

## Research on Modular Design of Three-Phase Smart IoT Electricity Meters

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### Abstract

This paper introduces the general technical specifications and modular design requirements for three-phase smart IoT electricity meters. The three-phase smart IoT electricity meter consists of a metering module, a management module, and expansion modules, featuring multiple functions and adapting to IoT requirements. This specification integrates the requirements of IEC electricity meter standards, the 2013 edition of State Grid smart meter technical and functional standards, and IR46 standards, and introduces modular design. The modular design enables the meter to expand functions on demand, improving flexibility and maintainability. Among them, the metering module possesses legal metrology capability and can operate independently, while the management module is responsible for user interface and communication functions. This paper provides a technical foundation and design guidance for the promotion, application, and long-term development of three-phase smart IoT electricity meters.

### Full Text

## Research on the Modular Design of Three-Phase Intelligent IoT Meters

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### Abstract

This paper introduces the general technical specifications and modular design requirements for three-phase intelligent IoT electricity meters. These meters consist of a metering module, a management module, and expansion modules,

offering diverse functions adapted to IoT applications. The specifications integrate requirements from IEC electricity meter standards, the 2013 State Grid smart meter technical and functional standards, and the IR46 standard, while introducing modular design principles. This modular approach enables functional expansion on demand, enhancing flexibility and maintainability. The metering module possesses legal metrology capabilities and can operate independently, while the management module handles user interface and communication functions. This work provides a technical foundation and design guidance for the widespread adoption and long-term development of three-phase intelligent IoT meters.

**Keywords:** three-phase intelligent IoT meter, modular design, expansion modules

On August 19, 2020, the State Grid Corporation of China released six volumes of general technical specifications for single/three-phase intelligent IoT meters and two volumes for single/three-phase smart meters (2020 edition). Among these, the general technical specification for three-phase intelligent IoT meters has attracted the most attention.

Since 2016, anticipating the development of a new generation of State Grid smart meters, the State Grid metering department, meter manufacturers, and the authors of this paper have published numerous articles detailing the content of the 2013 smart meter standards, interpretations and applications of the IR46 standard, multi-core modular architecture designs, and expectations for next-generation smart meters. When drawing upon this prior work, this paper only lists the key points without repeating detailed discussions. The general technical specification for three-phase intelligent IoT meters comprises six parts: general principles, technical specifications, functional requirements and application software testing specifications, security protection technical specifications, new technical requirements, and technical services, design liaison, factory inspection, and supervision. The content is extensive and widely distributed, with modular technology for the entire meter and on-demand functional expansion representing key design innovations in State Grid intelligent IoT meters.

This paper primarily consolidates the modular design requirements from various parts of the three-phase intelligent IoT meter general technical specification, extracting the logical characteristics of modular architecture design to pave the way for the upcoming widespread application and long-term development of State Grid intelligent IoT meters.

## 1. Overview of Three-Phase Intelligent IoT Meter General Technical Specifications

### 1.1 Definition of Intelligent IoT Meters

The intelligent IoT meter is defined as a smart electricity meter composed of metering, management, and expansion modules, capable of functions including

energy measurement, data processing, real-time monitoring, automatic control, environmental perception, information interaction, and energy routing, while adapting to IoT requirements. This definition carries three layers of meaning: First, intelligent IoT meters build upon conventional smart meters, adopting relevant content from current IEC electricity meter standards and the 2013 State Grid smart meter technical and functional standards. Second, they must implement measurement, data processing, monitoring, control, perception, interaction, and routing functions while meeting IoT requirements. Third, they employ modular structural design with IoT-required functionalities.

## 1.2 Architecture Analysis of Three-Phase Intelligent IoT Meter General Technical Specifications

The authors contend that the three-phase intelligent IoT meter specification represents a combination of requirements from IEC electricity meter standards/2013 State Grid smart meter technical and functional standards, IR46 standard requirements, and modular design requirements, along with other new provisions. The IR46 standard requirements are applied to active energy measurement accuracy and metrological characteristic protection. IR46 fundamentally changes the traditional active energy measurement technical system of IEC standards, with key metrological points including: The active energy measurement accuracy class of three-phase intelligent IoT meters uses English letters A, B, C, D, and E, covering the entire measurement operating range under reference conditions with broad coverage. In contrast, IEC standard accuracy classes use 2, 1, 0.5S, 0.2S, and (0.1S) grades, specifying error limits only under reference conditions, designated load ranges, and unity power factor. The load variation error curve for three-phase intelligent IoT meters uses starting current ( $I_{st}$ ), minimum current ( $I_{min}$ ), transition current ( $I_{tr}$ ), and maximum current ( $I_{max}$ ), representing a wide load range, rather than the basic current ( $I_b$ ) used as the load calculation basis in IEC standards. Influence quantities follow IEC/2013 State Grid standards plus interference allowances with error offset limits from IR46, whereas IEC standards separately specify influence quantities and interference effects. Metrological characteristic protection employs a dual-module (metering and management) design to achieve hardware and software separation between metrological and management components, a requirement absent from IEC standards.

Requirements from IEC standards and the 2013 State Grid smart meter standards are applied to reactive energy measurement (with accuracy classes 2, 1, 0.5S) and serve as general requirements for technical and functional specifications in the new standard. Specifically, this includes accuracy requirements (11 items), electrical requirements (7 items), insulation performance (2 items), and electromagnetic compatibility requirements (2 items) from Q/GDW 1827-2013 “Technical Specification for Three-Phase Smart Meters,” plus terminology and definitions (47 items), meter functional requirements (25 items), and event threshold ranges with default values (15 items) from Q/GDW 1354-2013 “Func-

tional Specification for Smart Meters.”

The hardware platform structural design employing metering modules, expansion modules, management modules, and software (operating system and applications) enables on-demand functional expansion and introduces new requirements, which constitute the focus of subsequent discussion.

## 2. Modular Design Requirements for Intelligent IoT Meters

### 2.1 Technical Design Requirements

**Modular Framework Design:** The intelligent IoT meter comprises structurally independent metering, expansion, and management modules (including embedded operating system and application software hardware platform). Expansion modules are classified as Type A or Type B. Except for the metering module, other modules connect via connectors supporting hot-swapping with fail-safe protection circuits.

**Metering Module Technical Requirements:** The metering module contains an MCU, battery, clock, ESAM, memory, and pulse signal units. Internally connected as: MCU ← battery, clock, ESAM, memory → pulse signal. The metering module enables legal metrology, can operate independently without other modules, employs tamper-proof design, prohibits disassembly, and does not support software upgrades.

**Management Module Technical Requirements:** The management module contains an MCU, buttons, ESAM, Bluetooth, memory, and LCD units. Internally connected as: MCU ← buttons, ESAM, Bluetooth, memory, LCD. It runs an embedded real-time operating system with data routing and online software upgrade capabilities, responsible for meter data management, module management, and inter-module data interaction. The logical working relationship between metering and expansion modules is uniformly managed by the management module without multiple cross-connections. The management module must include energy storage devices to actively send power outage information to Type A expansion modules within 10 seconds after meter power loss.

**Expansion Module Technical Requirements:** Type A expansion modules are dedicated independent modules with weak and strong electrical interfaces, primarily for meter data communication, supporting carrier and micro-power wireless communication. Using carrier communication, they can also communicate with meter slave devices, enabling upstream and downstream communication function multiplexing. Type A modules must incorporate energy storage devices to complete active power outage reporting within 3 minutes. Type B expansion modules include Types 1, 2, and 3, with compatible structural dimensions and hardware interfaces for interchangeable installation. They can be configured based on different application scenarios such as non-intrusive load sensing, power quality analysis, orderly charging control, and water/gas/heat meter data access. Type B modules must have independent power and signal

interfaces.

**Inter-Module Interface Pin Functions:** The metering-management module interface uses two dual-row connectors with 16 pins each (management module: dual-row pins; metering module: dual-row sockets). The first dual-row interface includes: power (Vcc) pins providing  $15V \pm 1V$  at  $600mA$  with dedicated ground from the meter mainboard; SPI *CLK*, SPI-MISO, SPI-MOSI at  $3.3V$  high level; and TEST1-5 output pins for energy pulses (active, forward row interface includes : power (Vdd) pins providing  $+3.3V \pm 0.16V$  at  $30mA$  with dedicated ground from the management module; UART communication pins (TXD, RXD); SPI-CS chip select signal; POWDET power loss signal; SECOND second synchronization; COM-RQ management module removal signal; SCLK SPI clock signal line from metering module with configurable rate; MOSI data output from metering module to Type B expansion modules (management module forwards, no data accepted from Type B to metering); CS chip select signal; and GND common ground.

The meter management module side-Type A expansion module weak electrical interface uses one dual-row socket with 12 pins (Type A module side: dual-row pins). Functions include: power (Vcc) providing  $12V \pm 1V$  at  $400mA$  average current with dedicated ground from AC power; PLUG-DET insertion detection signal directly grounded by management module; communication pins (RXD, TXD, /SET enable, STA address match, /RST reset); COM-RQ presence signal; and EVENT OUT event status output. This weak electrical interface must be isolated from strong electricity and, except for new PLUG-DET and COM-RQ signals, remains compatible with 2013 standard modules.

The meter (local communication unit) side-Type A expansion module carrier coupling interface (strong electrical) uses one dual-row pin connector with 20 pins (meter side: dual-row socket). Functions include: carrier (A, B, C) pins for three-phase lines as carrier coupling access; carrier (N) pin for neutral line coupling; empty pins for safety distance; and design considerations to minimize line interference and absorption of carrier signals.

The meter management module side-Type B expansion module interface is a weak electrical dual-row interface with 12 pins (Type B modules: pins; meter side management module: socket). Type B expansion modules 1, 2, and 3 must have consistent pin functions, including: power (Vcc) providing  $+5V$  at  $100mA$  average current with dedicated ground from management module; communication pins (RXD, TXD, /RST reset, COM-RQ presence); and forwarded SPI communication functions (SCLK clock, MOSI data output, CS chip select). The management module forwards these signals to implement Type B expansion module interchangeability without affecting metering module operation.

## 2.2 Functional Design Requirements

**Metering Module Functions:** The metering module provides energy measurement (forward/reverse active, harmonic, fundamental, and four-quadrant reactive energy; phase-specific measurement; decimal place requirements); legal

clock (temperature-compensated hardware clock with 1Hz output, automatic time conversion, time synchronization, security protection); minute freezing (1-minute and 15-minute intervals stored for one year with compensation for missed freezing during outages); event recording (ordinary/broadcast time synchronization, management module insertion/removal, online upgrades, terminal cover opening, meter cover opening, power loss, meter clearing); clearing functions (only in test key state, permanently recorded, with specified data directory and base value clearing rules); signal output (proportional active, harmonic active, reactive pulses; legal clock signal, second synchronization, power loss signal); measurement and monitoring (total/phase active/reactive power, voltage, current including neutral, total/sub-harmonic distortion, power factor, frequency with accuracy requirements); auxiliary functions (optional error self-detection, terminal temperature measurement); and security protection (software comparison, unmodifiable software version, metering module as authority for communication address, data preservation, fault self-check).

**Management Module Functions:** The management module, embedding an operating system and running multiple apps, saves various frozen data, handles external communication, and routes communication for metering and expansion modules. Functions include: energy data (forward/reverse active, fundamental, harmonic, and four-quadrant reactive energy; combined active/reactive energy; synchronization with metering module; phase-specific data; storage and transmission); demand measurement (maximum demand in specified intervals with timestamps, sliding window method, 12 settlement days); clock synchronization (with metering module after time correction, periodic synchronization); rates and time periods (5 requirements); freezing functions (10 requirements including instantaneous, minute, hourly, daily, monthly, agreed, and settlement day freezing; content identifiers; storage period; consistency with metering module); event recording (26 types including voltage/current anomalies, phase sequence, power direction, module events, magnetic interference, switch misoperation, programming, temperature alarms, module changes, harmonic distortion, neutral current anomalies; active reporting capability); clearing functions (3 requirements); signal output (pulses and alarms); display functions (8 requirements); measurement and monitoring (operating parameters from metering module, limit violation monitoring); tariff control (4 requirements); power retention (5 requirements); active reporting (3 requirements); and security protection (3 requirements).

**Software Requirements:** General requirements include software protection, parameter protection, authorized access measures, and manufacturer-provided embedded software specifications. Management module software must use clear version identification that is inseparable from the software, unique, and non-configurable. The software architecture must be layered, including at minimum a driver layer, platform layer, and application layer. Software comparison functionality must enable reading management module target code via encryption. Online upgrade capabilities are required but details are omitted.

**Metering Module Communication:** Synchronous communication with the management module uses SPI with CPOL=0, CPHA=1, MSB-first mode. The management module reads metering module data blocks using object container sets (OAD: F2130501) to maintain synchronization, with data block transmission details fixed before factory shipment. Asynchronous communication uses UART with the management module as master and metering module as slave, supporting DL/T698.45-2017 protocol. Metering modules do not evaluate logical addresses in received frames but respond using the received frame's logical address. Communication must be possible within 5 seconds of meter power-up.

**Management Module Communication:** Bluetooth communication must support interoperability with service UUIDs specified in appendices, operating in two-master three-slave mode for concurrent communication with two hosts and three slaves. The management module serves as the communication router, forwarding master station commands to metering and expansion modules and relaying responses. Logical addresses differentiate modules (00 for management, 01 for metering, extended addresses for expansion modules). Metering and expansion modules respond using the logical address from received messages without evaluating it.

**Expansion Module Communication:** Communication expansion modules (e.g., HPLC modules) use default 9600bps interface rates negotiable to higher speeds, with communication possible within 5 seconds of meter power-up. External antennas must ensure personal safety. Functional expansion modules must follow DL/T698.45-2017 protocol, with the management module supporting handshake and information reading.

### 2.3 Embedded Operating System

The intelligent IoT meter software functions must be developed on a unified operating system platform running on the management module hardware. The architecture comprises five layers: boot layer (hardware initialization and kernel boot), driver layer (main controller and peripheral drivers with unified interfaces for hardware compatibility), system layer (real-time OS multi-task scheduling, inter-task communication, memory allocation and protection, shared module interfaces), application layer (basic meter apps, business apps, and extended app management), and IoT management platform (data collection management for edge devices and app management for end meters). The OS must support memory management, thread management, inter-thread communication and synchronization, clock and device management, kernel-application separation, process management, resource permission allocation, and data security isolation. POSIX interfaces must be supported for compatibility and portability, with requirements for real-time performance, robustness, and compatibility.

## 2.4 Local Communication Unit for IoT Meters

This section summarizes the “General Technical Specification for IoT Meter Local Communication Units” released by State Grid in August 2020. The local communication unit installs on intelligent IoT meters and must use DC power (12V $\pm$ 1V) with immunity to three-phase distribution network single-phase ground faults, tolerating 1.9 times nominal voltage for 4 hours. After AC/DC power loss, supercapacitors must sustain normal operation for over 30 seconds. High-speed power line communication (HPLC) operates in 2-12MHz, 2.4-5.6MHz, 0.7-3MHz, or 1.7-3MHz bands with switchable usage. In isolated, shielded, non-competitive environments with 1:1 master-slave ratio and 512/1024-byte packets, communication rates must exceed 1Mbps. The unit must follow Q/GDW11612.41/42/43 for interoperability, supporting node management, channel access, automatic routing, whitelist management, multi-network management, and network information management. Business functions include active meter reading by concentrators or routing nodes (concurrent reading of 5 meters meeting Q/GDW1373-2013), broadcast time synchronization, slave node registration, event reporting (power outage events reported to master station within 90 seconds with <10% error rate), remote tariff control, and online upgrade via carrier channel. The unit must be interchangeable and compatible with intelligent IoT meters, with MTBF 10 years.

The three-phase IoT meter local communication unit management module weak electrical interface uses a dual-row socket with 12 pins (management module side: pins). Functions include: power (12V $\pm$ 1V at 400mA average), PLUG-DET insertion detection, communication pins (RXD, TXD, /SET enable, STA address match, /RST reset), COM-RQ presence signal, and EVENT OUT event status. The interface must be isolated from strong electricity and remains compatible with 2013 standard modules except for new signals. The carrier coupling interface (strong electrical) uses a dual-row socket with 20 pins for three-phase and neutral line coupling, with empty pins for safety distance and design considerations to minimize carrier signal interference.

## 2.5 Application Case: Remote Meter Data Access by Master Station

In this scenario, a concentrator at the distribution transformer side forwards master station commands to access meter data via HPLC to the IoT meter local communication unit (on AN/BN/CN phases). The command passes through the local communication unit-Type A expansion module carrier coupling interface (strong electrical), undergoes demodulation, transfers via the local communication unit-management module weak electrical interface to the management module. The management module forwards the command via UART asynchronous interface to the metering module, requesting it to start outputting raw measurement data. The metering module, without evaluating the logical address in the received message, responds using the received frame’s logical address. Within 3 seconds of receiving the command, the metering module transmits raw mea-

surement data through the SPI synchronous interface. Non-measurement raw data such as event records, measurement, and monitoring data are output via the UART asynchronous interface. The management module then sends the raw measurement data, event records, measurement data, and its own generated secondary measurement data and event records back to the concentrator through the local communication unit interfaces (including modulation by the carrier communication module). Finally, the concentrator forwards the meter data to the master station.

### 3. Logical Characteristics of Intelligent IoT Meter Modular Design

Compared with traditional integrated smart meter design, modular design employs logical changes between modules to implement IR46 standard applications and on-demand functional expansion.

#### 3.1 Data Classification and Raw Measurement Data Integrity

Measurement raw data is generated by the metering module, including three-phase forward/reverse active energy, fundamental active energy, harmonic active energy, and four-quadrant reactive energy, as well as phase-specific active energy. Raw data blocks use object container sets (OAD: F2130501) with transmission details fixed before factory shipment. The metering module also provides legal clock with second pulse output and minute freezing energy data. Signal outputs include all active energy pulses, forward/reverse harmonic active energy pulses, reactive energy pulses, legal clock signals, second synchronization signals, and power loss signals.

The management module processes raw measurement data to generate secondary measurement data, including combined active/reactive energy based on raw data, demand, rates and time periods, and frozen energy data. The management module's clock and measurement raw data originate from and must synchronize with the metering module. Current energy values must be synchronized between modules. Output of metering module raw data is uniformly managed by the management module to ensure data uniqueness, including for remote automatic meter reading by master stations and raw data collection by Type B expansion modules. This logical design between metering and management modules fulfills IR46 requirements for hardware and software separation between legal metrology and non-legal metrology components.

#### 3.2 Communication Forwarding and Modular Interchangeability

The management module provides forwarding communication functions: SPI synchronous communication clock, data, and chip select signals (SPI-SCLK, SPI-MOSI, SPI-CS) between the metering module and Type B expansion modules must be forwarded through the management module, enabling on-demand

replacement of Type B expansion modules without affecting metering module operation.

### 3.3 Unified Grid Communication Management

The local communication unit-Type A expansion module carrier coupling interface (strong electrical) uniformly manages communication between the meter and power grid.

### 3.4 Unified Functional Coordination

The management module uniformly manages and coordinates functional implementation of the metering module, Type B expansion modules, Type A expansion modules, and local communication unit through logical relationship changes.

## 4. Conclusion

As previously noted, the modular structural design of intelligent IoT meters represents an innovation in smart meter design technology that departs from traditional integrated approaches and offers significant utility. However, the release of the three-phase intelligent IoT meter general technical specification and other new standards, along with the inclusion of single/three-phase smart meters (2020 edition) in State Grid' s second 2020 smart meter tender, marks only the beginning of market application for the new generation of State Grid smart meters. These new specifications are transitional in nature for three main reasons: First, the International Organization of Legal Metrology' s IR46 standard for active energy meter legal metrology has been implemented for many years and requires supplementation and revision, while the timeline for OIML' s reactive energy meter legal metrology requirements remains unclear. Second, Type B expansion modules combined with management modules can achieve on-demand functional expansion, but currently State Grid only provides limited technical specifications for non-intrusive load identification and single/three-phase power quality monitoring. Widespread application of these new functions requires time, and IoT functions and other updated expansion functions need further research and development. Third, this paper only discusses meter modular structural design, while the three-phase intelligent IoT meter general technical specification introduces new measurement types such as fundamental active energy and harmonic active energy that require research on implementation options. The use of meter waveform data output for online monitoring technology also requires accelerated development.

The application prospects for new measurement types and extended functions of three-phase intelligent IoT meters are promising, but the development and application journey remains long. The authors will address these topics in separate papers.

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