Hindawi
Advances in Mathematical Physics
Volume 2023, Article ID 1296165, 8 pages
https://doi.org/10.1155/2023/1296165

Research Article

Research on Model Construction of Electric Energy Metering System Based on Intelligent Sensor Data

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Received 23 September 2022; Revised 31 October 2022; Accepted 20 March 2023; Published 3 May 2023

Academic Editor: S. E. Najafi

The informatization construction of the power grid is becoming increasingly popular, business application systems are constantly emerging, and power-related data is rapidly expanding. These discrete power data are scattered in various application systems, and it is not easy to directly provide advanced enterprise applications. The establishment of intelligent power statistical model is an urgent need for constructing power grid informatization. This paper proposes a model of an electric energy metering system based on intelligent sensor data and introduces the existing digital metering system. This model is the integration and promotion of business integration based on the digital metering system. It is the first time to apply new metering equipment, such as measurement and control devices with integrated metering functions, and new metering technologies, such as IEC 61850 electricity meter reading applications. It is hoped that this paper can lay a foundation for further research.

1. Introduction

Science and technology have developed rapidly, and the intelligence and informatization are becoming increasingly popular in the industrial field. The digital energy meter calibrator can accept the output signal of the standard power, and, after AD conversion, use the internal digital energy meter to calculate the electric energy and output the electric energy pulse to the higher precision electric energy metering equipment to carry out the calibration to achieve the quantity value transmission. Although the accuracy of digital metering equipment has been significantly improved, there are still many problems in actual operation, such as frequent communication failures and abnormally large measurement errors under the condition of good equipment performance, resulting in the inability to upload measurements and inaccurate upload data [1, 2]. The virtual load verification function controls the output of the standard power source by editing the verification scheme of the electric energy meter, verifies the digital electric energy meter in detail, and automatically generates a report. The actual load verification function can verify the inspected digital electric energy meter at the substation site without affecting the use of the inspected digital electric energy meter. Various problems, such as power imbalance, seriously hinder the engineering application process of digital metering technology. According to relevant data statistics, in 2020, among the 10 kV lines of Wuhan Power Supply Company, the ratio of users with a line loss rate of more than 5% was 12.6%, the percentage of users with a line loss rate of more than 10% was 7.1%, and the percentage of users with a line loss rate of more than 8% covered by unique transformer customers was 5.3%. During 2018-2021, more than 20000 defaulters and power thieves were found, saving more than 80 million yuan of economic losses. Currently, the annual loss due to electric energy theft in China is up to 20 billion yuan, and the value is increasing yearly. Taking the yearly electricity sales of 70 billion kWh in a province as an example, if the line loss caused by artificial electricity theft increases by one percentage point, the power loss will be up to more than 700 million kWh, equivalent to nearly 400 million yuan [3]. Inductive equipment must absorb active and reactive power from the power system during operation. Therefore, after installing shunt capacitor reactive power compensation equipment in the power grid, it will be able to provide reactive power consumed by compensating inductive load, reducing the reactive power supplied by the power grid side inductive load and transmitted by the line. To effectively grasp the existing issues in the actual operation of the digital electric energy metering system and to clarify the aspects and contents of the practical work of digital metering in the next step, the State Grid Jiangsu Electric Power Company selected Wuxi as the research object to investigate the operation of all digital electric energy meters under the jurisdiction of its urban area. Statistics were carried out, a field investigation was conducted on the application status of the digital electric energy metering system in Xijing intelligent substation, and valuable first-hand information was obtained [4].

The main work done in the paper can be described as follows: (1) introduces the statistics of operating faults of Wuxi digital electric energy meters and analyzes the possible causes of various spots; (2) taking the digital power measurement on the high-voltage side of the main transformer in Xijing No.1 substation as an example, combined with digital measurement; the basic structure of the system points out its shortcomings in practical applications; (3) this paper summarizes the current practical problems faced by the power metering system based on intelligent sensor data in engineering applications and proposes corresponding solutions to provide a reference for the next step in the development of intelligent power systems.

2. Theoretical Analysis on Electric Energy Metering

Electric energy measurement has two main functions: on the one hand, it is used for internal assessment and settlement of power grid enterprises, and on the other hand, it is used as the basis for trade settlement between power generation, power supply, and electricity consumption [5]. To ensure that the electric energy metering device can accurately measure the electric energy, first of all, the category of electric energy metering device should be correctly selected. Secondly, choose the electric energy meter and instrument transformer with excellent performance and quality, as well as the secondary circuit wire section, and install and maintain them as required to ensure the safe, accurate, and reliable operation of the electric energy metering device. Electric energy measurement accuracy directly affects the internal assessment and analysis results of power grid companies or the fairness of trade settlements. Therefore, the electric energy measurement system must be accurate and reliable. The role of electric energy measurement standards in energy conservation and consumption reduction includes that scientific and advanced electric energy measurement tools provide accurate data for energy-saving transformation, and the analysis of electric energy measurement data provides the scientific basis for energy-saving change.

In traditional substations, the energy metering system consists of transformers and electronic energy meters. The transformers convert high voltage/large current into small voltage/current signals of 100/57.7 V or 1/5 A and then input them to the electronic energy meter [6]. The structure of an electronic watt-hour meter is similar to that of an induction watt-hour meter, composed of two parts: a measuring mechanism and auxiliary components. The measuring instrument is mainly written as an electronic circuit. Its measuring elements are composed of a UI multiplier, U/f converter, and counter. The auxiliary components are the same as those of the inductive watt-hour meter. To complete the accumulation of electrical energy. In the intelligent substation, the electric energy metering system has two forms: the first is to use electronic transformers, digital input merging units, and digital electric energy meters. The electronic transformers directly output digital quantities, and the subsequent data transmissions all use optical fibers. The second is to use traditional electromagnetic transformers still. The analog input merging unit digitizes the voltage and current signals output by the conventional transformers on the spot. This measurement system structure is adopted because the technology of electronic transformers is immature [7]. The configuration principle of the electric energy metering device includes that the secondary circuit of the voltage transformer in the electric energy metering device for trade settlement above 35 kV shall not be equipped with the auxiliary contact of disconnector. The electric energy metering device for trade settlement is installed at the user's place, and the user supplying power at 10 kV and below should be equipped with a national unified standard electric energy metering cabinet or electric energy metering box. To improve the accuracy of low load metering, electric energy meters with the overload of 4 times or more shall be selected. Figure 1 shows the structural comparison of these three metering systems.

$$W = U \times I \times t, \tag{1}$$

or

$$\begin{aligned} W &= P \times t, \\ W_n &= W_1 + W_2 + W_3 + \cdots W_n. \end{aligned} \tag{2}$$

In the above formula, W represents electric energy, U represents the actual voltage value, I represents the actual current value, P stands for electrical power, and t represents the electricity consumption time.

3. Research and Analysis

3.1. Statistical Analysis on Operation of Wuxi Digital Electric Energy Meter. Wuxi, Jiangsu, has several smart substations. The city with the most extensive range of digital power metering systems in Jiangsu Province is Wuxi Power Supply Company. The technical advantages of intelligent substations include the following: the smart substation can achieve an excellent low-carbon environmental protection effect, and the intelligent substation has good interaction and reliability characteristics.

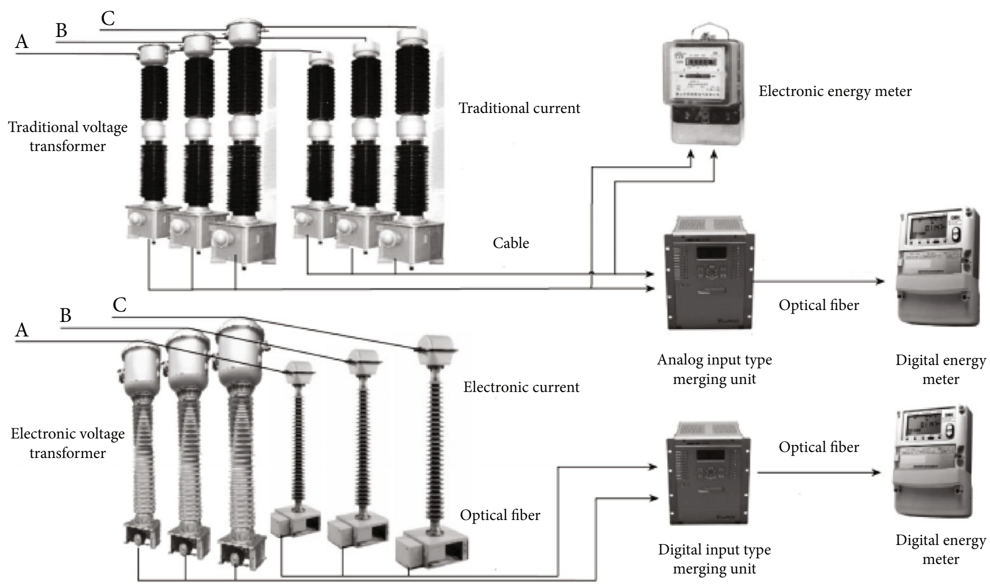

Figure 1: Structure comparison of three metering systems.

Up to now, the total number of digital meters under the jurisdiction of Wuxi city is 251, involving 43 substations of 3 voltage levels. Among them are three 500 kV substations involving 32 photoelectric meters, 17 220 kV substations involving 91 photoelectric meters, and 23 110 kV substations involving 128 photoelectric meters. The intelligent substation uses reliable, economic, integrated, low-carbon, and environment-friendly equipment and design, which can support the real-time online analysis and control decision-making of the power grid, with the basic requirements of the whole station information digitization, communication platform networking, information sharing standardization, system function integration, structural design compactness, high-voltage equipment intelligence, and operation status visualization.

This paper mainly conducts statistics on the operation of digital meters in operation under the jurisdiction of the Wuxi urban area. The failure rate of digital electric energy meters is generally 16%, which is higher than the failure rate of traditional electronic energy meters. To further analyze the operation of the digital electric energy meter, Table 1 is by voltage level, Table 2 is by fault type, and Table 3 is the classification statistics of manufacturers.

From the above data, we can preliminarily summarize the following conclusions (Figure 2). It can be seen from Table 1 that as the voltage level decreases, the failure rate gets higher and higher. Many faults include failure to upload power and power error. The primary responsibility is that the administration cannot be uploaded due to communication failure; different manufacturers' digital electric energy meters significantly differ in failure rate. The communication failures of digital watt-hour meters mainly include frame loss, communication delay, and channel abnormality (Figure 3).

Through exchanges and discussions with relevant technical personnel of the operation and maintenance unit and on-site inspection, the possible causes of various failures were further analyzed. A communication failure causes the inability to upload the electricity. The judgment is based on the standard measurement of the electric energy meter, but the centralized meter reading center cannot read the electric energy. The power error should be the wrong configuration of the parameters of the electric energy meter. The

Table 1: Statistics by voltage level.

Voltage level (kV)	Total number of digital tables	Number of failure tables	Failure rate (%)
500	32	1	3.1
220	91	5	5.5
110	128	39	30.5

Table 2: Statistics by fault type.

Fault type	Number of fault tables	Percentage of failure table (%)
Battery cannot be uploaded	21	46.7
Battery error	9	20.0
Other faults	15	33.3

Table 3: Statistics by manufacturer.

Manufacturer	The number of digital meters supplied by the manufacturer	Number of fault tables	Percentage of failure table (%)
1	90	2	2.2
2	74	19	25.7
3	36	2	0.56
4	17	2	11.8
5	9	7	77.8
6	5	3	60.0

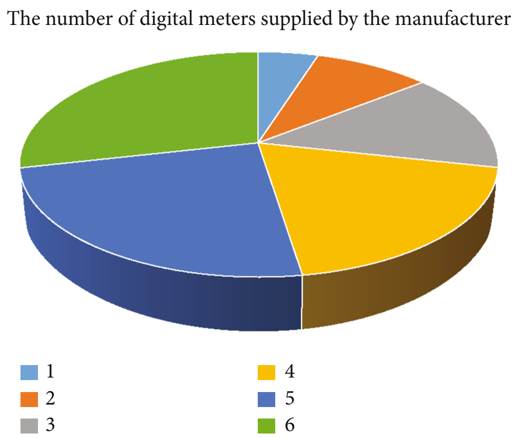

Figure 2: The digital meter number supplied by the manufacturer.

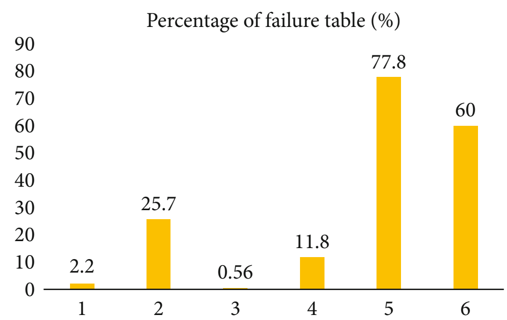

Figure 3: Percentage of failure table.

basis for the judgment is that the current protection and metering data sources in the intelligent substation are the same. If the data source is incorrect, the protection device should respond first. Other faults mainly refer to the crash of the electric energy meter, black screen, no indicator light, etc. The cause of such failures is defective software or hardware of the electric energy meter itself.

3.2. Investigation of the Fault Situation of Digital Electric Energy Metering in Xijing Substation. Xijing Substation is the first batch of pilot projects for intelligent substations of the State Grid Corporation of China. Construction started in July 2010 and was put into operation in December of the same year. The station is an intelligent substation in a complete sense. The operational characteristics and responsibilities of intelligent substations make them have good interactivity. It is responsible for the data statistics of power grid operation, which requires it to feed back safe, reliable, accurate, and detailed information to the power grid. After the intelligent substation realizes the function of information collection and analysis, it can not only share the data internally but also interact well with more complex and advanced systems in the network. It adopts the design of "three layers and two networks." The SV, GOOSE, and IEEE 1588 networks share the transmission network, and the dual network is redundant [8]. The voltage and current measurement equipment all uses electronic transformers. The current transformer is based on the optical principle, and the voltage transformer is based on the capacitive voltage divider principle [9]. The idea of single server sharing is to use one PC as the server to provide network-sharing services to other PCs. There are mainly two schemes to realize this method: (1) proxy server scheme and (2) URL conversion scheme.

Since Xijing Substation was put into operation, there have been relatively few problems in the digital metering system, but there are still faults, and on-site fault investigation is required.

Taking the digital power metering of the high-voltage side of the main transformer of Xijing Substation No. 1 as an example, the schematic diagram of the system structure is shown in Figure 4.

As shown in Figure 4, the digital energy metering system is very different from the traditional system in structure, mainly because the energy meter is no longer directly connected to the transformer, and there are more remote modules, photoelectric units, and merging units in the middle. The design principles of the electric energy metering system include that the electric energy metering system should be designed as an independent and complete system. Electric energy acquisition has low requirements for real time but high requirements for simultaneity, increased requirements for electric energy acquisition accuracy, the principle of uniqueness of data source, and the high reliability of software. The transmission signal has also become a digital quantity, switches, and other equipment. From the perspective of on-site operation and maintenance of metering, although the wiring is less, the remote modules, voltage-combining units, current-combining units, switches, and other equipment are widely distributed and partially overlap with the automation system in the substation. The secondary wiring of the metering system becomes less clear, making the whole system more complex. As electric energy is a cumulative value, even small errors will reach an incredible degree after accumulation. For both the seller and the user of electricity, this cumulative value is an economic loss. Therefore, the selection principle of measurement accuracy should be that the greater the capacity, the higher the accuracy. It is better to use energy meters with an accuracy of 0.2 level and above for large-capacity power plants and transmission lines.

During the on-site investigation of the digital power metering fault on the high-voltage side of the main substation of Xijing Substation No. 1, it was difficult for traditional substation operation and maintenance personnel to locate and analyze the fault. In contrast, professional technicians familiar with digital power metering could infer the fault point and cause. Substation operation and maintenance experiences are also difficult to verify and figure out. In addition, because the digital power metering system and the automation system in the substation have some overlapping equipment, such as merging units and switches, the equipment focal point is not clear, which makes troubleshooting very difficult. The problem-solving efficiency is low, so the coordination and cooperation of multiple departments are required to complete the work [10]. The electric energy acquisition device is the communication center of electric energy data. On the one hand, it collects and stores the electric energy data output by the digital electric energy meter in

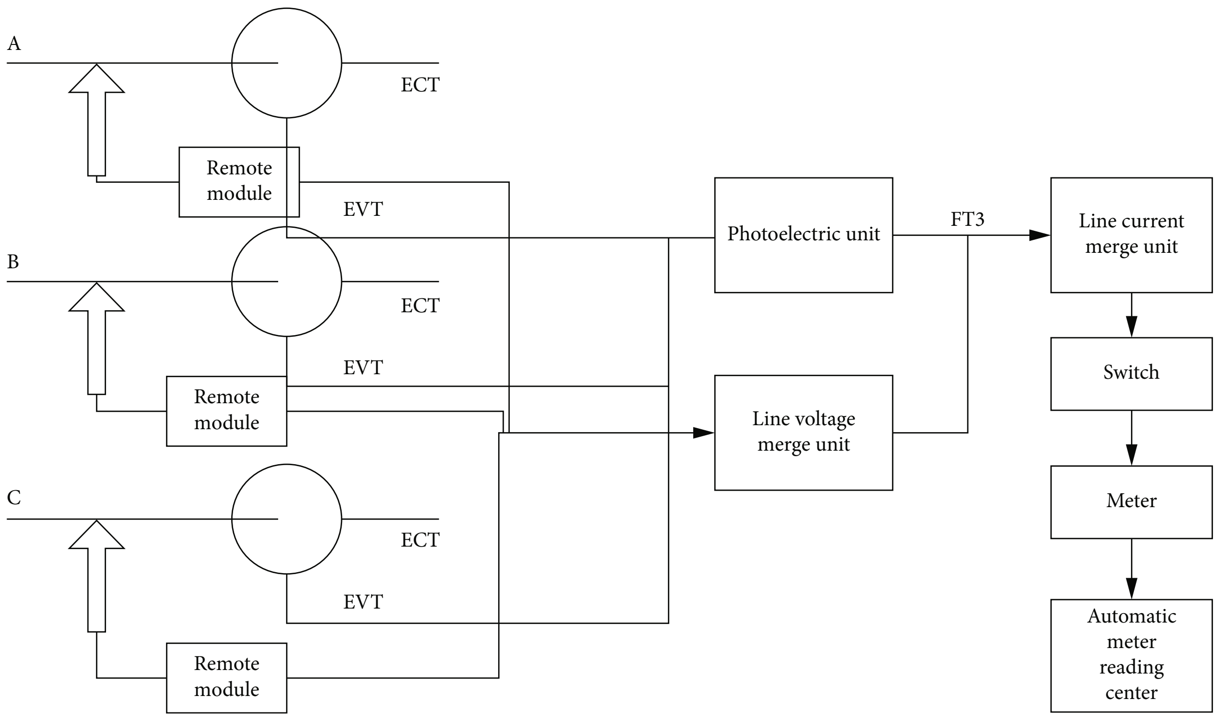

Figure 4: Xijing Substation No. 1 main transformer high-voltage side digital electric energy metering.

the form of serial communication. On the other hand, the collected electric energy data is transmitted to the master station of the electric energy billing automation system through the uplink channel.

4. Problems Faced by Digital Energy Metering

Through the research on the application of digital energy metering in Wuxi, Jiangsu Province, and combined with the actual situation of digital metering technology, the problems that still exist in trade settlement are divided into three aspects;

4.1. Normative. The meaning of normative includes the normativeness of the metering system structure and the normativeness of metering equipment management. The intelligent electricity meter can realize accurate and real-time cost settlement information processing, simplifying the complex process of past account processing. In the power market environment, dispatchers can switch energy retailers more timely and conveniently and even realize fully automatic switching in the future. At the same time, users can also obtain more accurate and timely energy consumption and accounting information.

(1) Structural normative

Electric energy metering not only requires correct functions, especially the electric energy metering system used for trade settlement, but also conforms to national mandatory requirements.

In the process of intelligent substation design, the design unit mainly focuses on the stability and reliability of the relay protection and measurement and control automation system. The method of the electric energy metering system is only at the functional level [11]. For example, in terms of synchronization time synchronization, some use IRIG-B code time synchronization, and some use IEEE 1588 time synchronization, while the “direct sampling and direct hopping” protection does not depend on time synchronization. Some sampling devices do not even access the time synchronization signal, relying entirely on interpolation synchronization, and the data source of the energy meter comes from the switch. In this extreme case, even if the errors of the various components of the power calculation system are acceptable, the overall measurement error will exceed the tolerance.

While for the Department of Metrology, due to the limitation of majors and responsibilities, most universities and scientific research institutions mainly focus on the research of measurement accuracy and traceability technology.

The normative aspect of statistical structure has not been paid enough attention to, so the design of the current digital measurement system is not unified, which affects the accuracy of measurement and the reliability of measurement data.

(2) Management normative

There should be a unified management specification to ensure that the digital energy metering system is accurate, stable, and reliable. Traditional energy metering systems, according to DL/T 448-2000 “Technical Management Regulations for Electric Energy Metering Devices” and SD 109-1983 “Inspection Regulations for Electric Energy Metering Devices,” strictly stipulate the classification of metering points, metering device configuration, procurement, installation, weekly inspection, and other links, so traditional electric energy metering system can measure electric energy accurately, stably, and reliably. However, no mandatory or recommended standard documents for managing digital energy metering systems exist. After the digital metering system is put into operation from the infrastructure, there is almost no management department, and its acceptance is also completed by the automation professional. In addition, the follow-up operation and maintenance of the digital energy metering system are also tricky. The data on water, gas, and heat consumption collected by smart meters can be used for load analysis and prediction. The total energy consumption and peak demand can be estimated and predicted by comprehensively analyzing the above information, load characteristics, time changes, etc. This information will provide convenience for users, energy retailers, and distribution network dispatchers; promote rational power use, energy conservation, and consumption reduction; and optimize grid planning and dispatching. (1) Up to now, there is neither detection equipment nor detection basis and means for judging the failure of digital electric energy metering equipment; (2) there are no relevant technical normative documents on how to deal with the disappointment after the occurrence of the fault; and (3) the digital power metering system and the substation automation system have some overlapping equipment, and it is necessary to coordinate multiple departments to carry out the daily operation and maintenance of the metering system. By feeding back the energy consumption information provided by smart meters to users, users can be encouraged to reduce energy consumption or convert energy utilization methods. For households equipped with distributed generation equipment, it can also provide users with reasonable power generation and electricity use schemes to maximize the interests of users.

Under the current situation of the lack mentioned above of normative management, it is impossible for the digital electric energy metering system to operate as accurately, stably, and reliably as the traditional electric energy metering system. In response to this problem, the design, operation and maintenance, marketing, and other relevant departments should be coordinated to formulate a multiparty recognized smart substation digital energy metering system design and operation and maintenance plan, including system wiring, equipment management, and equipment inspection, to form technical normative documents be enforced.

4.2. Detection Capability. In terms of laboratory testing, several testing standards, including electronic transformers, merging units, and digital energy meters, have been formulated concerning traditional electric energy metering equipment, and corresponding testing platforms have been developed or established. Although imperfect, it can guarantee the stable and reliable operation of the digital electric energy metering system under reasonable operating conditions. However, there are still deficiencies in an on-site inspection. It has also been mentioned that there is a lack of detection equipment and related technical specification documents for the current on-site fault detection of digital electric energy metering systems. For example, when there is a fault that cannot be transmitted back to the electricity, the cause of the defect cannot be determined, and the fault point cannot be located. The most common fault in the survey is the failure to send power back. Due to the numerous causes of such marks and the enormous scope involved, it is challenging to locate the spot. In response to this problem, related testing equipment should be developed. In Jiangsu, the electric energy accumulated by the user's intelligent meters is collected by the local collection terminal. Then, the electric energy is read by the remote server. Therefore, the equipment that detects the power that cannot be returned on-site should have the following functions:

(1) Simulate the local acquisition terminal to check whether the communication function of the electric energy meter is in good condition

(2) Simulate the remote server to check whether the function of the acquisition terminal is in good condition

(3) The simulated negative control center sends a meter reading instruction to check whether the remote server can be accessed commonly

4.3. Quantitative Traceability. For a digital energy metering system to be used for trade settlement, value traceability is one of the problems that must be solved. The value traceability research related to digital energy metering includes three aspects:

(1) High-precision digital energy metering algorithm

(2) A high-accuracy digital power source generation method

(3) Traceability of digital quantities to analog quantities. There have been many studies on the first two problems, and there is no recognized perfect solution for the third

5. Electric Energy Metering System with Intelligent Sensor Data

5.1. Electric Energy Metering System Model of Intelligent Sensor Data. At present, there is no research on electric energy metering system models based on intelligent sensor data at home and abroad. For the sake of realizing the metering data's standardization and ensuring the interoperability and interchangeability of various devices in the metering system, the following extensions are made on the premise of analyzing the research function of the model about power metering, demand calculating, freezing, incident report, time-sharing, and segmented metering which can be clearly shown in Figure 5.

(1) The extended model logic node MMTR is used for forward and reverse active energy and four-quadrant reactive energy and demand measurement (MMTR for three-phase electric energy meters, MMTN for single-phase electric energy meters).

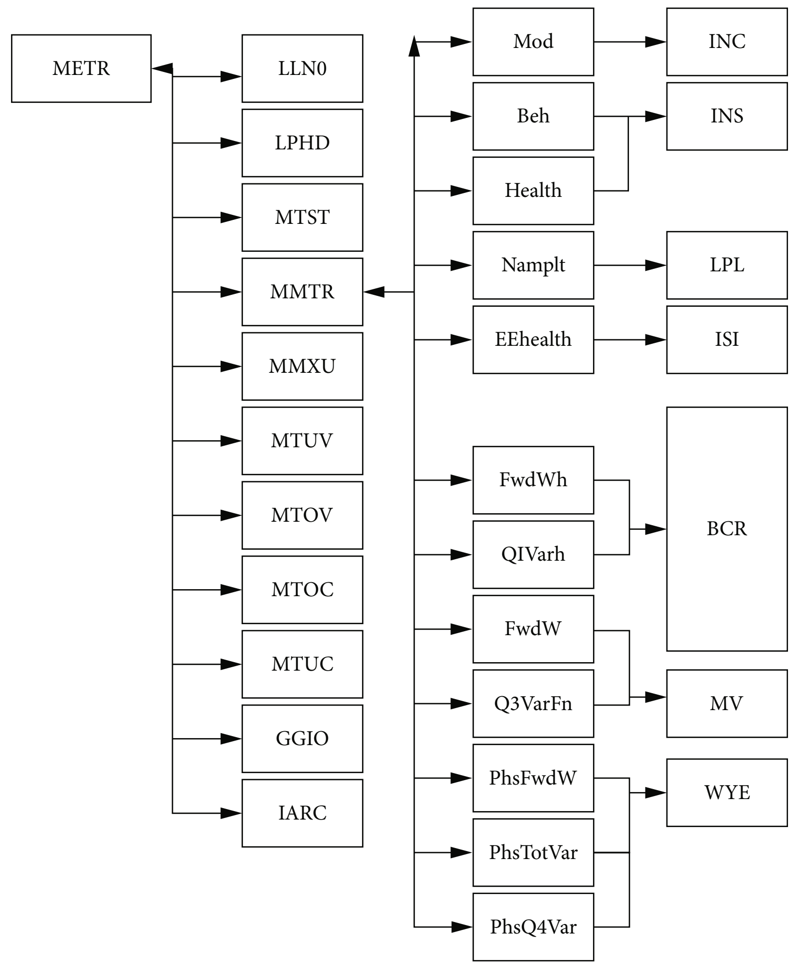

Figure 5: Smart energy metering model.

Under different conditions, such as electricity metering MMTR1 and demand metering MMTR2, they are distinguished by Arabic numerals suffixes

(2) The original MMXU logic node is used for remote measurement of voltage and current (MMXU for three-phase watt-hour meter and MMXN for single-phase watt-hour meter)

(3) Since metering has different limits for voltage loss, phase loss, and current loss and protection measurement and control alarm limits, new MTUV, MTOV, MTUC, and MTOC are created to complete the monitoring and alarm functions. Different alarms of the same type of event alarms are designed with other instances, respectively, such as undervoltage MTUV1 and undervoltage MTUV2; different models are distinguished by Arabic numeral suffixes

(4) Using the original logic node GGIO, there is no need to set customized alarm events such as sampling abnormality, watt-hour meter failure, power failure, and voltage reverse phase sequence

(5) Using the original IARC recording, the programming events, for example, the time zone timetable programming, the demand cycle programming, the energy meter clearing, the demand clearing, the event clearing, the opening of the meter cover, and opening the button box

(6) Create a new MTST logical node to save and record the time zone period table

(7) Take rated voltage and current, active or reactive combined status word, energetic energy pulse constant, reactive energy pulse steady, and other energy meter asset information as the extended data object of the symbolic logical node LLN0

5.2. Characteristics of Electric Energy Metering System Based on Intelligent Sensor Data

(1) With the design inspiration of simplifying the communication network in the station, we adopt a technical solution that combines all-digital computing systems and computing services with other specialties. The private communication network in the measurement system station is merged into the public communication network based on IEC 61850. The measurement service shares data sources and

hardware resources with other majors which simplifies the secondary system in the station and lays a foundation for improving the intelligence level of the measurement system

(2) According to the measurement business needs, the measurement is subdivided into three categories: assessment, settlement, and measurement points that may be converted into settlement points. Different metering points design various implementation schemes and propose other technical conditions

(3) The IEC 61850 node and service model are established for the new generation of intelligent substation metering and metering management. The IEC 61850 file service is used to realize the real-time recording of a large number of frozen data and the convenient transfer afterward and use of the IEC 61850 report. The service recognizes the real-time operational reporting of abnormal events

6. Conclusion

According to the research in this paper, we can see that the research and development of the digital electric energy metering system should be based on the actual application, supplemented by the feeling of use, and comprehensively consider the system operation efficiency and business needs, while meeting the subsequent expansion of the system. Therefore, with the development of science and technology, the following design principles should be followed in the design process of the system in the future:

(1) Reliability. When the environment changes or external virus attacks occur, the system needs to ensure the stable output of its functions. Therefore, in the design process, we should focus on the rigorous testing of the underlying database and various functional modules of the system. Automatic backup of internal data is realized during operation to ensure the safe and reliable operation of the system database and the realization of required functions

(2) Expandability. Thoroughly consider the development of computer hardware technology, new testing projects, and new electric energy metering devices, so the system should have good scalability and compatibility. It not only maximizes the utilization of existing software and hardware equipment and network resources but also can meet the construction needs of future development

(3) Ease of use. To meet the user needs of the system business as the central axis, the design of each functional module should be people-oriented, show the required content output concisely, and conform to the user's operating habits. The action and response process of the system, the typesetting sequence of information, the minimum eye movement distance, and the simple user interface all need to be designed from the user's perspective

(4) Standardization. For the content of the digital simulation module architecture, it is required to comply with the standards issued by the relevant national departments, applicable international regulations, corresponding industry requirements, and the provisions of pertinent power organizations to ensure the accuracy and standardization of the system simulation data. Distinguish the characteristics of metering devices in different cities and counties. Conduct digital simulation modeling of electric energy metering devices based on the principle of "unified standard, unified platform, and unified implementation"

Data Availability

The data underlying the results presented in the study are available within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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