Research on Fault Diagnosis Method of Electric Energy Metering Equipment Based on Expert System

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Abstract. The realization of the full coverage of the smart meter and the metering automation terminal across the entire network brings great challenges to the operation and maintenance of the field. Aiming at the long-term problems of on-site failure operation and maintenance of the electric energy metering equipment, this paper combines the metering and collecting of failure types to analyse the main causes of equipment failure, based on the field topology structure for fault reasoning, and designs fault diagnosis and fault knowledge base as the core module for fault diagnosis. The expert system has been proved by practice that this method can effectively diagnose and solve the failure problem of the energy metering equipment, which is beneficial to realize the intelligenitization of on-site fault diagnosis and improve the on-site maintenance efficiency of the energy metering equipment, and has practical reference value.

1. Introduction

Since the 12th Five-Year Plan, China Southern Power Grid has actively carried out the planning and construction of smart meters and metering automation terminals. In 2011, China Southern Power Grid issued the smart meter series enterprise standard, and in 2013, China Southern Power Grid issued the metering automation terminal series enterprise standard, which comprehensively promoted the application of smart meters and metering automation terminals. The network-level and provincial-level metering automation systems covering customs, special changes, public changes and resident users have been built. As of December 2018, the coverage of China Southern Power Grid's entire network of smart meters reached 100%, and the coverage of low-voltage meter reading reached 100%. Cumulatively completed the installation and construction of more than 80 million smart meters and more than 8 million metering automation terminals.

The stable and reliable operation status of such a huge amount of electric energy metering equipment is directly related to the vital interests of the people and the harmony and stability of society. Even small faults and quality problems will have an inestimable impact. Therefore, the operation of massive equipment not only puts forward strict requirements on its own quality, but also brings a huge burden to the on-site metering abnormality and the operation and maintenance of the collection network. According to the current on-site failure operation and maintenance of electric energy metering equipment [1-3], this article has conducted in-depth analysis and research, combined with the actual
failure phenomena of smart meters and metering automation terminals, analyzed the metering and collecting failure types, and then established the on-site topology structure and fault reasoning of electric energy metering equipment. It proposes an on-site topology structure suitable for electric energy metering equipment, designs corresponding fault diagnosis expert system, uses forward reasoning mechanism to establish and improve the fault knowledge base, and verifies the efficiency, correctness and practicability of the system through practical application. The results will play an important role in the future construction of intelligent operation and maintenance systems to meet the development requirements of intelligent metering systems.

2. Analysis and Research on the Failure of Electric Energy Metering Equipment

2.1. Analysis of metering failure types

Smart meters have the characteristics of highly integrated software and hardware, continuous online operation, real-time communication, instant response, and other embedded metering systems, so the quality of their software and hardware is particularly important to control. In order to ensure the normal operation of smart meters, maintain unbiased measurement, reduce the failure rate, and improve the power service level, it is necessary to analyze the typical failure types of smart meters [4, 5].

Through the feedback information of after-sales and operation and maintenance personnel on the failure events of smart meters on site, the 57 field failure cases collected are analyzed. The failure modes and probability statistics are shown in Figure 1. From the probability statistics, it is not difficult to find that the probability of failure occurrence in descending order of failure ratio is: metering failure, communication failure, display failure, charge control failure, low-battery voltage, clock failure, etc.

![Figure 1. Failure modes and probability statistics occurring on site.](image-url)

According to the specific case analysis, the main causes of smart meter failures are summarized into data category, normal or abnormal power failure category, program failure category, software abnormalities caused by hardware and external interference, as shown in the specific Figure 2 shows.
Figure 2. Failure types of smart meter.

The possible impact of these failure types mainly includes the failure of each functional module, such as communication failure, power freezing data error, metering error, clock deviation, low-battery voltage, load curve storage error, etc.

1. Data category: including communication data (baud rate, communication address, and communication protocol), parameters, input and output data, storage data, etc. Among them, the probability of failure of data, data integrity, and data input and output sequence under abnormal conditions such as boundaries, fault tolerance, and limits is high.

2. Normal or abnormal power failure category: there are many metering, communication, clock and storage failures caused by power fault, and most of them are serious failures.

3. Program failure category: including incomplete program function design and incomplete reliability design, resulting in abnormal program reset, etc.

4. Software abnormalities caused by hardware and external interference: abnormal operating conditions such as external electromagnetic and power grids cause damage to the smart meter hardware, which affects the operation of the program or directly causes the program to reset, run away, and other failures.

2.2. Analysis of collecting failure types

The metering automation terminal is a particularly important part of the electric energy metering system and plays a key role in the electric energy billing system. The metering automation terminal is installed in the field to connect with smart meters, collect electrical energy data, load data, power outage events, etc. of the client, and timely transmit all kinds of collected data and information to the main station. The type of collecting failures [6, 7] can be analyzed based on the statistical data of the failures of the metering automation terminal in a province of the Southern Network, as shown in Figure 3 below.
Through statistics, it can be seen that the failures of the metering automation terminal are roughly divided into the following categories: terminal working anomaly, display error, metering inaccuracy, and communication anomaly, etc.

1) Terminal working anomaly. The terminal cannot run normally, and generally needs to go to the site for operation and maintenance or return to the factory for repair. Through on-site inspection and repair analysis, it is found that the terminal does not work because of the following reasons: 1) Flashing the terminal program too fast results in fragmentation and system instability; 2) When the terminal program is upgraded, the power is suddenly cut off, which results in the completion of the upgrade of some programs, but the upgrade of some programs has not been completed. There is a compatibility problem between the two parts, which eventually leads to abnormal operation of the terminal; 3) The terminal belongs to a regional plan or sudden power fault, resulting in abnormal terminal operation; 4) The terminal is subjected to lightning strikes or high pulse surges, which causes the terminal power module or power protection circuit to burn out, resulting in the terminal not being able to work normally.

2) Display error. The LCD white screen, black screen, and splash screen of the terminal are abnormal. Through on-site inspection and analysis of repairs returned to the factory, the main reasons found were: 1) LCD or accessories do not meet the environmental requirements (such as the LCD needs to display normally at -20~75°C; 2) LCD power supply fault; 3) The program and parameters of the terminal do not match, causing the LCD to be stuck all the time; 4) The LCD control part of the terminal program is abnormal, resulting in LCD white screen or splash screen.

3) Metering inaccuracy. The software and hardware of the metering module are abnormal, resulting in metering inaccuracy.

4) Communication anomaly. Generally, it means that the terminal is offline (the master station cannot be connected for a long time) or frequently offline. The reasons for abnormal communication are: 1) Incorrect remote communication parameters; 2) Communication card business and tariff issues; 3) Loss of communication antenna or weak signal; 4) Damage to the remote communication module; 5) Defect in the design of the communication module; 6) The problem of cooperation between terminal and communication module.

5) Other failures. Generally, there are problems such as abnormal clocks, damaged buttons or casings. The main reasons are: 1) The hardware of the clock chip is abnormal; 2) The voltage of the clock battery is low; 3) The terminal keys are damaged due to external force, resulting in slow or no response of the keys.
3. On-site Topology Structure and Fault Reasoning of Electric Energy Metering Equipment

Since smart meters and metering automation terminals have their own respective clear equipment standard specifications, the software architecture and the hardware architecture have been basically determined, and the acquisition networking technology also has corresponding specifications for a period of time. Therefore, the types of metering failures and collecting failures on the spot can be exhaustive [8-10]. The complexity of on-site operation and the complexity of equipment combination make the fault resolution path have diverse characteristics.

In order to collect the failure problems of electric energy metering equipment and facilitate the construction of the equipment fault knowledge base, it is necessary to sort out the on-site topology structure of the electric energy metering equipment and establish the corresponding networking model.

First of all, the master station system establishes a device connection model according to the specific communication networking mode, such as GPRS for upstream communication and carrier wave for downstream communication. The established primary networking model is shown in Figure 4 below.

![Figure 4. Primary networking model.](image)

This model is mainly used to collect the initial location of abnormalities. According to the connection relationship between the master station and multiple concentrators, the connection relationship between the concentrator and multiple smart meters, as well as the historical communication records and current connection status, it can be preliminarily judged that the scope of the communication failure device belongs to the master station, the mobile network, concentrator or smart meter.

Secondly, according to the needs of equipment configuration and operation and maintenance, the networking mode of concentrators and smart meters can be further decomposed to the second layer. The established equipment connection networking model is shown in Figure 5 below.

![Figure 5. Node networking model.](image)

According to the production knowledge representation rules, knowledge can be expressed as: "Concentrator is not online" → "GPRS module abnormality" or "Concentrator body abnormality", with a confidence of 50% each; "Abnormal meter reading" → "Concentrator body abnormality" or "Concentrator carrier module abnormality" or "Smart meter carrier module abnormality" or "Smart meter body abnormality" or "carrier link abnormality", with a confidence of 20%. In the specific judgment, the verified rules can be established: 1) If the concentrator can normally read part of the data of the smart meter, the abnormality of the concentrator and the downlink carrier module can be ruled out; 2) If there is no problem in the above, it can be considered that the collection process of the meter reading software of the concentrator is unreasonable.

From the above analysis, it can be seen that after decomposing to the second layer, the failure location is more refined and more accurate. The GPRS module, concentrator body, etc. can still be decomposed to the third layer according to the requirements of operation and maintenance. For example, the GPRS module can be decomposed into the content shown in Figure 6 below.
Figure 6. GPRS module decomposition.

In this way, you can locate the failure problem that occurs in the module to any of the GPRS card hardware problem, information problem, GPRS module body problem, communication parameter setting problem, etc.

According to the above method, when constructing the on-site topology structure of electric energy metering equipment, a primary network model can be established according to the device connection method, and a layer-by-layer node network model can be established according to the layer decomposition method. Then, according to the type of each node, the failure model of each node is established. Combining the precedence relationship and dependency of faulty nodes, fault reasoning is performed to provide support for the construction of fault knowledge base.

4. Design of Expert System for Fault Diagnosis
This paper proposes a fault diagnosis expert system suitable for electric energy metering equipment. Its main components include: database, fault reasoning machine, fault knowledge base, reasoning and interpretation module, and human-computer interaction interface. The specific structural relationship is shown in Figure 7. The main functions of each module are as follows:
(1) Database: Store the necessary basic original data of the system and all data and records generated during the operation (especially the reasoning process).
(2) Fault reasoning machine: It is a thinking process that simulates experts to analyze and solve problems. This is an indispensable and important part of the system. It can ensure the rapid and accurate diagnosis of the faults of the electric energy metering equipment, determine the cause of the failures in the shortest possible time, and use the knowledge in the fault knowledge base according to the information. A certain control strategy is adopted to solve the problem and realize fault diagnosis and reasoning.
(3) Fault knowledge base: It is a collection of failure feature information displayed by electric energy metering equipment in failure modes, including system knowledge, equipment failure characteristics, inference rules, etc. It is required that the knowledge contained in the knowledge base is as rich as possible, and at the same time it can complete the functions of knowledge storage, retrieval, modification, deletion, etc. It is the core part and important foundation of the fault diagnosis expert system.
(4) Reasoning and interpretation module: In the process of fault diagnosis, in addition to providing accurate diagnosis results, it is necessary to make necessary and rigorous interpretation of the results. This module can be used to explain the behavior and execution results of the fault diagnosis expert system to the user, making it easier for the user to accept the inference results.
(5) Human-computer interaction interface: It is the interaction point of human-computer information. The friendliness and ease of operation of the interface are particularly important. It needs to reach a simple and easy-to-understand operation level to facilitate the user's use.
After collecting the failure information of the electric energy metering equipment being diagnosed, the built fault diagnosis expert system comprehensively uses various rules to perform a series of fault reasoning, so as to quickly find the final fault or the most likely fault, and complete the intelligent detection of the fault. And quickly solve the recovery through the corresponding fault handling method, saving a lot of fault diagnosis time for business personnel and improving the efficiency of operation and maintenance.

The performance of fault diagnosis expert system mainly depends on the quantity and quality of knowledge in the fault knowledge base, and the rationality of fault reasoning mechanism [11, 12]. The following are the two core modules in the system: fault reasoning machine and fault knowledge base, to expand the design of fault diagnosis process for electric energy metering equipment.

4.1. Fault reasoning machine
The diagnosis and prediction of the failure will provide an important decision basis for the evaluation of the impact of the failure and the selection of mitigation measures.

The fault reasoning machine is a key component of the fault diagnosis expert system. It is a thinking process for simulating and analyzing problems and solving problems. It is a program for fault diagnosis and reasoning [13]. Based on the current abnormal state information, the fault reasoning machine uses corresponding algorithms to simulate the expert's thinking process when solving the problem, selects the relevant knowledge in the fault knowledge base according to a certain control strategy, and infers the most likely cause of failure of the electric energy metering equipment, and gives the corresponding troubleshooting method to solve the current equipment failure problem.

The fault diagnosis of electric energy metering equipment adopts a forward reasoning mechanism. Based on the failure events or predicted failures that will be reported on the spot, using the knowledge stored in the equipment fault knowledge base, according to the rules defined in advance, the reason for the failure occurrence is introduced and explained, and the final conclusion is drawn.

4.2. Fault knowledge base
The fault knowledge base draws on technologies such as information storage, information sharing, concurrency control, and data recovery in the database to realize the storage and management of fault knowledge. At the same time, it uses effective knowledge representation and reasoning mechanisms to
diagnose and locate the fault mechanism [14]. In addition, the knowledge base is an open system, and its main frame must meet the needs of knowledge update.

The establishment of a fault knowledge base for electric energy metering equipment is different from the application programs that generally implicate knowledge into the code. It is an explicit expression of the problem solving method in the application field, drawing on database technology storage and management knowledge, and using targeted knowledge representation method and reasoning mechanism, quickly search and locate the final fault or the most likely fault, call the most relevant typical failure case solution stored in the knowledge base to solve real-time fault, is a practical knowledge-based fault diagnosis method. The operation process of the fault knowledge base is shown in Figure 8 below.

![Figure 8. Operation process of fault knowledge base. ](image)

Using the above fault reasoning mechanism and fault knowledge base to design a set of on-site fault diagnosis expert system for electric energy metering equipment, the design process follows the following principles:

1) Establish a unified fault knowledge base to realize the collecting and metering knowledge sharing within the scope of the China Southern Power Grid.

2) Establish a base of typical on-site operating modes and model the system in a hierarchical mode, that is, modeling based on the master station, upstream communication network, terminal, collector, meter, and local communication network, and the communication mode is based on the three modes of full load, half load and 485, each equipment is modeled according to the equipment body and module.

3) Model the operating failure modes of each module node.

4) Summarize typical troubleshooting methods on site and establish a base of typical troubleshooting methods.

5) The system can realize the automatic matching of failure phenomena and typical failure cases through fuzzy query and pattern matching inference mechanism according to the types of on-site failures, and improve the accuracy of automatic fault diagnosis.

6) Establish a layer-by-layer reporting mechanism for difficult problems at the China Southern Power Grid, province, city, and county levels to achieve simple problems at the grassroots level and complex problems in a centralized manner.
5. Application Practice of Fault Diagnosis Expert System

After the system development is completed, import the 10 Dingxin carrier program's station files, collected data and GPRS communication records in a certain area, and find the following failure cases from the historical data: the terminal of a certain plot has not been online for the last 5 days; a certain smart meter has not been able to collect data. Arrange business personnel to bring the handheld devices and detection tools to the failure occurrence site, use the device’s APP to remotely connect to the local fault diagnosis expert system through GPRS, and select the failure object for remote diagnosis. It was finally determined that the reason for the terminal not going online was that the terminal's upstream GPRS module had been operating in a high-temperature and high-humidity environment for a long time, which resulted in deformation of the card holder and poor contact with the SIM card. After replacing the module, the failure was eliminated. It is determined that the reason why the data cannot be collected by the smart meter is that the power supply radius is too long, which results in a wrong carrier routing. After adding the relay device, the failure is eliminated. The above failure cases have proved the practicality of the fault reasoning mechanism and the correctness of the fault knowledge base through practical application. The fault diagnosis expert system for on-site fault diagnosis of electric energy metering equipment is of practical significance.

6. Conclusions

In this paper, based on the current collected cases of on-site electric energy metering equipment operation and maintenance failures, combined with failure phenomenon analysis, metering and collecting of failure types, based on the summary of the main causes of failures, the construction of the topological structure of the metering equipment on-site structure and fault forward reasoning, forming a fault diagnosis expert system with fault inference engine, fault knowledge base and other core parts. Through practical verification, the research results can achieve efficient and intelligent diagnosis and immediate resolution of on-site failure problems of metering equipment, improve on-site maintenance efficiency, play a major role, and meet development requirements. The method in this paper can strengthen the operation and maintenance of on-site metering abnormality or collecting abnormality, to ensure the quality of metering equipment operation, improve the data collection complete rate, reduce the number of missed reports, false positives, and repeated reports, eliminate measurement abnormalities, and improve the completeness and accuracy of data collection. It helps on-site operation and maintenance personnel save a lot of equipment fault diagnosis time, and provides technical support for the implementation of intelligent operation and maintenance systems that adapt to the smart grid architecture, and has guidance and application value.

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