Industrialization Exploration of Low-Voltage Power Line Carrier Automatic Meter Reading Systems

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Date: 2024-01-28T00:00:00+00:00

Abstract

We primarily discussed the emerging demand and application status of low-voltage power line carrier automatic meter reading systems (low-voltage PLC AMR). First, we analyzed the factors driving the market demand growth for low-voltage PLC AMR, including power management requirements, strategic risk response, and guaranteed project funding. Regarding power management requirements, automatic meter reading systems constitute a critical component of modernization, standardization, and refined management, while low-voltage PLC AMR represents an effective solution to the challenges of automatic meter reading in low-voltage power grids. In terms of risk response, suppliers have established a foundation in key technology research and fault handling capabilities, formulated relevant standards, and possess short-range, wireless, self-organizing network automatic meter reading systems as technical supplements. Concerning project funding, power grid construction and technical transformation enjoy sufficient funding, with the capital requirements for low-voltage PLC AMR being relatively modest. Regarding application status, the estimated number of carrier energy meters nationwide is 9 million, accounting for 85% of terminals in low-voltage power grid local automatic meter reading systems. Among these, the application of low-voltage PLC AMR has achieved several significant accomplishments. Certain companies have independently developed carrier communication chips and system solutions, enhancing technical performance and first-read success rates. Simultaneously, multiple system solutions have been provided according to the requirements of different regions. Additionally, certain companies have developed System-on-Chip (SOC) carrier communication chips employing BPSK modulation and the OSI seven-layer protocol model, featuring automatic routing algorithms and dedicated network management functions. However, low-voltage PLC AMR still faces certain issues, such as unstable first-read success rates and relatively high system construction costs. Furthermore, several technical problems require resolution during system construction

and operation, including carrier communication interference and communication protocol standardization. Therefore, further advancement of the industrialization development of low-voltage PLC AMR is necessary, with strengthened technology R&D and standardization efforts to improve system performance and stability while reducing construction and operational costs. In summary, low-voltage PLC AMR possesses advantages in power management, technology, risk response, and funding guarantee, with market demand gradually emerging. As technology continues to improve and application experience accumulates, the application prospects for low-voltage PLC AMR will become even broader.

Full Text

Exploration of Industrialization of Low-Voltage Power Line Carrier Automatic Meter Reading Systems

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Abstract

This paper examines the emerging demand and current application status of low-voltage power line carrier automatic meter reading (low-voltage PLC AMR) systems. We first analyze the key factors driving market demand growth: power management requirements, risk mitigation strategies, and secure project funding. Regarding power management needs, automatic meter reading systems constitute a critical component of modern, standardized, and refined management practices, with low-voltage PLC AMR offering an effective solution to the challenges of automatic meter reading in low-voltage power grids. In terms of risk management, suppliers have established foundational research in key technologies and fault handling capabilities, formulated relevant standards, and developed short-range wireless ad hoc network AMR systems as technical supplements. For project funding, while grid construction and technical transformation enjoy ample capital, the financial requirements for low-voltage PLC AMR remain relatively modest.

In application status, national carrier energy meter installations are estimated at 9 million units, representing 85% of terminals in low-voltage grid local automatic meter reading systems. The application of low-voltage PLC AMR has achieved several significant accomplishments. Some companies have independently developed carrier communication chips and system solutions, improving technical performance and first-attempt meter reading success rates. Additionally, multiple system solutions have been provided according to regional requirements. Furthermore, some companies have developed System-on-Chip (SOC) carrier communication chips employing BPSK modulation and OSI seven-layer protocol models, featuring automatic routing algorithms and dedicated network management functions. However, low-voltage PLC AMR still faces challenges, including unstable first-attempt meter reading success rates and high system construction costs. Moreover, several technical issues must be addressed during system construction and operation, such as carrier communication interference and communication protocol standardization. Therefore, further advancement of low-voltage PLC AMR industrialization is necessary, requiring strengthened R&D and standardization efforts to improve system performance and stability while reducing construction and operational costs. In summary, low-voltage PLC AMR demonstrates advantages in power management, technology, risk response, and financial security, with market demand gradually emerging. As technology continuously improves and application experience accumulates, the prospects for low-voltage PLC AMR applications will become increasingly broad.

Keywords: Low-voltage power line carrier; Automatic meter reading; CLC number: TM933.4

Entering 2007, the energy meter industry presented a bustling scene of thriving markets and technologies. The main product hotspots included three categories: automatic meter reading and terminals, three-phase energy meters, and innovative contactless energy meters and high-voltage sensor-based meters employing novel energy measurement methods. Among these, demand for low-voltage power line carrier automatic meter reading systems (hereinafter referred to as low-voltage PLC AMR) has surged prominently, with new rounds of construction launching in Heilongjiang in the north, Guangdong in the south, and provinces including Shaanxi, Guangxi, Hebei, and Tianjin. The estimated 2007 investment reaches 700 million yuan, with demand for 2.4 million carrier energy meters.

Domestically, low-voltage PLC AMR has experienced a decade-long 曲折 development process, representing a massive energy meter project that is controversial, risky, yet promising. Facing this new wave, the energy meter industry must take a long-term perspective. In this intense market competition, most large-scale meter enterprises occupy a passive technological position, with key system technologies still lacking. They must seize business opportunities to advance the industrialization of low-voltage PLC AMR.

Based on this consideration, after compiling and researching recent domestic journal articles and diverse information regarding low-voltage PLC AMR with carrier frequencies of 3-500 kHz, this paper will discuss the factors driving this new round of system demand, current application status, existing problems, international experiences, and explore approaches for system industrialization.

1. Why is Demand for Low-Voltage PLC AMR Surging?

In recent years, opinions on low-voltage PLC AMR construction and application have varied. What factors, then, are driving this market surge? Through observation and analysis, we identify the following:

1.1 Power Management Requirements

1) Addressing Weak Links in Power Marketing Management and First-Class Construction

In recent years, power grids have developed rapidly, with comprehensive modernization, standardization, and refined management implementation. Automatic meter reading networks have attracted significant attention as a component of modernized power marketing management. While power plants' grid-connected electricity has long been remotely and automatically read through grid energy measurement and billing systems, and large customers have gradually established remote wireless automatic meter reading systems, automatic meter reading in low-voltage grids remains problematic. Resident energy meters—accounting for 90% of total grid meters—and three-phase meters within public distribution transformer supply areas still rely primarily on manual reading. Although some power supply companies have conducted low-voltage PLC AMR pilots, no reports of complete, large-scale resident electricity automatic meter reading systems have emerged.

2) Urgent Need to Strengthen Grid Line Loss Rate Management

In 2005, the grid line loss rate reached 7.18%, with annual energy losses of 154.9 billion kWh—equivalent to the annual electricity consumption of a major consumption province. Traditional line loss rates are monthly averages, with manual reading making index fluctuations difficult to explain. Recently, Heilongjiang Power established a provincial grid line loss comprehensive daily management system, achieving daily electricity statistics, daily busbar balancing, and daily loss analysis, with obvious line loss reduction effects. The Suihua regional power authority in that province proposed integrating massive data collected at 15-minute intervals. It can be said that with manual reading methods, even current low-voltage PLC AMR systems struggle to meet the 15-minute reading cycle requirement for resident electricity.

3) Alleviating Staffing Shortages Caused by Manual Meter Reading

Since the implementation of the one-meter-per-household project in 1999, directly managed users in State Grid and Southern Grid supply areas increased from approximately 20 million to 167 million by 2006. Based on current manual reading capacity averaging 10,000 meters per month per person , staffing would need to increase eightfold, yet power departments are implementing personnel reduction policies.

4) Expanding Value-Added Services in Future Power Marketing Management

The domestic understanding of Enel, Italy's largest power company, is relatively comprehensive. In 2006, Enel built the world's largest automatic meter management system, embedding value-added service functions to meet market liberalization challenges, with plans to become Europe's most efficient power company.

1.2 Risk Mitigation Strategies

1) After years of exploration, both Heilongjiang and Guangdong provinces have accumulated management and operational experience with low-voltage PLC AMR systems exceeding 100,000 households.

2) Low-voltage PLC AMR solution suppliers have established key technology research foundations and multi-year fault handling capabilities.

3) Heilongjiang Power has formulated the "Electric Energy Information Acquisition and Management System" series standards, with over 40 experts from the National Electrical Instrument Standardization Committee, power departments, and meter enterprises participating in development, summarizing experience, compiling information, and pooling collective wisdom.

4) Recently, short-range wireless ad hoc network automatic meter reading systems have achieved preliminary trial results in Xinjiang, with a 99.5% first-attempt meter reading success rate, serving as a technical supplement for low-voltage PLC AMR blind spots.

1.3 Project Funding Security

In recent years, power grids have continuously improved management, with growing corporate profits. In 2007, the two major grids' estimated investment in grid construction and technical transformation exceeds 300 billion yuan. This new round of low-voltage PLC AMR funding requirements represents only 0.23% of total grid development investment.

In summary, the combination of demand, strategy, and funding propels the surge in low-voltage PLC AMR demand.

2. Application Status of Low-Voltage PLC AMR

Currently, national carrier energy meter installations are estimated at 9 million units, accounting for 85% of terminals in low-voltage grid local automatic meter reading systems.

2.1 Major Recent Achievements

1) Independent Development of Carrier Communication Chips and System Solutions with Continuously Improving Technical Perfor-

mance and First-Attempt Meter Reading Success Rates Reaching 90%

- *Qingdao Company Carrier Communication Chip:* Employs baseband spread spectrum technology, BFSK modulation, embedded fuzzy recognition, fuzzy control, and modern digital signal processing technologies, high-efficiency forward error correction, programmable network addresses, and frame relay forwarding support, with maximum relay depth of 7 levels. The DLL protocol is based on HDLC specifications with a code rate of 20.8 kbps. The company independently developed concentrators and routing/relay algorithms, providing multiple system solutions according to different power company requirements.
- *Shenzhen Company Intelligent Network Control (SOC) Carrier Communication Chip:* Employs BPSK modulation; designed according to EIA709.1 and EIA709.2 power line transceiver module protocol standards; adopts OSI seven-layer protocol model; independently designed automatic routing algorithms and dedicated network management commands to complete self-organizing network and adaptive network management tasks for entire automatic meter reading systems; the physical layer can provide quantitative received signal SNR, maintaining automatic communication even under high impulse interference and 1 mV received signal strength, with data rate of 5.5 kbps.

For concentrators: The central master station system communicates with concentrators via GPRS, CDMA, PSTN, broadband network, and other physical channels; the logical layer employs TCP/IP communication protocols; concentrators and meters use EIA709.1 protocol; maximum meter reading capacity is 1,000 units.

2) Network Routing and Relay Algorithm Research Achieving Certain Results
Recent domestic journal articles have reported information in this area, with some algorithms already applied to carrier communication chip design: - "Analysis of Low-Voltage PLC Network Structure" - "Automatic Routing Technology for Low-Voltage PLC AMR Based on EIA7091 Protocol" - "Development and Characteristics of SOC-Based Carrier Energy Meters" - "Application of Topology Relay Technology in AMR"

3) Research Achievements in Low-Voltage PLC Channel Characteristics and Simulation Platform Design
According to domestic journal articles, major works include: - "Power Line Channel Analysis and Modeling" - "Design of Low-Voltage PLC Channel Simulation Platform" - "Anti-Interference Issues in Low-Voltage PLC" - "Research on Low-Voltage PLC Channel Characteristics and Novel Modulation/Demodulation Algorithms"

4) Low-Voltage PLC AMR Employing LonWorks Distributed Networks

Developed by a Wenzhou company and currently in large-scale trial stages, this system employs self-organizing, dual-band automatic frequency hopping technology with comprehensive network listening mechanisms to select appropriate timing and frequency bands. A power line node includes: power line carrier modem chip, neuron chip, coupling circuit, and power supply. Using LonTalk open protocols with relay functionality, the system achieves 2.5 kbps data rates.

5) Cross-Distribution Transformer Area Data Communication
Research by a Nanjing university employs router technology to enable signal communication between two independent distribution transformers, achieving cross-transformer automatic meter reading.

6) Completion of "Electric Energy Information Acquisition and Management System Low-Voltage PLC Protocol Set" by Heilongjiang Power
Meanwhile, the Standardization Administration of China (SAC) has formally adopted American control network standards ANSI/CEA709 and ANSI/CEA852 as GB/Z 20177-2006, establishing LonWorks technology as Chinese national standardization guidance documentation, which will advance low-voltage PLC AMR industrialization.

2.2 Major Existing Problems

Currently, low-voltage PLC AMR suffers from low real-time performance and insufficient first-attempt meter reading success rates, requiring relaxation to 24-hour cycles to achieve 100% customer reading, which has impacted broader PLC AMR applications.

1) Multi-faceted Grid Issues - Lack of in-depth, specific research on low-voltage grid topology structures, preventing the provision of provincial, prefecture-level city, and county-level low-voltage grid topology diagrams and mathematical models. - Absence of standardized interference signal monitoring: - Excessive interference signals: testing by a Beijing company revealed maximum interference reaching 120 dB microvolts. - Household appliances introducing severe high-frequency, low-frequency interference and harmonic current pollution. - Excessive carrier signal attenuation: - For a 315 kVA distribution transformer, full-load per-phase load impedance is only 0.46 ohms, with numerous power factor compensation capacitors connected to the distribution network. - T-type connection joints in distribution lines also cause problems, with poor contact creating significant carrier signal attenuation. - No large-scale sampling tests conducted for low-voltage grid carrier signal and interference signal testing, nor any institutions established for testing services.

2) System Technical Challenges and Lagging Communication Protocol Research - Communication Network Collision Detection: Domestic journal articles note that due to limited communication distances, long-distance meter reading on the same power line phase relies solely on relaying, causing bus splitting that leads to collision detection misjudgment. Given the complexity and time-varying nature of low-voltage PLC networks, simple CSMA multiple access protocols are insufficient; special multiple access protocols should be employed, such as MACA, MACAW, or simpler ALOHA protocol variants. Communication network collision detection belongs to the medium access control sublayer of the data link layer. Currently, domestic automatic meter reading communication protocols lack corresponding research and specifications.

- **Insufficient Depth in Network Routing and Relay Algorithm Research:** Currently, after implementing routing and relay algorithms, low-voltage PLC AMR achieves average first-attempt meter reading success rates of 80-85%, with maximum rates reaching 90%. Domestic journal articles indicate that the EIA709.1 protocol network layer provides multiple network addressing methods, handling packet delivery within a region including unicast, multicast, and broadcast, providing destination addressing, address resolution, packet routing, and other network services to complete automatic forwarding functions. Domestic automatic meter reading communication protocols currently employ three-layer protocols: physical layer, data link layer, and application layer. It should be noted that research talent in network routing and relay algorithms is currently insufficient. Due to intellectual property protection issues, corresponding algorithm information is difficult to obtain from international and domestic technical literature.
- **Duplicate Packet Detection Function:** Domestic journal articles note that the transport layer of the EIA709.1 protocol includes a transaction control sublayer providing duplicate packet detection functionality, enabling target nodes to process data packets most efficiently by discarding duplicates. Domestic automatic meter reading protocols lack transport layer protocol specifications in the OSI seven-layer protocol model.
- **IEC62056 and DL/T645 Protocols:** The new round of systems employs IEC62056 for upstream concentrator protocols and DL/T645 for downstream protocols:
  - *IEC62056:* According to online reports, Heilongjiang Power's "Electric Energy Information Acquisition and Management System adopts the IEC62056 international standard system, with advanced design concepts, complete architecture, and clear objectives, featuring standardization, openness, and advancement, filling domestic gaps in this field." Domestic research on the IEC62056 standard series has spanned approximately five years, with preliminary achievements in translation and trial application. Current priorities include accelerating IEC62056 standard conversion to national standards for publication and implementation, and importing complete test software from the DLMS Association to verify the accuracy of domestic translation and trial applications, striving for DLMS Association recognition of upstream concentrator protocols.
  - *DL/T645:* Recently, the revised draft of DL/T645 has passed review

by the Electric Power Industry Electric Measurement Standardization Committee. The revision significantly expands multifunction meter data identification codes from the original two-byte four-field structure to four-byte eight-field structure. Data identification content has increased data freezing, load curves, and definitions for copper and iron loss algorithms, basically satisfying current and appropriately forward-looking development needs. This concentrator downstream protocol design must account for DL/T645 content modifications and additions, leaving room for software expansion.

3) System Design Controversies - Communication Mode Selection: Domestic low-voltage PLC AMR employs point-to-point, point-to-multipoint, and distributed network communication modes—will network control technology become the design trend for carrier communication chips? - **Narrowband vs. Broadband Communication:** While narrowband suffers from more interference, broadband offers advantages; however, low-voltage PLC quality factors decrease with bandwidth, and strong interference frequently causes interruptions when frequency bands are similar. - **Conflict Between Meter Reading Time and Relay Path Learning:** Accurate relay path identification within limited time requires adaptive path or neural network relay technologies. - **Relationship Between Communication Performance and Cost:** Carrier signal access sensitivity is limited by cost. Some imported carrier communication chips integrate DSP and high-bit A/D converters, providing higher reception sensitivity. - **Hardware Selection for Concentrators and Carrier Energy Meters:** Due to functional differences and significant performance variations, hardware optimization design is required, though current design specifications are lacking.

4) System Technology Gaps
Beyond the aforementioned grid issues, communication protocol lags, and system design controversies, low-voltage PLC AMR technology also suffers from technical gaps including system design standards and test methods, carrier communication simulation networks, design specifications for carrier communication chips, concentrators, and carrier energy meters, and system engineering design and management guidelines—all critical aspects for future system industrialization.

3. Enel's Automatic Meter Management Solution

Enel's automatic meter management solution employs low-voltage PLC AMR for local meter reading.

3.1 System Scale

The system serves 30 million users, utilizing 360,000 concentrators, with total investment of 2 billion euros, five meter integration factories, and 50 meter component suppliers.

3.2 System Component Characteristics

1) Remote Control Carrier Energy Meters: Class 2 accuracy, lifespan exceeding 15 years, built-in circuit breakers, equipped with self-diagnostic systems, and failure rates below 0.3%. Products are globally tendered.

2) Concentrators: Concentrator-to-meter communication uses low-voltage PLC with primary carrier frequency of 82 kHz and secondary carrier frequency of 75 kHz, FSK modulation, and 2,400 bps data rate.

3) Modems: Employing TCP/IP protocols, modems transmit data collected by concentrators to central master station systems via public communication networks (GSM, ISDN, etc.).

3.3 System Application Status

Building upon traditional AMR, the system adds new remote customer management and potential value-added service functions. In 2006, Enel's automatic meter management system achieved:

1) Remote reading of 160 million energy meters, averaging 13 million meters monthly .
2) Remote execution of 6 million technical and commercial operations.
3) Implementation of six new hourly-based tariff schemes, with 1.5 million users selecting new tariff standards, reducing peak electricity consumption and costs.
4) 2 million remote operations on delinquent customers, reducing power supply by 90% to provide only essential electricity (e.g., lighting, one appliance).
5) Uploading 15-minute interval load curves for customers. According to Italian law, customer bills must be based on load curves. By the end of 2007, Enel will integrate customers to launch specific tariff standards based on consumption patterns.
6) Fraud detection and energy balancing: installing total energy meters on distribution transformers to monitor total electricity consumption.

3.4 Observations on Enel System Trends

1) Enel's Strategy: Enel is "industrializing" its intellectual property through partnership with IBM to launch automatic meter management systems for global utilities.

2) Enel's Field Testing Experience: Enel can provide unique global testing capabilities to assess new development requirements and monitor product quality. At system engineering launch, Enel's testing subsidiary conducted low-voltage grid field tests to reproduce typical noisy grid environments, connecting 1,000 energy meters with over 3,000 residential and small business electrical appliances in daily operation. Currently, the company tests new household appliance products and new energy meter and concentrator models to verify system communication reliability.

3) Enel's Cost Reduction Achievements: Enel saves 400 million euros annually through the system.

4) Enel's Value-Added Services: Enel has begun developing metering service networks to provide customers with new value-added services.

5) Technical Note: Enel's low-voltage PLC AMR employs LonWorks control network standards as core system technology. Given the complexity and time-varying nature of China's low-voltage grids, LonWorks technology application remains in initial stages with insufficient experience, requiring attention and practical application assessment.

6) Enel's System and China: Since system engineering launch, Enel has prioritized China's vast potential power market: - In May 2001, Enel held discussions with China's former State Power Corporation, introducing Enel's automatic meter management system and discussing market entry strategies. - In May 2003, Echelon Corporation, inventor and technology platform provider of LonWorks technology, introduced Enel's automatic meter management system engineering progress at the Shanghai International Metering Exhibition. - Approximately in 2002 and 2005, a Shenzhen company produced approximately 7 million uniformly designed carrier energy meters for Enel. - In 2004, domestic journals published "Progress in Italy's Enel Telege Store Project." - In 2005, domestic journals published "The World's Largest AMM Project." - In 2007, the Shanghai International Metering Exhibition provided materials on "Enel Facing the Future: Automatic Meter Management Solutions."

4. Industrialization Exploration of Low-Voltage PLC AMR

4.1 Industrialization Prospects

1) In 2006, China's urban residents reached 164 million households, with existing local automatic meter reading coverage at 6.45%, indicating substantial potential market capacity for low-voltage PLC AMR.

2) The 2007 new round of low-voltage PLC AMR construction has attracted widespread attention. If expanded trials prove successful, annual grid investment could reach 1.5 billion yuan in coming years, requiring 5 million carrier energy meters . Heilongjiang Power has decided to invest funds during the 11th Five-Year Plan period to complete province-wide unified electric energy information acquisition and management system construction within three years.

4.2 Industrialization Requirements

Basic conditions for low-voltage PLC AMR industrialization include: 1) Substantial application demand and promising market prospects. 2) Complete system product series standards enabling product interchangeability and interconnectivity. 3) Independent development of core system technologies. 4) High production automation levels with good product consistency. 5) Established product quality assurance systems with low annual failure rates. 6) High-level product after-sales service. 7) Product development human resources adapting to industrialization development requirements.

4.3 Industrialization Content

1) First-Step Industrialization Targets (Recommended): - Annual production of approximately 5 million carrier energy meters within three years. - Average first-attempt meter reading success rate increased to 85-90%, with maximum rates reaching 95%. - For residential areas with 1,000-meter reading capacity, complete one round of polling within 40 minutes. - Carrier energy meter annual failure rate below 0.3%. - Concentrator operational reliability: (omitted)

2) Grid and Testing Technology Research: - Typical Topology Structure Diagrams: - Three-phase meter location topology diagrams within public distribution transformer supply areas. - Energy meter location topology diagrams within residential areas. - **Power Line Parameters:** - Low-voltage cable distribution, length, and service life. - Overhead line distribution, length, and service life. - Low-voltage compensation capacitors. - **Customer Electricity Information:** - Energy meter access system diagrams. - Household appliance and lighting types, power ratings, power supply structures, and service life. - Typical customer electricity consumption curves. - **Low-Voltage Grid Testing:** - Low-voltage line voltage curves, per-phase voltage drop, equivalent impedance. - Distribution transformer three-phase power imbalance, 24-hour load coincidence factor, peak power load, high-frequency and low-frequency interference signal amplitude and direction. - Voltage and current harmonic content. - Carrier signal attenuation conditions.

3) Low-Voltage PLC AMR Standard Series: - Product Technical Specifications: - System and master station technical requirements and test methods. - Concentrator technical requirements and test methods. - Carrier energy meter technical requirements and test methods. - Carrier communication chip technical requirements and test methods. - **Communication Protocols:** - Concentrator upstream protocols and test methods. - Concentrator downstream protocols and test methods. - Concentrator internal software system test methods. - Carrier energy meter internal software system test methods. - **Design Specifications:** - Concentrator hardware and software design specifications. - Carrier energy meter hardware and software design specifications. - System engineering design and acceptance specifications. - **Quality Testing:** - Carrier communication simulation network technical conditions and test methods. - Concentrator quality test methods. - Carrier energy meter quality test methods.

4) Key Technology Research: - Carrier signal collision detection algorithms and related communication protocols. - Topology-based routing and relay algorithms and related communication protocols. - Communication chip design employing new carrier communication technology achievements. - Research on low-voltage grid parameter and information test methods and instrumentation. - System master station test methods and instrumentation research.

5) Carrier Communication Simulation Network: - Simulation Network Test Objects: - Topology structure changes. - Communication range testing, meter reading bus splitting effects. - Communication rate effects. - Carrier signal reception sensitivity and interference testing. - Signal attenuation conditions. - Communication direction irreversibility degree. - Cross-phase signal effects. - Relay depth testing. - **Simulation Network Capacity (Three Grades):** - 1,200 energy meters, 6,000 household appliances and office automation equipment. - 800 energy meters, 4,000 household appliances and office automation equipment. - 400 energy meters, 2,000 household appliances and office automation equipment. - **Outdoor Simulation Network Structure:** - Simulation network ends must be isolated from low-voltage grids to purify test environments. - Simulation networks consist of overhead lines, low-voltage cables, energy meters, and household appliances/office automation equipment. - Simulation signals: carrier frequency band 3-500 kHz, interference signals up to 120 dB microvolts. - **Residential Area Grid as Simulation Network:** Selected residential areas must have certain scales with typical low-voltage grid topology structures.

6) Industrialization Planning: (omitted)

4.4 Establishing a PLC AMR Technology Cooperation Organization

The cooperation organization's purpose is to unite and leverage existing carrier communication chip and system solution suppliers and universities' technological leadership, domestic large-scale meter enterprises' financial and human resources, and power departments' grid resource advantages and AMR operational experience to expand and deepen the low-voltage PLC AMR industry toward internationalization. Primary tasks include:

1) Organizing the formulation of PLC AMR industry standard series.
2) Organizing market demand surveys for low-voltage PLC AMR and testing typical low-voltage grid parameters and information.
3) Accelerating key technology and priority project development, including high-speed PLC technology research with carrier frequencies of 10 MHz and above.
4) Organizing carrier energy meter quality testing, formulating new product technical specifications, and developing new products.

5) Organizing new product pilots in large residential areas of key cities to provide design improvement basis.
6) Organizing low-voltage PLC AMR technology and operational experience exchanges and industrialization planning formulation.

Finally, it should be noted that high-speed PLC technology commercialization for low-voltage grids represents an international hotspot. Domestic high-speed PLC technology research has been ongoing for many years and is entering grid trials. Due to space limitations, this aspect will not be discussed further.

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