Review and Outlook of the Development of Harmonic Energy Metering Technology

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Abstract

This paper primarily reviews the development and application of harmonic power metering technology in China since the 21st century. Driven by escalating demand for harmonic power measurement in power grids, the introduction of the world' s first harmonic power definition standard, IEEE 1459-2000, has significantly catalyzed advancement in harmonic power metering technologies. The text also addresses key facets in the application and evolution of harmonic energy metering technology, including the expanding scope of harmonic pollution in power grids, inconsistencies among harmonic energy metering instruments adopted by different users, and emerging novel harmonic energy metering technologies introduced worldwide. Furthermore, this paper discusses domestically independently-developed harmonic energy measurement technologies, such as 0.2S-class three-phase electricity meters, 0.2S-class three-phase harmonic active energy metering product series, three-phase waveform active energy metering products, and cutting-edge practical technologies involving the development of harmonic reactive power metering chips utilizing Hilbert digital filters and low-frequency filter calculations. In summary, this paper provides a comprehensive overview of the developmental trajectory, current application status, and future directions of harmonic power measurement technology in China, along with related technological and product achievements.

Full Text

Review and Prospect of the Development of Harmonic Energy Metering Technology

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Abstract

This paper reviews the development and application of harmonic power metering technology in China since the 21st century. The introduction of IEEE 1459-2000, the world' s first harmonic power definition standard, has accelerated the advancement of harmonic power metering technology in response to growing grid demands. The paper discusses key elements in the evolution of harmonic energy metering, including the expanding scope of harmonic pollution in power systems, confusion arising from different harmonic metering instruments used by various customers, and emerging harmonic energy metering technologies introduced globally. Additionally, the paper highlights China' s independently developed harmonic energy measurement technologies, such as 0.2S-class three-phase electricity meters, 0.2S three-phase harmonic active energy metering series products, three-phase wave active energy metering products, and cutting-edge practical techniques employing Hilbert digital filters and low-frequency filters for harmonic reactive power metering chip development. Overall, this paper summarizes the developmental trajectory, current application status, and future directions of harmonic power measurement technology in China, along with related technological and product achievements.

Keywords: Harmonic metering, power system
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0 Introduction

Since the 21st century, harmonic power measurement technology in China has developed rapidly, with the definition of harmonic power shifting from theoretical controversy to practical implementation. The introduction of harmonic reactive energy metering chips, harmonic fundamental wave active energy metering chips, and the trial deployment of imported and domestic three-phase harmonic wave meters and three-phase fundamental wave meters in power networks have enabled a major leap in energy measurement technology from sinusoidal to non-sinusoidal wave measurement.

Several factors have driven the application and development of harmonic energy metering technology. First, harmonic pollution in power grids has become increasingly severe, with an expanding scope of contamination. Traditional smelting enterprises, electrified railways, and industries using high-power rectification equipment have long exhibited prominent power quality issues. Moreover, small and medium-sized enterprises using small rectification equipment, computers, and color frequency conversion appliances, as well as urban residential communities, often exhibit current harmonic content exceeding 50%. This diversity has created confusion regarding the principles underlying harmonic energy metering instruments adopted by different users. Second, the introduction of IEEE 1459-2000, the world' s first harmonic power definition standard, provided a summary of historical theoretical disputes while meeting the practical needs of harmonic energy metering technology development. Third, new international technologies have emerged, including online harmonic power meters, high-performance integrated circuits, and harmonic power metering standards with high traceability. In recent years, measurement institutions in many countries can provide detection reports for harmonic active power and harmonic apparent power. Finally, new concepts for power grid development and marketing have emerged, exploring how to leverage existing electricity billing policies and new harmonic power metering technologies to improve power marketing and formulate economic policies that restrain harmonic loads.

This paper summarizes the introduction of harmonic energy measurement technology, domestic independent development achievements, network trials, and provides explanations for frontier practical technologies in harmonic energy measurement development.

1. Introduction of Harmonic Energy Metering Technology and Domestic Independent Development Achievements

As an initial stage, the introduction of harmonic energy metering technology and domestic independent development represent fundamental means and technical forerunners for exploring and understanding the distribution and characteristics of power harmonic loads, as well as accumulating measurement data.

1.1 Harmonic Active Energy Metering

0.2S-Class Three-Phase Watt-Hour Meter (Imported): This meter features harmonic and fundamental active energy metering functions with a sampling rate of 256 points per waveform. Its internal modular structure employs various modules according to different logic, including A/D sampling measurement modules, FFT modules, harmonic power calculation modules, and integration modules to realize fundamental and 2nd-63rd harmonic energy metering functions.

0.2S-Class Three-Phase Harmonic Active Power Metering Series Products (Domestic): These products feature a sampling rate of 256 points per cycle and employ FFT transformation techniques. Three application modes exist: (1) A 0.2S-class three-phase harmonic active power meter based on digital multiplier principles with harmonic analysis functions, providing harmonic active power and harmonic active power current direction; (2) A 0.5S-class three-phase fundamental wave active energy meter based on sinusoidal wave power theory; and (3) A mode calculating total active electric energy using the sum of absolute values of fundamental and harmonic electric energy, with harmonic analysis functions providing harmonic active power and power flow direction.

Design Specifications: Within the design frequency range of 40-960Hz, all voltage and current harmonics are phase-shifted by 90° with maximum phase error not exceeding 0.025°. Direct metering of fundamental wave and each subharmonic' s reactive power shows a relative error of 0.020% compared with simulation results. This measurement method offers advantages of lower order, reduced computation, and minimal data storage requirements.

Domestic Harmonic Reactive Electric Energy Metering Chip: Designed and produced using Hilbert digital filters, this chip measures amplitude and initial phase of 2nd-49th current harmonics. Specifically, harmonic amplitude accuracy is 2% and initial phase accuracy is 2°.

0.2S-Class Active Electric Energy Metering Products (Imported): These three-phase fundamental wave products exhibit harmonic suppression capabilities: 3rd harmonics better than 30dB, 5th harmonics better than 60dB, and 7th harmonics better than 90dB. They measure harmonic voltage up to 50th order, current amplitude, initial phase, and active power. They also measure forward, reverse, and four-quadrant fundamental wave energy of divided phases and three phases, along with maximum fundamental wave demand.

Three-Phase Harmonic/Fundamental Wave Active Electric Energy Metering Chip: With a load dynamic range of 1000:1 and active power linearity of 0.1%, this chip uses bandpass filters to separate fundamental and harmonic components. When measuring fundamental electric energy, a low-pass filter provides -30dB attenuation for harmonics above 3rd order; when measuring harmonic energy, a fundamental suppressor provides -30dB attenuation for the fundamental wave.

1.2 Harmonic Reactive Energy Metering

Metering Chip Using Low-Frequency Filter (Imported Harmonic Reactive Power Products): This approach adds a unipolar low-frequency filter with a cutoff frequency of 2Hz in both voltage and current circuits—far lower than the fundamental frequency. This causes each harmonic to phase-shift by 90°, followed by 20dB/decade attenuation. By calculating the signal cycle, dynamic compensation for gain attenuation at following frequencies is completed to realize harmonic reactive power measurement. Testing shows that with 10% added to the voltage circuit and 20% to the current circuit, along with 30° initial phase for voltage and current harmonics, the error between harmonic reactive power measured by the low-frequency filter and that defined by the IEEE standard is 1%. The chip achieves near-Hilbert conversion effects.

0.2S-Class Three-Phase Fundamental Wave Reactive Meter (Imported Products): This meter measures forward, reverse, and four-quadrant fundamental wave reactive electric energy for phase and three-phase configurations. Its harmonic suppression capability and metering functions are identical to the 0.2S-class three-phase fundamental wave active power meter described above.

Three-Phase Harmonic Reactive Power Measurement Method Using Hilbert Digital Filter (Patented Technology): This proprietary technology employs Hilbert digital filters for harmonic reactive power measurement.

1.3 Harmonic Vision in Electric Energy Metering

0.2S-Class Low-Cost Three-Phase Multifunctional Meter (Imported Products): This meter uses a Type IIR Hilbert digital filter design. Active electric energy metering accuracy is 0.2S class, while dependent power and electric energy metering accuracy is 2%. Visual power employs two different algorithms: (1) Vector algorithm where vector VA = $\sqrt{}$(active power^2 + reactive power^2); and (2) Arithmetic algorithm where arithmetic VA = Urms × Irms. When harmonic current is present but harmonic voltage is zero, vector VA contains no harmonic effects while arithmetic VA includes harmonic effects, making arithmetic VA always greater than or equal to vector VA.

Power Factor Calculation: Power factor equals active power divided by apparent power. Using vector VA calculates power factor without harmonic influence, while using arithmetic VA includes harmonic effects. The maximum harmonic frequency is 6 kHz with output up to 100 harmonics. The addition of harmonics significantly weakens measurement accuracy or traceability.

The introduced harmonic energy measurement technology and domestic independent development achievements are suitable for steady-state and continuous integer harmonic energy measurement. Internationally, harmonic power metering technology has completed the transition from online metering products to traceability for harmonic active and apparent power, though harmonic reactive power metering traceability requires verification. In China, online harmonic active and reactive power measurement technology development is highly characteristic, though the development of online electric power measurement technology has not yet started. The harmonic electric power measurement standard remains blank, which has affected the application and development of domestic harmonic energy measurement technology.

1.4 Harmonic Electric Energy Metering Standard Technology

Europe: Level 0.001 three-phase standard watt-hour meter features harmonic active and reactive power and apparent power measurement functions, with fundamental wave measurement from 15-70Hz and harmonic measurement up to 3500Hz. Verified by internationally recognized measurement institutions, with 30% harmonic content for 2nd-9th harmonics and 5% for 11th-40th harmonics in voltage and current, the total uncertainty for active and apparent power is 90-150 $\times 10^{-6}$.

America: Electric energy meter automatic calibration systems achieve $±$0.005-0.05% accuracy for electric energy measurement under 30% total harmonic content. Power standard sources provide seven optional methods for calculating reactive power of non-sinusoidal signals, with fundamental frequency measurement ranges from 16-850Hz.

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2. Application of Harmonic Electric Energy Metering Technology

Domestic journals have published numerous articles providing guidance for harmonic electric energy metering technology development, including research on the influence of impact loads on electric energy metering, electric power sampling and measurement technology, and development overviews. These publications have promoted product trials: since 2002, harmonic reactive energy metering became a technical hotspot; in 2003, harmonic active energy metering technology trials began; and harmonic vision products entered the power market. After years of operation, preliminary application experience has been accumulated, informing adjustments to measurement product structure concepts.

2.1 Application of Harmonic Reactive Energy Metering Technology

Traditional reactive energy metering methods face several problems. Electronic sinusoidal reactive electric energy meters and cosine induction reactive meters used to calculate harmonic reactive power exhibit maximum absolute errors of 3 times (for 60° wiring) and 2 times (for 90° wiring) the harmonic apparent power. The fundamental wave reactive power calculation formula is $Q_1 = V_1 \times I_1 \times$ sin . Analysis of the harmonic reactive power calculation formula adopted by electronic sinusoidal reactive meters (which delay voltage fundamental wave by 1/4 fundamental period) reveals that for odd harmonics of frequencies 5, 9, 13 ···(4K+1), the measurement is correct. However, for even harmonics (2, 6, 10··· 4K+2), phase shift is 180°; for odd harmonics (3, 7, 11···4K+3) and (4, 8, 12··· 4K+4), the reactive power measurement is incorrect, with maximum absolute error reaching 2 times the power.

Testing demonstrates that with 10% added to the voltage circuit and 20% to the current circuit, and voltage/current harmonic initial phases at 30°, the error between harmonic reactive power measured by the sinusoidal fundamental wave cycle and that defined by the IEEE standard is 4%. Using Hilbert digital filters or low-frequency digital filters to measure harmonic reactive power currently lacks measurement accuracy standards, limiting its application range.

It is estimated that four million three-phase reactive power metering points exist nationwide, including user metering for power factor billing, distribution transformers, and substation reactive power energy metering. In most cases, voltage remains basically sinusoidal while harmonic current content exceeds standards. Therefore, adopting fundamental wave reactive meters under non-sinusoidal conditions is not reasonable.

2.2 Application of Harmonic Active Power and Electric Energy Metering Technology

Since 2003, Hunan, Shandong, and Northeast China power systems have trialed approximately 1,500 sets of three-phase harmonic active power meters and fundamental wave active power meters. After years of operation, readings calculated according to the power triangle from harmonic/fundamental meters show discrepancies from traditional three-phase active meters, with some measurement data being opposite to expectations. Preliminary analysis suggests this results from low voltage harmonic content at metering points or incorrect harmonic active power flow discrimination.

Harmonic active meters, similar to harmonic reactive meters, can only measure active electric energy of the fundamental wave and harmonics with identical voltage and current frequencies, limiting their application range. It is estimated that 600,000 large users with capacity of 315 kVA and above exist nationwide, with less than 5% having excessive voltage and current harmonic content. However, these large users consume enormous amounts of electricity, with active power energy fluctuations estimated in the billions of kWh annually. Therefore, studying and developing active power measurement for dynamic harmonic loads and shock loads holds great practical significance.

2.3 Application of Harmonic Vision in Electric Energy Metering Technology

The IEEE 1459-2000 standard stipulates using the arithmetic algorithm' s harmonic apparent power to calculate harmonic power factor: PF = P/S = P/(V×I), where P is harmonic active power and S is harmonic apparent power (S = VI).

For users with 100 kVA or above implementing power factor adjustment electricity charges (estimated at 3 million households nationwide), 95% have only excessive current harmonic content. Taking a computer batch application forming a power distortion load as an example, the power factor measured by sinusoidal reactive meters is close to 1.0, while the power factor calculated by arithmetic algorithm is only 0.6—a significant difference. According to power factor electricity charge adjustment methods (with rated power factors of 0.9 for large users and 0.85 for medium capacity), users with actual power factors higher than the rated value receive rewards, while those lower face increased charges. From power factor 1.0 down to 0.65 or below, users' electricity bills fluctuate by 15%. The power factor calculated using arithmetic algorithm' s dependent power not only reflects actual power load conditions but also improves power grid operation and management.

Additionally, power systems and electricity meter industries should proactively report to and communicate with pricing authorities, recommending that residential electricity gradually transition to apparent energy-based charging to reduce harmonic content in household appliances, save energy, and purify the electromagnetic environment. Feasibility studies for incorporating harmonic vision into single-phase and three-phase electricity meter product designs should be conducted.

2.4 Harmonic Metering Technology for Urban Residential Electricity Consumption

Sampling tests reveal that home computers, color TVs, and color display power supplies exhibit voltage harmonic content of 6%, 3rd harmonic current content of 50%, 9th harmonic content of 30%, and 17th harmonic content at significant levels. Currently, only active electric energy metering methods exist for residential electricity charging. Electronic active power meters with sufficiently high sampling rates should be selected to measure harmonic active electric energy. To restrain rapid harmonic current growth, simple online harmonic metering instruments adapted to urban residential electricity consumption characteristics must be developed, with main metering functions including total voltage harmonic content and total current harmonic content.

Summarizing network trial experience, harmonic power metering technology and products enter the power market primarily by aligning with actual power loads and meeting power marketing and management improvement needs. Currently, while basic problems in harmonic active power measurement remain controversial and harmonic reactive power measurement standard technology is still being explored, harmonic vision in electric energy measurement and harmonic power factor calculation may serve as entry points to the market. Additionally, harmonic measurement for urban residential electricity should be placed on the agenda.

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3. Frontier Practical Technologies for Harmonic Electric Energy Metering

Actual power loads are not limited to steady-state, continuous integer harmonic loads; specific situations are far more complex. Examples include power grid voltage fluctuations at 1-15Hz frequencies with 30% third harmonic current content, maximum negative sequence current of 86%, and minimum power factor of 0.1; large-capacity AC-AC frequency synchronous motors with 18% harmonic content and 0.3, 3.7, 9.7 harmonic current content exceeding 2%; and 23rd, 25th harmonic currents. These complex load situations require solutions.

In response, China has proposed several frontier practical topics for harmonic electric energy metering in recent years, with preliminary theoretical research results:

3.1 Theory and Algorithm of Impact Load Electric Energy Metering

This approach applies generalized power theory to define power in single-phase and three-phase circuits of arbitrary waveforms, using sinusoidal circuit power theory, traditional non-sinusoidal circuit power theory, and generalized power theory to calculate active power, reactive power, dependent power, distortion power, and three-phase asymmetric power for impact loads.

3.2 Wavelet Transform Method for Harmonic and Active/Reactive Electric Energy Measurement

Wavelet transform offers excellent time-frequency characteristics. Using multiphase IIR Butterworth wavelet filter sets for harmonic analysis solves qualitative and quantitative analysis problems for unstable harmonics. After measuring simulated and actual signals, the accuracy of active power and reactive power measurement using wavelet transform multiphase filter sets reaches the 10^{-5} order.

3.3 Short-Time FFT Transformation for Interharmonic Measurement

This method measures effective value, phase, harmonic content, and direction of 0-2500Hz interharmonic voltage and current. Fundamental wave 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 achieves amplitude relative error of 10^{-4} order for strong harmonic signals through simulation experiments, with prerequisites that absolute phase error is better than 0.003°. For weak harmonic signals, amplitude relative error is 3.4% and absolute phase error is 2.4°, far superior to current window interpolation harmonic analysis algorithms.

These frontier practical measurement topics employ not only traditional FFT, short-time FFT transformation, and improved algorithms, but also introduce generalized power theory, wavelet transformation, and other technologies to solve complex measurement problems. These cutting-edge topics require follow-up research and development to transform preliminary theoretical research into online measurement products, testing instruments, or measurement standard equipment.

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4. Summary

After only a few years of network trial, domestic harmonic electric energy metering technology has achieved preliminary results, revealing differences and gaps with similar international metering product technologies. The next steps involve deepening design improvements for harmonic measurement products and preparing for expanded trials.

Domestic industry must launch reliable, applicable harmonic active power, reactive power, and dependent electric energy metering series products with traceability capabilities. The focus should be on practical product design for harmonic vision in electric power and harmonic power factor calculation, harmonic active power flow analysis technology, electric energy metering technology for dynamic harmonic loads and shock loads, and improving the dynamic characteristics of AC sampling power measurement methods. For harmonic reactive power, thorough investigation of harmonics' effects on reactive electricity meters is needed.

Harmonic electric energy metering standard construction requires comprehensive strengthening of independent design and development of measurement standards, introducing internationally advanced measurement standard equipment to address domestic shortages. As a first step, the working standard of standard electricity meters points out that "distortion wave can be decomposed into a series of algebraic sums of sinusoidal vectors, so the active power and reactive power algorithm of distortion wave are the algebraic sum of harmonic power." The computational accuracy of Fourier algorithm depends on integration accuracy of digital discrete sequences. Since ST 1000 adopts asynchronous sampling with fixed sampling frequency, the simplified integration formula of full cycle sampling is no longer applicable, requiring new algorithms to improve integration accuracy of asynchronous sampling.

Finally, it should be noted that network trials of harmonic electric energy metering represent only the initial stage. Expanded trials, promotion, and application are needed to fully complete the transformation from sinusoidal to non-sinusoidal electric energy metering technology.

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5. Research Examples and Developments

March 2011: Zhejiang Metrology Institute and China Metrology Institute conducted experimental research on the dynamic characteristics of electricity meters.

Tsinghua University Scholar and Panzhihua Iron and Steel Company: Testing and research on the effect of harmonic phase on network access harmonics.

June 2006: Tsinghua University scholar developed a harmonic reactive power measurement method based on 2 pairs of Hilbert phase shift filters.

September 2007: China Metrology Institute conducted research on power frequency harmonic power standards.

October 2008: China Metrology Institute developed cyclic signal sampling and measurement strategies.

April 2010: Weisheng Group Company launched China' s first DTSD 341-9ZV 1.0 high-precision impact load three-phase multi-functional electricity meter.

2010: Former Henan Star High-tech Co., Ltd. developed the ST 1000 0.01-level three-phase standard meter.

2010: IEEE 1459-2010 standard was introduced to replace IEEE 1459-2000.

Around 2012: GE launched the KV2c™ three-phase multi-function electricity meter featuring distortion power and harmonic power factor calculation functions.

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6. Prospects and Market Analysis

From 2002 to 2010, harmonic electric energy metering technology application and development in China experienced high activity, characterized by: (1) Strong electricity meter enterprises cooperating with provincial power grids to develop impact load/harmonic load active power meters for network trials; (2) Colleges and universities focusing on harmonic reactive power metering schemes, algorithms, and simulation technologies, frequently publishing in domestic/international journals; and (3) Electric meter enterprises introducing and selling electronic three-phase electric energy meters with harmonic vision power and arithmetic algorithms for power factor calculation.

However, after 2010, application and development of harmonic electric energy metering technology was restricted and cooled down. Primary factors include: (1) The State Grid' s metering work focus shifted to promoting smart electricity meters and constructing a massive electricity information collection system to support smart distribution network development; (2) State Grid implemented unified planning and whole-process management for key metrology science and technology projects, including development fund management, making it difficult for most provincial power grid metering centers to declare or obtain allocation for key metering science and technology projects; and (3) Measurement experts reported harmonic grid pollution issues including line loss calculation, reactive power balance, quality monitoring, and economic measures to suppress harmonic load growth, but received no response, and pricing authorities have not introduced economic measures to restrain grid harmonic pollution.

2018 may represent a turning point. In 2017, State Grid achieved full coverage of smart electricity meters and electricity information collection systems. In early 2018, the State Grid Metrology Promotion Meeting arranged key metering new technology development and management projects for the year, expecting to propose new demands for harmonic power metering technology development and application, integrating it into the new journey of high-quality intelligent distribution network construction.

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