Research on Intelligent Terminals Extending from Measurement Technology to Intelligent Control Compensation Technology

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Date: 2024-02-19T22:03:02+00:00

Abstract

Intelligent terminals, building upon measurement technology, have already expanded into research on intelligent control and compensation technologies. The development and application of this technology hold significant importance for improving the efficiency and stability of power systems. First, measurement technology constitutes a fundamental component of smart grids. Through high-speed bidirectional information communication systems, smart grids can perform real-time monitoring of various grid parameters and convert the detected grid parameters into data information for use by various systems within the smart grid. This information can promptly reflect the complete state of the power grid, assist in comprehensive assessment of grid security and reliability, and improve energy utilization efficiency. Meanwhile, intelligent control and compensation technology serves as an important means to further enhance grid efficiency and stability. Intelligent control technology requires the introduction of preset expert systems to automatically diagnose, analyze, and predict grid status within smart grids. Within the scope defined by the expert system, appropriate measures are taken to prevent power supply interruptions and power quality disturbances. These measures may include adjusting the active and reactive power of the grid to achieve intelligent control and compensation of electrical energy. Therefore, the expansion of intelligent terminals from measurement technology to research on intelligent control and compensation technologies represents an important trend in the development of power system technology. This development can not only improve the efficiency and stability of power systems but also facilitate the realization of intelligence and automation in power systems, thereby meeting the high demands of modern society for power supply.

Full Text

The Evolution of Intelligent Terminals: From Measurement Technology to Intelligent Control and Compensation Technology

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Abstract

Intelligent terminals have evolved from measurement technology to encompass intelligent control and compensation technology research. This technological development and its application are of great significance for improving the efficiency and stability of power systems. Measurement technology serves as a fundamental component of smart grids. Through high-speed bidirectional information communication systems, smart grids can monitor grid parameters in real time, converting detected parameters into data information for use by various smart grid systems. This information can promptly reflect the complete status of the power grid, facilitate comprehensive evaluation of grid safety and reliability, and improve energy utilization efficiency.

Intelligent control and compensation technology represents a crucial means to further enhance grid efficiency and stability. This technology requires the introduction of a preset expert system that automatically diagnoses, analyzes, and predicts grid conditions within the smart grid. Within the limits set by the expert system, appropriate measures are taken to prevent power supply interruptions and power quality disturbances. These measures may include adjusting active and reactive power in the grid to achieve intelligent control and compensation of electrical energy. Therefore, the expansion of intelligent terminal research from measurement technology to intelligent control and compensation technology represents an important trend in power system technology development. This evolution can not only improve power system efficiency and stability but also help realize power system intelligence and automation, thereby meeting modern society's high demands for power supply.

Keywords: Smart terminals; Measurement technology; Intelligent control and compensation products

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1. Market Analysis: New Challenges and Opportunities for the Meter Industry (2017-2018)

Since 2017, the author and industry experts have published the following articles on expanding technological innovation and product industrialization in the meter industry:

1. January 16: "Meter Industry: The Time is Right to Expand Technological Innovation Product Development and Application in Electricity, Water, Gas, and Heat Energy Metering!"
2. March 4: "Adapting to High-End Technology Needs of Smart Distribution Network Construction: Promoting Industrialization Exploration of Intelligent (Advanced) Terminal Series Products for Distribution Transformer Areas"
3. March 19: "Discussion on Preliminary Design Technology for Advanced Application Systems of Intelligent (Advanced) Terminals in Distribution Transformer Areas"

1.1 The Time is Right for Expansion In December 2016, the Central Economic Work Conference proposed new policies of "revitalizing the real economy" and "implementing innovation-driven development," while smart distribution network and energy internet construction were being advanced in an orderly manner. These policies pointed out the development direction for the meter industry, which had already fallen into difficulties.

Entering 2017, after summarizing and analyzing the confusion and opportunities facing the meter industry's development in the new year, the author proposed the topic: "Meter Industry: The Time is Right to Expand Technological Innovation Product Development and Application in Electricity, Water, Gas, and Heat Energy Metering!"

This article primarily describes the new situation facing meter industry development from 2017 to 2018, along with ideas and countermeasures for promoting the expansion of technological innovation product development and application in electricity, water, gas, and heat energy metering fields.

1.2 Confusion and Opportunities 1) Traditional electric meter product market demand has fallen into a trough

In recent years, the author has repeatedly emphasized that the meter industry must cherish and conscientiously maintain three basic markets: smart meters, data acquisition terminals, and low-voltage metering boxes. In 2014-2015, the State Grid's annual demand for smart meters peaked at 90 million units, and meter enterprises correspondingly expanded production capacity.

- **Smart meters:** In 2017, with the comprehensive application of smart meters and the completion of electricity information collection systems, the total demand for smart meters from the State Grid would decline significantly. Online forecasts predicted that the State Grid's 2017 centralized bidding volume for smart meters would be 20-40 million units, a decrease of 78%-56% compared to 2014-2015.

- **Data acquisition terminals:** Online forecasts suggested that "acquisition terminals would lag meters by 2 years, with 2017 acquisition terminal bidding continuing to expand," estimating acquisition terminal demand at

7 million units and broadband carrier communication modules at 6 million units. However, the annual bidding amount for acquisition terminals was only one-third that of smart meters.

- **2018:** New-generation State Grid meters entered sample trial and improvement phases, while electricity information collection systems shifted to comprehensive deepening applications. Both smart meters and acquisition terminals were expected to remain in a trough.
- **Post-2018:** New-generation State Grid meters entered mass application, and smart meter demand might recover. However, the demand situation for smart meters and acquisition terminals remained uncertain.

Facing these new market conditions in the coming years, meter enterprises need to carefully study enterprise transformation and new product development issues while continuing to conscientiously handle State Grid smart meter centralized bidding and new-generation State Grid meter sample development and testing.

Meter enterprises have two paths for transforming new product development:

- **Shortcut approach:** OEM, imitation, or merging with enterprises that have demand for the products. However, since transformed new products must follow new markets, marketing remains very difficult.
- **Recommended approach:** Meter enterprises with economic and technical strength should take the path of technological innovation development, selecting related fields with market prospects and development difficulty that are not closely related to grid centralized bidding—namely, technological innovation product development and application in electricity, water, gas, and heat energy metering fields.

2) Demand for new principle metering meters temporarily weak

In December 2016, the State Grid Metering Center released the report "Smart Metering System Construction and Development."

In recent years, there have been numerous reports on the construction and application of the State Grid's electricity information collection system, "multi-meter integration" information collection construction and application, and automated metering verification.

The newly released "Smart Metering System Development" attracted attention: the State Grid would build a new-generation collection system using cloud computing, big data, Internet of Things, and mobile communication technologies to achieve efficient, flexible, and secure operation. The system architecture includes:

- **Master station:** Supports more complex and diverse business application requirements
- **Communication:** Integrates multiple high-speed communication technologies for interconnectivity

- **Terminals:** Modular terminals with plug-and-play capability and automatic synchronization
- **Electric meters:** Dual-core smart meters supporting online upgrades

Expected indicators: - Connected terminals: 5 million - Connected metering points: 80 million - Master station to meter acquisition frequency: 5 seconds - Conventional data query response time: <3 seconds - Fuzzy data query response time: <10 seconds - Terminal concurrent processing: 10,000 units - Fault recovery time: 2 hours

Dual-core smart meter: - Metering core: Serves as the legal metering part, with functions that cannot be upgraded. Design focuses on independence, data traceability, accuracy and reliability, and secure clock. - **Management core:** Adopts modular design (display, communication, load curve, fee control, events, etc.). Upgrade data download uses data encryption + link authentication to identify whether new programs and parameters match, ensuring download and updates do not affect normal metering core operation.

As can be seen from the above, the State Grid's smart metering system development in the coming years will focus on building a new-generation collection system, with research on modern technologies such as communication, computing, and IoT as the main direction. The new-generation State Grid meter adopts "dual-core" architecture, with direct data exchange through SPI interface, achieving independence between legal metering functions and non-metering functions. The metering core function does not allow software upgrades.

3) Power/meter enterprises expanding to water, gas, and heat energy metering has become a trend

- **State Grid:** With support from higher-level energy authorities and some local governments, strongly promotes "multi-meter integration" information collection construction for electricity, water, gas, and heat meters. The China Electricity Council released the cross-industry power industry group standard "Electricity, Water, Gas, and Heat Energy Metering Management System." By the end of 2016, State Grid's "multi-meter integration" information collection had cumulatively connected 1.63 million households.

- **Media expansion:** In recent years, technology and information dissemination business has expanded from power metering media to "four-meter integration" for electricity, water, gas, and heat, promoting energy metering integration construction.

- **Weisheng Group:** After years of operational experience accumulation, has developed from an electricity metering and power energy efficiency management supplier to an energy metering and energy efficiency management system solution and product supplier for electricity, water, gas, and heat.

Domestically, an estimated 20+ meter enterprises have won bids for "multi-meter integration" information collection projects.

4) Modernization of water, gas, and heat energy metering requires introduction of high-end metering and communication technologies

Water, gas, and heat energy metering work is managed in separate areas by local governments, making it difficult to introduce new technologies and capital investment. The industry lags significantly behind the power/meter industry in meter intelligence, industry standardization, new communication technology research and application, and integrated collection master station technology. A nationwide electricity, water, gas, and heat energy metering technology industry alliance is needed to coordinate and promote the development of energy metering work.

The meter industry has long had a unified national industry authority to carry out industry standardization, new technology development, information exchange and training, and IEC international cooperation, with long-term work experience. It can be said that the meter industry has advantages in exporting new business to water, gas, and heat energy metering fields.

5) As a real economy, technological innovation is the future development trend and driving force for meter enterprises

The Central Economic Work Conference proposed the "revitalizing the real economy" policy, with key points including: "Implementing innovation-driven development, promoting the vigorous development of strategic emerging industries while focusing on using new technologies and new business forms to comprehensively transform and upgrade traditional industries" and "Guiding enterprises to form their own unique comparative advantages, promoting the 'craftsman spirit,' strengthening brand building, cultivating more 'century-old shops,' and enhancing product competitiveness."

With the implementation of the "revitalizing the real economy" policy, it is expected that the state will provide preferential policies in terms of taxes, development funds, and product sales subsidies for innovative products.

In November 2016, the "China Smart Metering Industry Technology Innovation Strategic Alliance" was established in Beijing, led by China Electric Power Research Institute, and the "China Smart Metering Technology Forum" was held, which has enlightening significance for the development of the meter industry.

The forum introduced special reports representing new achievements in smart metering technology research in China in recent years, especially from the State Grid, including: "Current Status and Future of Metrology Science in China," "Overall Research on New Generation Electricity Information System Technology Architecture," "Application of Online Monitoring in Electric Energy Metering," "Integrating Power Cryptography Technology to Ensure Grid Communication Security," "Introduction to Intelligent Sensing Technology for Power Facilities," "Big Data-Based Collection Intelligent Operation and Maintenance

Technology," "Energy Efficiency Metering Promotes Green Development," "Enterprise Energy Comprehensive Management Technology," "Smart Metering Innovation and Development," "New Energy Metering Technology," "Smart Energy Solutions," and "Research on Smart Metering Products Complying with 'Industry 4.0' Intelligent Manufacturing."

Smart meter centralized bidding allows enterprises to focus on ensuring metering product quality. Due to stable markets and weak demand for new principle metering products, enterprises have developed. Facing the current new situation, meter enterprises need to deploy diversified technological innovation product development and cultivate new markets, but they appear to lack new product development and marketing strength. Therefore, meter enterprises need to concentrate efforts, increase investment in high-end development talent and funds, and carry out technological cooperation with universities and provincial grid metering centers that have development strength to conduct technological innovation product development and application in electricity, water, gas, and heat energy metering fields.

How can meter enterprises become "century-old shops"?

According to the requirements of the 2016 Central Economic Work Conference on "revitalizing the real economy," the key for meter enterprises is to transform their development philosophy from long-term reliance on low-technology product expansion and mergers to cultivating "craftsman spirit," focusing on brand building, and exploring high-end markets for technological innovation products in electricity, water, gas, and heat energy metering fields.

2. Adapting to High-End Technology Needs of Smart Distribution Network Construction: Promoting Industrialization of Intelligent (Advanced) Terminal Series Products for Distribution Transformer Areas

In 2016, the State Grid released the "Technical Specification for Intelligent Distribution Transformer Terminals (Draft for Comment)," indicating the trend of grid automation terminals developing toward intelligent terminals.

In 2016, the author published online articles: "Preliminary Exploration of Intelligent Electric Energy Metering System Technology (Third Edition)," "Further Discussion on Controversies and Development of Electricity, Water, Gas, and Heat 'Four-Meter Integration'—State Grid 'Four-Meter Integration' Collection: Adjusting Strategy, Moving Toward Great Harmony," and "Discussion on Development Challenges of Smart Meter and Communication New Products During the '13th Five-Year Plan' Period," proposing a batch of promising intelligent technology innovation product development topics for reference.

6) On meter enterprises becoming "century-old shops"

In the new year, facing the significant decline in smart meter bidding volume and temporarily weak demand for new principle meters, how can meter enterprises develop further? The author believes that while continuing to conscientiously handle the State Grid smart meter base market centralized bidding work, the main optional development paths are:

- Development of specialized small-batch products such as grid digital meters, DC meters, and user photovoltaic grid-connected monitoring management systems
- Exploring power user self-procurement markets, marketing traditional meter terminal products, statistical meters, and user internal power load and energy efficiency monitoring and control products

Comprehensive analysis shows:

- Meter enterprises expanding technological innovation product development and application have prospects
- Traditional meter terminals can be exported after technical improvements
- Enterprise transformation product development, including distribution equipment/systems and new energy products

The meter industry itself is currently experiencing a trough in traditional meter product market demand, with temporarily weak demand for new principle meters. Meter enterprises need to work hard on grid measurement technology innovation product development.

The water, gas, and heat energy metering fields urgently need industry integration modernization transformation to achieve comprehensive and balanced development of electricity, water, gas, and heat industry integration, thereby promoting smart city energy total control and balance, and loss management. Meanwhile, facing the technological innovation product development and application market in water, gas, and heat energy metering fields, meter enterprises need to explore and cultivate this new market.

Challenges for meter enterprises expanding technological innovation product development and application:

Since 2010, meter enterprises have mainly faced the State Grid and Southern Grid markets, taking shortcuts of OEM imitation or merging with other enterprises.

However, competition in these conventional industry markets is fierce with low prices, and expanding new users in batches is also difficult. Under the current new situation, according to the requirements of the Central Economic Work Conference to "revitalize the real economy" and "implement innovation-driven development," meter enterprises with economic and technical strength should focus on selecting the development of grid monitoring and control technology innovation products with long-term market prospects and certain development difficulty.

After summarizing and analyzing the development prospects of China's smart distribution network and the application of new technologies in the grid measurement and control field, the author proposes the topic "Adapting to High-End Technology Needs of Smart Distribution Network Construction: Promoting Industrialization Exploration of Intelligent (Advanced) Terminal Series Products for Distribution Transformer Areas" as a recommended key topic for the meter industry to expand technological innovation product development in the coming years.

Importance of new topic development for the long-term development of the meter industry:

1) Appropriate timing for creating new intelligent product industries

In recent years, the focus of State Grid's strong smart grid construction investment has been on UHV projects and the initial smart distribution network framework and master station reconstruction. Distribution transformer areas—from distribution transformer high-voltage terminals to user supply areas—consist of distribution transformers, smart meters, distribution monitoring and control terminals, low-voltage lines, and user-side equipment. Among these, distribution monitoring and control terminals (referred to as distribution terminals) are used in large quantities.

Existing distribution transformer area low-voltage grid operation index monitoring and control management, including low-voltage grid operation voltage, current and phase difference, active and reactive power, electric energy, power quality, and distribution transformer area line loss, are mainly conducted through online monitoring by smart meters and distribution terminals, with single-index automatic control, belonging to open-loop fixed-value management of low-voltage grid operation indicators.

Given that the State Grid is busy with high-voltage smart grid construction projects and distribution network framework master station reconstruction requires a long cycle, the meter industry's early entry into high-end technology development for low-voltage grid intelligence in distribution transformer areas will explore and pave the way for the development of smart distribution network user-side intelligence, accumulate experience, and cultivate a group of intelligent control technology development talents for the meter industry's long-term development, creating an intelligent product new industry.

2) Development of smart advanced application functions on the user side of distribution networks reflects technological innovation concepts

For a long time, the State Grid's distribution network technology has lagged behind and is a shortcoming, and is now concentrating efforts on supplementing distribution network standardization, framework master station reconstruction, and launching the distribution network intelligence process.

What is the goal of smart distribution network construction? So far, no systematic research report from the State Grid has been seen on this aspect. In September 2009, scholars from Tsinghua University proposed: "Smart grid refers to a grid with standardized access as the foundation, information sharing, intelligent decision-making, and comprehensive regulation as the main means, and has multi-index, self-optimization operation capabilities." In distribution transformer areas of distribution networks, this statement reflects power users' expectations for reliable and high-quality power while minimizing costs.

Facing the user side of distribution networks with thousands of households, how to improve the operation capability of distribution transformer areas and achieve high-end goals of multi-index and self-optimization? This is a difficult technological innovation problem.

As previously pointed out, the existing online monitoring and control system for distribution transformer areas belongs to open-loop fixed-value management of operation indicators, making it difficult to quickly achieve high-end goals of multi-index and self-optimization.

In 2015, the power industry standard "Technical Conditions for Intelligent Distribution Transformer Terminals (DL/T1442-2015)" was released, specifying that intelligent distribution transformer terminals need to integrate functions such as distribution transformer monitoring and protection, user electricity information monitoring, distribution transformer total meter monitoring, distribution equipment status monitoring, power load management, power quality management, line loss calculation, economic operation analysis, interactive management, and distributed power access—18 online monitoring and control functions in total. Particularly for power quality management, it requires "supporting hybrid mode of dynamic reactive power compensation and active filtering, performing rapid dynamic compensation for reactive power in distribution transformer areas, suppressing harmonics with changing frequency and magnitude, being able to track and compensate harmonics of rapidly changing loads, and managing three-phase load imbalance problems in transformer areas."

In 2016, the State Grid released the "Technical Specification for Intelligent Distribution Transformer Terminals (Draft for Comment)," proposing that intelligent distribution transformer areas should "achieve functions such as power distribution, power metering, reactive power compensation, and automatic measurement, collection, and monitoring of power supply and consumption information, with standardized, informatized, automated, and interactive intelligent characteristics."

"Intelligent distribution transformer terminals are secondary equipment integrating power supply and consumption information collection, equipment operation status monitoring, intelligent control, and communication functions."

In terms of adopting new communication technologies, the technical specification stipulates that the terminal remote communication interface should have Ethernet, 2G/3G/4G public network remote communication interfaces; the terminal local communication interface should have RS232/RS485 serial ports, Ethernet, broadband carrier communication interfaces, and micro-power wireless communication interfaces.

The functional requirements for intelligent distribution transformer terminals listed in this technical specification are basically the same as the power industry standard DL/T1442-2015, but are divided into basic functions and extended functions. The "power quality comprehensive management: supporting hybrid mode of dynamic reactive power compensation and active filtering" is listed as an extended function requirement.

The above successive intelligent distribution transformer terminal standards integrate numerous distribution transformer area operation indicators, adopt multiple modern communication methods, modular structure design, and have standardized, informatized, automated, and interactive intelligent characteristics, thus defining intelligent distribution transformer terminals. It should be noted that the focus of these intelligent distribution transformer terminal standards is to specify multi-index online monitoring and single-index automatic control requirements for distribution transformer areas. Power quality comprehensive management projects are listed as extended function requirements.

The "four modernizations" intelligent characteristics of the terminals basically conform to the characteristics of the State Grid's strong smart grid. However, there are still many differences from the high-end goals of multi-index, self-optimization for distribution transformer area operation and intelligent control technology routes, belonging to the primary stage of intelligent technology.

Before describing intelligent (advanced) terminals, three concepts need to be clarified:

Beijing University of Posts and Telecommunications' "Intelligent Information Technology" proposes:

- **Intelligent machine:** "A machine that can autonomously or interactively with operators perform various tasks usually requiring human completion in a specific environment."
- **Automatic control:** "The process of automatically operating or controlling machines or devices according to prescribed procedures."
- **Intelligent control:** "The process of driving intelligent machines to autonomously achieve their goals, or 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: organizing the actual environment or process, i.e., decision-making and planning." "Low-level control generally belongs to conventional control systems."

Intelligent (advanced) terminals for distribution transformer areas are intelligent machines with autonomous decision-making and planning/response functions

The low-voltage grid of distribution transformer areas uses intelligent (advanced) terminals to build multi-input multi-output (MIMO) intelligent control systems, i.e., to build low-voltage grid multi-index online monitoring and control compensation closed-loop optimization systems. According to fuzzy neural network algorithms, using information sharing, intelligent decision-making, and comprehensive regulation as means, through fast, repeated, and precise system operations, the high-end goal of multi-index, self-optimization operation of distribution transformer areas is achieved.

To expand the application fields of intelligent (advanced) terminals for distribution transformer areas, their intelligent advanced application functions are designed to:

- Improve multi-index, self-optimization operation capability of low-voltage grids in distribution transformer areas
- Autonomously handle emergency events on-site
- Multi-path optimization search
- Achieve interaction between distribution networks and users, i.e., having multi-communication method gateway functions

3) Long-term market prospects for intelligent (advanced) terminals in distribution transformer areas

Currently, the distribution terminals applied in State Grid distribution transformer areas mainly include four categories: public distribution transformer terminals, user dedicated transformer terminals, acquisition concentrators, and user power load management terminals, totaling about 12.8 million units. Among them:

- **Public distribution transformer terminals:** About 4 million units, including 1.4 million urban network 10kV public distribution transformer terminals and 2.6 million rural network 10kV public distribution transformer terminals, managed by grid power supply production departments.
- **User dedicated transformer terminals:** Estimated 4.7 million units, managed by grid marketing departments.
- **Acquisition concentrators:** About 3.2 million units after conversion, managed by grid marketing departments.
- **User power load management terminals:** Estimated 900,000 units, including 500,000 large industrial user power load management terminals and 400,000 other dedicated transformer user power load management terminals, managed by grid marketing departments.

[Note: Feeder terminals (FTU) and station monitoring terminals (DTU) for distribution networks are mainly used for distribution network framework safe operation management and are not discussed in this article.]

Expected demand for intelligent (advanced) terminal series products for distribution transformer areas:

- **Public distribution transformer terminals (4 million units):** With the advancement of State Grid smart distribution network user-side construction, if 50% of public distribution transformer terminals are replaced with intelligent (advanced) terminals, the State Grid will need 2 million units.

- **User dedicated transformer terminals (4.7 million units):** If 30% are replaced with intelligent (advanced) terminals, the State Grid will need 1.4 million units.

The above two items combined require 3.4 million intelligent (advanced) terminals for distribution transformer areas for State Grid smart distribution network user-side construction.

This article temporarily does not include acquisition concentrators and user power load management terminals in the expansion application scope of intelligent (advanced) terminals, requiring further demonstration.

Furthermore, the technological innovation concept and advanced application functions of intelligent (advanced) terminal series products for distribution transformer areas are suitable for expanding technological innovation product development and application in water, gas, and heat energy metering fields, which will be discussed in special topics in subsequent parts of this article.

3. Discussion on Preliminary Design Technology for Advanced Application Systems of Intelligent (Advanced) Terminals in Distribution Transformer Areas

As preliminary design for technological innovation products, this article collects and refines intelligent-related materials, focusing on describing the framework design and reference technology for using intelligent (advanced) terminals in distribution transformer areas to build multi-input multi-output (MIMO) online monitoring, control, and compensation closed-loop optimization systems for low-voltage grids in distribution transformer areas, providing references for the design of advanced application system solutions for intelligent (advanced) terminals in distribution transformer areas.

3.1 Optimization Control Theory: "Power Hybrid Control Theory"

Given that the advanced energy management system built by the "Power Hybrid Control Theory" proposed by Tsinghua University scholars has been applied in the Shanghai grid to solve multi-objective optimization control problems of large grids, reflecting technological innovation ideas, this article adopts "Power Hybrid Control Theory" as the design technology foundation for advanced application functions of intelligent (advanced) terminals.

The following content is excerpted from Tsinghua University scholars' "Smart Grid Foundation":

1. **Dominant idea of Power Hybrid Control Theory:** Classify and define all unsatisfactory requirements and states as events. Through control, the system is returned to an event-free operation state, then the system's

various indicators (stability, power quality, and economy) must be sufficiently satisfactory.

2. **Operation architecture of Power Hybrid Control Theory:** Composed of the highest decision-making command layer, middle processing and operation layer, and bottom layer (hybrid control instruction receiving and execution devices).
3. **This article uses set theory language from "Power Hybrid Control Theory" to describe the intelligent control process for distribution transformer area low-voltage grid operation to achieve multi-index, self-optimization:**

- **Equation (1):** $[\![MATH_1]\!]$
  Where operation index data d measured from the low-voltage grid, through logical judgment (logical function) $\hat{e}$, determines whether index anomalies form $e = \hat{e}d$.
- **Equation (2):** $[\![MATH_2]\!]$
  Where index anomaly events e, using logical function f, determine event types and convert them into control commands c.
- **Equation (3):** $[\![MATH_3]\!]$
  Where a control command set c, using logical function $\hat{f}$, is converted from commands to operation instruction set o.
- **Equation (4):** $[\![MATH_4]\!]$
  Where operation instruction set o is a composite logical function of index anomaly event set e.
- **Equation (5):** $[\![MATH_5]\!]$
  Where the entire low-voltage grid operation state x is controlled and can be changed to x^* through time-discrete operation instructions o.
- **Equation (6):** $[\![MATH_6]\!]$
  Where the result of operation instruction action a is to make index anomaly event set e become an empty set. Equation (6) means that distribution transformer area low-voltage grid has achieved the high-end goal of multi-index, self-optimization operation.

From the above, distribution transformer area low-voltage grid is always in the process of discovering, processing, and eliminating index anomaly events.

3.2 Assessment Indicators and Control Measures for Distribution Transformer Area Low-Voltage Grid Operation 1) Multi-index indicators mainly include: - Voltage and voltage qualification rate - Current and active power limits - Reactive power and power factor limits - Three-phase load imbalance degree - Voltage/current harmonic content rate - Line loss rate, etc.

2) Multi-index control means for low-voltage grids mainly include: - On-load tap-changing distribution transformers for voltage regulation - Capacitor compensation/dynamic reactive power compensation for regulating fundamental reactive power and power factor/voltage/line loss - On-load phase-changing load switches for regulating three-phase load imbalance - On-load capacity-changing distribution transformers for regulating line loss - Active power filters and fixed-order harmonic filters for regulating harmonic content rate, low power factor caused by distortion power, and voltage waveform distortion - High-voltage circuit breakers and power load management terminals for alarm and tripping when distribution transformers are overloaded

Thus, there are internal connections and mutual influences among power quality and economy indicators and their regulation means in low-voltage grid operation. When multi-indices exceed limits and require comprehensive regulation, weighted methods for each index need to be introduced.

"Smart Grid Foundation" points out: "Self-optimization means the grid has the ability to automatically maintain its state within a multi-index optimization state set during operation. Making grid operation state points achieve certain standards for various indicators, i.e., approaching the optimal state, is reasonable and possible. Multi-index optimization rather than multi-index optimum is due to calculation speed, solution difficulty, and other reasons."

3.3 Multi-Index Operation Optimization Model for Distribution Transformer Areas Referring to the "Multi-Objective Voltage Reactive Power Harmonic Optimization Algorithm" proposed by Hunan University scholars in "Design of Integrated Power Quality Control System with Harmonic Suppression Function," combined with multi-index operation conditions of distribution transformer areas, this article below will describe the design outline of the multi-index operation optimization model for distribution transformer areas.

This optimization system design, on the one hand, takes distribution transformer area operation reliability as the foundation, taking voltage and voltage qualification rate compliance, current and active power not exceeding limits, reactive power and power factor not exceeding limits, three-phase load imbalance not exceeding standards, harmonic content rate compliance, and line loss not exceeding limits as target requirements. Using optimization methods, the optimal solution of control parameters is obtained. On the other hand, taking on-load tap-changing distribution transformer tap adjustment amount, capacitor reactive power compensator/dynamic reactive power compensator compensation amount, on-load phase-changing load switch switching capability, active filter technology compensation amount, and on-load capacity-changing distribution transformer power adjustment amount as control variables, the distribution transformer area multi-index operation optimization model is established.

The distribution transformer area multi-index operation optimization model mainly includes the following components:

- **Reliability calculation method for this optimization system:** Joint probability density function calculation, taking the minimum value. This function equals the sum of the product of each target indicator and its weighting factor. The weighting factor value depends on the magnitude and importance of each target indicator.
- **On-load tap-changing distribution transformer tap voltage percentage adjustment range limits**
- **Capacitor reactive power compensation/dynamic reactive power compensation adjustment range limits**
- **On-load capacity-changing distribution transformer capacity adjustment range limits**
- **Active filter technology harmonic compensation range limits**
- **On-load phase-changing load switch current switching limits**

3.4 BP Neural Network Design Reference Technology Refined from Different Case Types This section summarizes "High-Precision Detection of Power Grid Based on Feedforward Neural Network" by Chongqing University and Chongqing Electric Power Research Institute, "Photovoltaic Grid-Connected Inverter Fault Diagnosis Based on Information Fusion" by Haihe University, "A Multi-Dimensional Influenced Operating Electric Energy Meter Performance Evaluation Method" by China Electric Power Research Institute, "Intelligent Information Technology" by Beijing University of Posts and Telecommunications, and arranges them as needed.

BP Feedforward Neural Network Working Process

Here, the BP feedforward neural networks in three reference cases all adopt a 3-layer topology of input layer, hidden layer, and output layer, with nodes in each layer interconnected according to certain rules.

"(BP) feedforward neural network uses the gradient descent method, consisting of two parts: information forward propagation and error backward propagation. During information forward propagation, input signals propagate layer by layer from the input layer through hidden units to the output layer. The state of neurons in each layer only affects the state of neurons in the next layer. If the expected output cannot be obtained in the output layer, it turns to error backward propagation, returning the error of the output signal along the original connection path. Using iterative operations to solve weights, by modifying the weights of neurons in each layer, the error signal is reduced until the expected target is reached. A 3-layer neural network with only one hidden layer, as long as there are enough hidden nodes, can approximate a nonlinear function with arbitrary precision."

BP Feedforward Neural Network Design Outline:

1. **Network input quantity normalization processing:** Input layer neurons (nodes) have a one-dimensional input, multi-dimensional output structure. Input quantities are low-voltage grid operation voltage, current, power, and other data. Normalization processing for each input quantity (calculation formula: omitted) can obtain the functional relationship between input layer elements, i.e., the function relationship between measured input values of input layer neurons (nodes) and normalized output values of input layer neurons (nodes).

2. **BP feedforward neural network parameter selection:** "When designing BP feedforward neural networks, consideration is generally given to three aspects: network layers, number of neurons (nodes) in each layer, and training functions."

   - **Determination of hidden layer node count:** "Hidden layer node count directly affects network capacity, generalization ability, learning speed, and output characteristics. Considering network capacity and function approximation universality, the more hidden units, the better. Considering network generalization ability, each additional layer will cause exponential increase in computing capacity, thus training time becomes longer, and it's easy to fall into local minima without obtaining the optimum." "Using least squares method to fit the hidden layer, the calculation formula for hidden layer node count is obtained":

     $[\![MATH_7]\!]$

     Hidden layer node count can also be calculated and selected by empirical formula:

     $[\![MATH_8]\!]$

     Where: m = input node count, n = output node count, a = optional number $(1 < a < 10)$

     For example, for intelligent (advanced) terminals in distribution transformer areas, both input nodes and output node count are taken as 6, and hidden layer node count is determined as 11.

   - **Determination of transfer functions and training functions:** Including hidden layer neuron (node) transfer functions: such as using S-shaped tangent function tansig; output layer neuron (node) transfer functions: such as using S-shaped logarithm function logsig; training functions: such as using trainlm function with LM (Levenberg-Marquardt) training rule. "LM algorithm combines gradient descent method and Gauss-Newton method, ensuring high stability and precision on the basis of fast convergence."

3. **Determination of learning samples and target samples:**

- Number of network input quantities and selection of data samples: (to be determined)
- Usually 40-200 groups of data samples are selected for training. Among them, 80% of data samples are randomly selected as training samples, and the remaining 20% are used for simulation verification of the trained BP feedforward neural network.

4. **Simulation testing:**

- On the built BP feedforward neural network, training is conducted with training samples, requiring setting training error and learning rate indicators, compiling network training learning flowcharts, and performing network initialization.
- "Using selected training samples to repeatedly act on the network, continuously adjusting network internal parameters to minimize network performance function, making the experimental standard deviation of network evaluation for training sample groups meet design precision requirements, thereby achieving nonlinear mapping between input and output and establishing functional relationships between network neurons (nodes)."
- After training, using the trained BP network to test test samples.

Reference materials: This article adopts the backpropagation (BP) learning algorithm. "BP algorithm is currently the most important learning algorithm. This algorithm developed after adding a hidden layer to perceptrons and using generalized specialized algorithms for learning." "In teacher-learning algorithms, teacher-learning problems can be solved in two steps: Step 1, specify network topology structure, the relationship between input X(t) and output y(t) must depend on a set of connection strength coefficients w, and w can be adjusted. Step 2, specify a learning rule, i.e., how to adjust w to make actual output $\hat{y}(t)$ as close as possible to expected output y(t)." "It should be noted here: feedforward network is a powerful learning system with simple structure and easy programming. From a system perspective, feedforward network is a static nonlinear mapping, and complex nonlinear processing capabilities can be obtained through composite mapping of simple nonlinear processing units. However, from a computational perspective, feedforward network is not a powerful computing system."

3.5 High-End Network: Fuzzy Neural Network This section is excerpted from "Intelligent Information Technology" and "Power Control Method for Photovoltaic Generation System Based on Fuzzy Neural Network" by Henan Pingdingshan Power Supply Company.

Neural networks are not suitable for expressing rule-based knowledge, and fuzzy logic systems lack self-learning and adaptive capabilities. Fuzzy neural networks absorb the advantages of fuzzy logic into neural networks, making them better networks.

Fuzzy neural network is a multi-input multi-output (MIMO) system.

1) Model: The fuzzy neural network here adopts a five-layer structure, with nodes in each layer interconnected according to certain rules.

- **Layer 1: Input layer.** Each node inputs each measured component and passes input values to the next layer.
- **Layer 2:** Each node represents a linguistic variable value, such as NB (negative big), PS (positive small), etc. Its function is to calculate the membership function of each input quantity belonging to each linguistic variable value fuzzy set. The total number of nodes in this layer is selected by calculation based on input quantity dimension and fuzzy partition number of input quantities (calculation formula: omitted).
- **Layer 3:** Each node represents a fuzzy rule, used to match fuzzy rule antecedents and calculate the fitness of each rule. The total number of nodes in this layer is selected by calculation (calculation formula: omitted). For given input quantities, only those linguistic variable values near the input quantities have larger membership degrees.
- **Layer 4:** Node count is the same as Layer 3. Its function is to implement normalized calculation of fitness for each fuzzy rule.
- **Layer 5: Output layer.** Implements defuzzification calculation (calculation formula: omitted).

2) Learning algorithm: "Fuzzy neural network model is essentially a multilayer feedforward network. The learning algorithm for adjusting parameters can be designed by imitating BP network error backpropagation method. It is assumed that the fuzzy partition number of each input component is predetermined, and the parameters that need to be learned are mainly the connection strength of the last layer and the center value and width of the membership function of the second layer."

3) Reference case: "Power Control Method for Photovoltaic Generation System Based on Fuzzy Neural Power Network"

"Probabilistic fuzzy neural network controller (used to) obtain active and reactive current reference values injected into the grid by three-phase inverters."

The probabilistic fuzzy neural network controller includes a 6-layer network structure: "Layer 1 is input layer, Layer 2 is membership degree layer, Layer 3 is probability layer, Layer 4 is TSK fuzzy inference mechanism layer, Layer 5 is rule layer, Layer 6 is output layer." Among them, input layer nodes are 2, output layer nodes are 1. "In the membership degree layer, each node uses asymmetric Gaussian functions to implement fuzzification operations." "Probabilistic fuzzy neural network controller (adopts) error backward propagation learning algorithm mechanism, constructing a gradient vector where each element is the first-order differential of energy function relative to algorithm parameters, thereby completing online self-tuning of probabilistic fuzzy neural network parameters."

4) Given that there are few reported application cases of multi-input multi-output (MIMO) fuzzy neural networks in grid measurement and control fields, how to apply fuzzy neural network technology to the design technology exploration of advanced application systems for intelligent (advanced) terminals in distribution transformer areas is a topic requiring further research.

3.6 Reference New Technologies for Intelligent (Advanced) Terminal Design in Distribution Transformer Areas

- **Integrated Distribution Terminal Unit (IDU) for Distribution Network Waveform-Level Real-Time Monitoring**

  Reportedly, on January 3, 2017, the first domestic integrated distribution terminal unit (IDU) was put into operation in Xiamen Torch High-tech Zone.

  "Integrated Distribution Terminal Unit (IDU) is a key complete set of devices for the national 863 project 'Active Distribution Network Key Technology Research and Demonstration.' It mainly achieves precise monitoring of distribution network power flow through high-speed synchronous phasor measurement, online monitoring and prevention of line potential faults, supports situation awareness of power supply capacity and load, and provides rich data for instantaneous profile state estimation, power quality optimization, and harmonic management of distribution networks, effectively improving distribution network observability, measurability, and controllability."

- **"Design of Adaptive Load Type Distribution Transformer" (China Electric Power Research Institute)**

  "The structure of adaptive load type distribution transformer includes distribution transformer main body unit, on-load capacity and voltage regulation integrated unit, supporting equipment unit, and integrated control unit."

  This new type of distribution transformer "can automatically adjust distribution transformer tap and capacity operation mode according to system voltage and load actual conditions without cutting off load, and has online load phase-changing and phase-separated reactive power compensation functions, effectively solving serious three-phase load imbalance problems and ensuring timeliness and accuracy of voltage and capacity determination."

- **Fuzzy PI Controller**

  "Design of Intelligent Controller for HVDC Transmission" by Northeast Electric Power University

  PI (Proportional Integral) controller

Fuzzy PI controller input: the difference between current reference value and measured current as "deviation" and "deviation change" → fuzzy inference unit (calculates and outputs correction amounts for two PI controller parameters that can be automatically adjusted according to fuzzy control rules) → PI controller unit (outputs adjustment commands) → trigger unit → controlled object → measured current (feedback to fuzzy PI controller input).

"The following rules can be selected for fuzzy adjustment:"

- "If steady-state deviation is large, then increase proportional coefficient"
- "If response oscillates, then increase differential coefficient"
- "If response is slow, then increase proportional coefficient"
- "If steady-state deviation is too large, then adjust integral coefficient"
- "If overshoot is too large, then reduce proportional coefficient"

Advantages of fuzzy PI controller: "When controlled object parameters or operation conditions change, it can automatically adjust PI parameters online to achieve intelligent control."

- **Integrated Power Quality Control System**

  "Design of Integrated Power Quality Control System with Harmonic Suppression Function" by Hunan University scholars

  This integrated power quality control (regulation) device consists of on-load tap-changing transformers, parallel compensation capacitor banks, and injection-type parallel active power filters (HAPF).

  The system adopts optimization algorithms for multi-objective voltage, reactive power, line loss, and harmonic functions and their weighting factors, optimizing the system globally.

  This new product "integrates measurement, protection, control, fault recording, power quality monitoring, distribution transformer monitoring, load management, and communication functions. Product functions are internationally leading, with no similar products domestically or internationally."

  This new product "adopts plug-in structure, 'three-stage protection function,' 'integrated current transformer for measurement and protection,' and 'circuit breaker that can be verified on calibration platforms.'"

  Main technical indicators of this new product:

  - Rated voltage: AC 400V
  - Rated current: 250A, 400A, 630A
  - Rated operating short-circuit breaking capacity: 42.5kA

Note: The above describes the preliminary design technology for the first advanced application function of intelligent (advanced) terminals in distribution transformer areas. The preliminary design technologies for the remaining three advanced application functions—“autonomously handling emergency events on-site,” “multi-path optimization search,” and “achieving interaction between distribution networks and users, i.e., having multi-communication method gateway functions”—will be published in separate articles by the author.

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