and smaller data storage requirements. Note: Domestic design and production of harmonic reactive energy metering chips using Hilbert digital filters have been implemented.

Metering Chip Using Low-Frequency Filter for Harmonic Reactive Power Calculation (Imported): By adding a single-pole low-frequency filter with a cutoff frequency of 2Hz (far below the fundamental frequency) to voltage and current circuits, the fundamental and each harmonic are phase-shifted by 90° with 20dB/decade attenuation. Through signal period calculation, dynamic compensation following frequency-dependent gain attenuation is completed to achieve harmonic reactive power metering. Testing shows that with 10% 3rd harmonic added to the voltage circuit and 20% to the current circuit, both with initial phase of 30°, the error between reactive power measured by the low-frequency filter and that defined by IEEE standards is 1%. This chip achieves effects close to Hilbert transformation.

0.2S-Class Three-Phase Fundamental Reactive Meter (Imported): This meter measures phase-by-phase and three-phase total forward, reverse, and four-quadrant fundamental reactive energy. Its harmonic suppression capability and function for metering harmonic voltage and current are the same as the 0.2S-class three-phase fundamental active meter mentioned above.

1.3 Harmonic Apparent Energy Metering

0.2S-Class Low-Cost Three-Phase Multifunction Meter (Imported): This meter provides 0.2S-class active energy metering with 2% accuracy for apparent power and energy measurement. It employs two different algorithms for apparent power calculation. The first is the vector algorithm: Vector VA = $\sqrt{}$(active power^2 + reactive power^2). The second is the arithmetic algorithm: Arithmetic VA = Urms $\times$ Irms. If harmonic current exists but harmonic voltage is zero, the vector VA excludes harmonic influence while arithmetic VA includes it, with arithmetic VA always being greater than or equal to vector VA.

For power factor calculation, PF = active power / apparent power. The power factor using vector VA excludes harmonic influence, while that using arithmetic VA includes it. Consequently, the power factor calculated using arithmetic VA is always less than or equal to that calculated using vector VA.

1.4 Harmonic Energy Metering Standards

0.01-Class Three-Phase Standard Energy Meter: This standard meter features harmonic active, reactive, and apparent power metering functions, with fundamental measurement from 15–70Hz and harmonic measurement up to 3500Hz. Verified by internationally recognized metrology institutions, the meter's total uncertainty for active and apparent power is 90–150$\times10^{-6}$ when harmonic content is 30% for 2nd–9th order harmonics and 5% for 11th–40th order harmonics.

Automatic Energy Meter Calibration System: This system achieves energy metering accuracy of $\pm$0.005–0.05% under arbitrary waveforms with total harmonic content below 30%.

Power/Energy Standard Source: This source provides seven optional methods for calculating reactive power of non-sinusoidal signals. It offers fundamental frequency measurement from 16–850Hz, maximum harmonic frequency of 6kHz, and outputs up to 100 harmonics. Harmonic injection does not significantly degrade measurement accuracy.

The above introduced technologies and domestic development achievements are applicable to steady-state, continuous integer-order harmonic energy metering. Internationally, harmonic active and apparent energy metering technologies have been fully equipped from online metering products to metrological traceability, though international comparisons of harmonic active and apparent power metering standards have not been conducted; traceability for harmonic reactive metering remains to be investigated. Domestically, online harmonic active and reactive metering technologies feature distinctive designs, while online apparent energy metering has not received adequate attention and development has not yet started. The lack of harmonic energy metering standards has already affected the application of domestic harmonic energy metering technology.

2. Application of Harmonic Energy Metering Technology

In recent years, domestic journals have published articles such as "Practical Calculation of Power in Non-Sinusoidal and Three-Phase Unbalanced Systems," "Analysis of Reactive Power Definitions Under Non-Sinusoidal Conditions," "Impact of Impact Loads on Energy Metering," and "Overview of Electric Power Sampling Measurement Technology and Its Development," providing guidance for harmonic energy metering technology development and promoting product grid trials. Harmonic reactive energy metering became a technical hotspot in 2002, harmonic active energy metering technology was trialed in 2003, and harmonic apparent energy metering products entered the power market in 2005. Years of operation have accumulated preliminary application experience and insights for adjusting metering product structures.

2.1 Application of Harmonic Reactive Energy Metering Technology

Traditional reactive energy metering methods have encountered problems in application. Electronic sinusoidal reactive energy meters calculate fundamental reactive power using $Q_1 = V_1 \times I_1 \times \sin$, while IEEE 1459-2000 defines harmonic reactive power differently (formula omitted). Electronic sinusoidal reactive meters implement a quarter-cycle delay of the fundamental voltage component, but analysis shows that odd harmonics of order 5, 9, 13, etc. (4K+1) are phase-shifted by 90° and are correctly measured, while even harmonics of order 2, 6, 10, etc. (4K+2) are shifted by 180°; odd harmonics of order 3, 7, 11, etc. (4K+3) by 270°; and even harmonics of order 4, 8, 12, etc. (4K+4) by 360°, all resulting in incorrect reactive power measurement with maximum absolute error reaching twice the harmonic apparent power. Testing demonstrates that with 10% 3rd harmonic on voltage and 20% on current, both at 30° initial phase, the error between the quarter-cycle delay method and IEEE standard definition reaches 4%. Therefore, using electronic sinusoidal reactive meters under non-sinusoidal conditions constitutes unreasonable measurement. Note: Most domestic three-phase standard meters adopt this quarter-cycle delay principle for reactive power measurement.

Reactive power calculation based on the power triangle also produces additional errors under harmonic conditions. Testing with the same 10% voltage and 20% current 3rd harmonic at 30° phase shows an error of 1.9% compared to IEEE-defined harmonic reactive power. Using cosine-type induction reactive meters for harmonic reactive power calculation yields maximum absolute errors of three times (60° connection) and two times (90° connection) the harmonic apparent power. The method using three electronic single-phase active meters in a cross-phase 90° connection requires further verification of its measurement accuracy.

Methods using Hilbert digital filters or low-frequency digital filters for harmonic reactive energy metering currently lack standards, making their accuracy temporarily unverifiable or comparable. Harmonic reactive energy meters can only measure fundamental reactive energy and reactive energy from same-order voltage and current harmonics, thus limiting their application scope. China has approximately 4 million three-phase reactive metering points, including power factor billing user metering and distribution transformer/substation reactive energy metering. In most cases, voltage remains essentially sinusoidal while harmonic current content exceeds limits.

2.2 Application of Harmonic Active Energy Metering Technology

China has approximately 7 million three-phase active energy metering points of various types. Since 2003, power systems in Hunan, Shandong, and Northeast China have trialed about 1,500 three-phase harmonic active meters/fundamental active meters. Years of operation show little difference between readings from harmonic/fundamental active meters and traditional three-phase active meters, with some data even contradicting expectations. Preliminary analysis suggests this is due to low voltage harmonic content at metering points or incorrect discrimination of harmonic active power flow direction.

Three main analysis methods for harmonic active power flow have been summarized from domestic literature. The first method includes four key points: (1) Fundamental power generated by generators is partially converted into harmonic energy by harmonic source users; (2) Harmonic source users inject harmonic energy into the grid, polluting it while reducing their own electricity expenses; (3) Non-harmonic source users passively absorb harmonic energy, increasing their costs; and (4) For generators, harmonic energy reduces grid economic efficiency and affects safe operation.

The second method argues based on energy conservation that both harmonic and fundamental energy originate from the source, with total energy being their sum. It claims measurement errors caused by harmonic active power are essentially negative, though this view is incomplete as error magnitude depends on harmonic content, initial phase relationships, and requires further verification of harmonic active power flow impacts on energy metering.

The third method views nonlinear loads as harmonic sources that convert part of sinusoidal energy into "grid garbage" fed back to the system, deducting this from energy measurement. While accumulated harmonic energy at metering points is negative, line loss energy from harmonic currents is positive. As an interim solution, fundamental active meters are used for such users.

Continuing the debate between fundamental versus harmonic meters shows blindness; the urgent priority is to unify active power flow analysis methods, design harmonic active power flow analyzers, and provide fundamental energy plus forward/reverse harmonic active energy with harmonic orders, amplitudes, and initial phases. Total active energy calculation can be customized by power systems and users based on metering data. Accumulating years of metering data will enable proposing discrimination methods for harmonic active power flow direction and total active energy measurement approaches for different enterprises under various conditions.

Similar to harmonic reactive meters, harmonic active meters can only measure fundamental active energy and same-order harmonic energy, limiting their application scope. Among approximately 600,000 large users with capacity of 315kVA and above, less than 5% have both voltage and current harmonic content exceeding limits, though these large consumers have enormous electricity usage. Harmonic-induced fluctuations in active energy are estimated to reach several billion kWh annually, making research on dynamic harmonic load and impact load active energy metering critically important.

2.3 Application of Harmonic Apparent Energy Metering Technology

IEEE 1459-2000 specifies using the arithmetic algorithm for harmonic apparent power to calculate harmonic power factor: $PF = P/S = P/(V \times I)$, where P is harmonic active power and S is harmonic apparent power ($S = V \times I$). For users with capacity of 100kVA and above subject to the "Power Factor Electricity Tariff Adjustment Method" (approximately 3 million users nationwide), 95% have only excessive current harmonic content. For example, in power distortion loads from bulk computer applications, power factor measured by sinusoidal reactive meters approaches 1.0, while that calculated using the arithmetic apparent energy algorithm is only 0.6.

According to the Power Factor Adjustment Method, users with actual power factor above the rated value (0.9 for large users, 0.85 for medium capacity) receive rewards with reduced electricity expenses, while those below face increased costs. Electricity expense fluctuations range up to 15% from power factor 1.0 down to 0.65 and below. Thus, power factor calculated using the arithmetic apparent power algorithm both reflects actual load conditions and improves grid operation management.

2.4 Harmonic Metering Technology for Urban Residential Electricity Consumption

Sampling tests show that power supplies for household computers, color TVs, and displays contain 6% voltage harmonics, 50% 3rd harmonic current, 30% 9th harmonic, and 8% 17th harmonic. Urban residential electricity consumption is thus also characterized by severely excessive current harmonic content. Currently, only active energy metering is used for residential billing, requiring electronic active meters with sufficiently high sampling rates to measure harmonic active energy.

To suppress rapid harmonic current growth, simple online harmonic metering instruments suitable for residential electricity characteristics need development. Primary functions should include: total voltage harmonic content, total current harmonic content, and harmonic pollution degree defined as non-fundamental apparent power divided by fundamental apparent power. Additionally, power systems and meter industries should proactively communicate with pricing authorities to recommend gradual implementation of apparent energy billing for residential users, which would help reduce harmonic content in household appliances, save energy, and purify the electromagnetic environment. Feasibility studies for single-phase and three-phase apparent energy meter product design should also be conducted.

3. Development of Cutting-Edge Practical Technologies for Harmonic Energy Metering

Actual power loads at grid user ends are far more complex than steady-state, continuous integer-order harmonic loads. For example, large steelmaking arc furnaces have extremely volatile reactive loads causing grid voltage fluctuations at 1–15Hz frequency, with over 30% 3rd harmonic current, maximum negative sequence current of 86%, and minimum power factor of 0.1. Large-capacity AC-AC frequency conversion synchronous motors have 18% harmonic current content, with interharmonics and subharmonics of order 0.3, 3.7, 9.7, etc. exceeding 2%, plus 23rd and 25th harmonic currents. Such complex load conditions require cutting-edge harmonic energy metering technologies.

In recent years, China has proposed several cutting-edge practical topics with preliminary theoretical research results:

3.1 Impact Load Energy Metering Theory and Algorithms

Applying generalized power theory to define power for arbitrary waveforms in single-phase and three-phase circuits enables calculation of active, reactive, apparent, distortion, and three-phase unbalanced power energy for impact loads using sinusoidal circuit power theory, traditional non-sinusoidal circuit power theory, and generalized power theory.

3.2 Wavelet Transform-Based Harmonic and Active/Reactive Energy Metering Methods

Wavelet transform offers excellent time-frequency characteristics. Using multiphase IIR Butterworth wavelet filter banks for harmonic analysis solves qualitative and quantitative analysis problems for non-steady-state harmonics. Simulations with both analog and actual signals show that wavelet transform-based multiphase filter banks achieve active and reactive power measurement accuracy at the 10^{-5} level.

3.3 Short-Time FFT Transform for Inter-Harmonic Measurement

This method measures RMS values, phases, and harmonic content for voltage inter-harmonics from 0–2500Hz and current inter-harmonics from 0–2500Hz, including direction. Fundamental phase accuracy is $±$0.5° with measurement range of 0–360°.

3.4 Fractional Harmonic Analysis Method

A new window function harmonic analysis method constructed from the time domain has been developed. Simulation experiments show that with double Hanning windows, amplitude relative error for strong harmonic signals reaches 10^{-4} magnitude, with phase absolute error better than 0.003°; for weak harmonic signals, amplitude relative error reaches 3.4% with phase absolute error of 2.4°, far superior to current windowed interpolation harmonic analysis algorithms.

Domestic journals have also published related articles including “Power Factor Measurement Using Wavelet Transform” and “Non-Integer Harmonic Measurement Method Based on Continuous Wavelet Transform.”

These cutting-edge topics employ not only traditional FFT, short-time FFT transforms, and improved algorithms, but also introduce new technologies such as generalized power theory and wavelet transform to solve complex metering problems. Subsequent research and development are needed to convert these theoretical preliminary results into online metering products, test instruments, or metrological standard equipment.

4. Concluding Remarks

After several years of grid trials, domestic harmonic energy metering technology has achieved preliminary results, exploring application and development pathways and identifying differences and gaps compared with international products. The next steps require deepening product design improvements for expanded trials, premised on launching reliable, grid-suitable series products for harmonic active, reactive, and apparent energy metering with traceability. Priorities include practical product design for harmonic apparent energy and power factor calculation, harmonic active power flow analysis technology, dynamic harmonic load and impact load energy metering technology, and improving dynamic characteristics of AC sampling power measurement methods. For harmonic reactive power, in-depth research is needed on harmonic impacts on reactive energy meters and exploration of transitional measures for verifying harmonic reactive power metering accuracy. In terms of standards construction, comprehensive strengthening of independent standard design and development is required, along with introducing internationally advanced standard equipment that is lacking domestically. As a first step, harmonic power metering working standards should be launched to meet application and development needs. Simultaneously, harmonic distribution in power systems should be investigated to estimate market capacity, clarify application and development targets, and formulate plans, including those for cutting-edge practical topics.

It must be noted that grid trials represent only the initial stage. The complete transition from sinusoidal to non-sinusoidal energy metering technology, through expanded trials, promotion, and comprehensive implementation, represents a development trend in energy metering technology, but the entire process will be lengthy. Market prospects indicate that harmonic apparent energy metering and harmonic power factor calculation technologies will likely be applied first, while applications of harmonic active and reactive energy metering will gradually become clear after expanded trials.

Post-2005 Research Achievements on Key Development Topics

1. **June 2006:** Tsinghua University scholar published "Harmonic Reactive Power Measurement Method Based on Two Pairs of Hilbert Phase-Shift Filters."
2. **September 2007:** National Institute of Metrology published "Research on Power Frequency Harmonic Power Standards."
3. **October 2008:** National Institute of Metrology published "Periodic Signal Sampling Measurement Strategy."
4. **2010:** Wasion Group launched China's first DTSD341-9ZV1.0 high-precision impact load three-phase multifunction energy meter.
5. **April 2010:** Original Henan Star High-Tech Company published "Development of ST1000 0.01-Class Three-Phase Standard Energy Meter," stating that "distorted waves can be decomposed into algebraic sums of sinusoidal vectors, so distorted wave active and reactive power algorithms are algebraic sums of each harmonic power algorithm." It also noted that "calculation accuracy using Fourier algorithms depends on integration accuracy of digital discrete sequences. Since ST1000 uses fixed-sampling-frequency asynchronous sampling, all simplified integration formulas for integer-period sampling no longer apply, requiring new algorithms to improve asynchronous sampling integration accuracy."
6. **March 2011:** Zhejiang Provincial Metrology Institute and National Institute of Metrology published "Experimental Research on Dynamic Characteristics of Energy Meters."
7. **Collaboration between Tsinghua University scholars and Panzhihua Iron & Steel Company:** "Testing and Research on Harmonic Phase Impact on Grid Harmonics."

International Reference Technologies

1. **2010:** IEEE 1459-2010 standard was released to replace IEEE 1459-2000.
2. **Around 2012:** U.S. GE Company launched the KV2c™ three-phase multifunction energy meter featuring distortion power and harmonic power factor calculation.

Expectations for 2018

From 2002–2010, domestic harmonic energy metering technology maintained high development momentum, evidenced by: (1) Leading meter enterprises collaborating with provincial grids to develop impact load/harmonic load active energy meters for grid trials; (2) Universities focusing on harmonic reactive metering schemes, algorithms, and simulation technologies with frequent publications; and (3) Meter enterprises importing and selling electronic three-phase meters with harmonic apparent power and arithmetic algorithm-based power factor calculation.

However, after 2010, application and development cooled due to several factors. State Grid's metering priorities shifted to smart meter application and electricity information collection system construction—a massive metering project supporting smart distribution network development. State Grid also implemented unified planning and full-process management for key metering technology projects, including development funding, making it difficult for most provincial grid metering centers to apply for or receive key project allocations. Years earlier, State Grid Electric Power Research Institute metering experts reported harmonic energy metering technology controversies and grid harmonic pollution issues to national metrology authorities without response. To date, pricing authorities have not issued economic measures to suppress user harmonic pollution. State Grid's smart meter enterprise standards define metering functions primarily according to current tariff policies, rarely reflecting multi-disciplinary grid application needs or comprehensive development requirements, including grid loss calculation, distributed reactive power balance, smart distribution network power quality monitoring, and economic measures to suppress harmonic load growth.

2018 may be a turning point for scientific metrology work. In 2017, State Grid achieved full coverage of smart meter application and electricity information collection systems. The early 2018 State Grid metering work conference will arrange key new technology development and management projects for the year, with expectations for new demands in harmonic energy metering technology development and application to be integrated into high-quality smart distribution network construction.

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