Key Technologies of Intelligent Manufacturing of Protection and Control Equipment in Ubiquitous Power Internet of Things

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Abstract. As the most basic and lowest data node of ubiquitous power Internet of things, power system protection and control equipment plays a vital role in the stable operation of ubiquitous power Internet of things. The current status and problems of power system protection and control equipment manufacturing are discussed. Aiming at the National Equipment Manufacturing Industry Standardization and Quality Improvement Plan, the production intelligent manufacturing standards and related test verification standards of power system protection and control equipment are put forward. Four key points of intelligent manufacturing of power system protection and control equipment are studied. Technical features: intelligent design verification, intelligent production scheduling verification, intelligent production, power control and protection equipment life cycle data management. Through the gradual implementation of these technologies, the level of intelligent manufacturing of protection and control equipment for ubiquitous power network interconnection has been improved, hoping to promote the implementation and application of national equipment manufacturing standards in the power industry.

Keywords. Ubiquitous internet of things; intelligent manufacturing; intelligent production scheduling; intelligent testing; intelligent scheduling.

1. Introduction
In 2019, State Grid Corporation of China creatively put forward the strategic goal of being a world-class energy Internet enterprise of “Three Types and Two Networks”, that is, to build both strong smart grid and ubiquitous power Internet of things of “hub type, platform type and sharing type”. Strong smart grid is a new modern power grid with ultra-high voltage and extra-high voltage power grids as the backbone grid frame, and coordinated development at all levels, featured by informationization, automation, interactive characteristics, intelligent response capability and system self-healing capability [1-2]. The ubiquitous power Internet of things is an intelligent service system which focuses on all aspects of the power system, fully applies modern information technologies and advanced communication technologies such as mobile Internet and artificial intelligence to realize the interconnection of all things and human interaction in the power system, and has the characteristics of comprehensive state perception, efficient information processing, convenient and flexible application, etc. [3-4]. As the core secondary equipment of power system, protection and control equipment plays an important role in the
ubiquitous power Internet of things. Its design, production, operation and maintenance, life cycle quality management and information collection are important factors for the safe and stable operation of power system. At the same time, it is inevitably an important part of ubiquitous power Internet of things due to its own high-speed sampling of system information, signal processing and storage and LAN communication functions.

In recent years, with the increasing maturity of high-speed communication technology, artificial intelligence (AI) technology and system on chip (SOC) technology, protection and control equipment has been more miniaturized with higher system integration level. The application of big data algorithm and the comparison with existing traditional physical models of power system make the system analysis, operation and maintenance more intelligent and efficient. Intelligent manufacturing of protection and control equipment and its process data are the basis of ubiquitous interconnection.

Under the macro background of the current ubiquitous power Internet of things construction, this paper deeply discusses the relevant standards and related key technologies of intelligent manufacturing of protection and control equipment, which is the most basic data node of ubiquitous power Internet of things, hoping to provide corresponding support for the implementation and application of national equipment manufacturing standardization in the power industry.

2. Current Situation, Problems and Standards

At present, the power system control and protection equipment has gone through three steps, including selection of components, manufacturing of single board and then manufacturing of device, realizing small-batch production. As a product in small-batch production, the power system protection and control equipment is still in manual production stage in general. Ref. [5] discusses the feasibility of flexible testing in single board and device testing, and puts forward a general intelligent testing solution, which, taking the production testing of low-voltage protection device as the pilot, designs and develops flexible on-line intelligent testing system for relay protection device by adopting technical means such as using industrial robots for intelligent handling, designing a testing flow line for on-line transfer of devices, and developing a matching flexible intelligent testing station, thus realizing intelligent testing of low-voltage protection device; Refs. [6-8] put forward an automatic testing platform for protection and control equipment of power system, realizing the automatic testing of protection and control equipment and effectively improving the testing efficiency of protection and control equipment of power system; and Ref. [9] puts forward an automated testing method for smart distribution grid FTU, effectively reducing the burden of testers and improving the production and testing efficiency of FTU. Refs. [10-15] put forward automatic testing solutions for the production and R&D testing of relay protection device in power system respectively, effectively improving the production and R&D testing efficiency. Refs. [16-19] put forward a general testing platform for relay protection devices in intelligent substation to solve the problems of relay protection devices in site testing. The current researches have shown that mere improvement in the testing of protection and control equipment in the power system protection and control equipment manufacturing industry can achieve local automation and intelligent testing, while the intelligent manufacturing of the whole industry needs to be further improved.

In August 2016, the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, the Standardization Administration of the People’s Republic of China and the Ministry of Industry and Information Technology issued the National Equipment Manufacturing Industry Standardization and Quality Improvement Plan for promoting standardization breakthroughs in key areas and improving the quality competitiveness of the equipment manufacturing industry, which pointed out that we should drive the transformation and quality upgrading of equipment manufacturing industry with advanced standards and implement intelligent manufacturing standardization and quality improvement projects. In September 2016, the Ministry of Industry and Information Technology and the Ministry of Finance issued the Intelligent Manufacturing Development Plan (2016-2020), which put forward work requirements for the construction of intelligent manufacturing standard system as showing in figure 1, the development of standard research and experimental verification, and the acceleration of formulation, revision, popularization and application of standards.
Figure 1. Basic characteristics of intelligent manufacturing technology.

Basic common standards for safety, reliability, testing, evaluation, etc. are formulated according to the principle of “common first, urgent need first” to promote the development of industry application standards. In power protection and control equipment manufacturing industry, an intelligent characteristic of resource sharing and interconnection has been put forward from two dimensions including life cycle (design, production, logistics, etc.) and system level (equipment, unit, workshop, etc.) of power protection and control equipment, to establish relevant technical standards for intelligent manufacturing of power system protection and control equipment, so as to realize the implementation of intelligent manufacturing standards for power protection and control equipment.

3. Key Technologies of Intelligent Manufacturing of Power Protection and Control Equipment

This paper will elaborate the key technologies of intelligent manufacturing of power system protection and control equipment from the following aspects: intelligent design verification, intelligent production scheduling, intelligent production, etc. of power system protection and control equipment.

3.1. Intelligent Design Verification

Digital design and simulation of power protection and control equipment are key technologies of its feasible manufacturing. In the early design stage of embedded products, DFM rule simulation technology is used to improve the manufacturability of hardware to make parts and various processes easy to manufacture and the product design needs meet the requirements of product manufacturing with good manufacturability, so that products can be manufactured with the lowest cost, the shortest time and the highest quality.

In the design stage of hardware PCB, DRC rules are used to identify and modify potential defects immediately through automatic inspection of design specifications and three-dimensional simulation as shown in figure 2 ensuring the reliability of product and the first-pass rate and effectively reducing the product development cycle and cost.

For structural parts of the embedded device, 3D printing technology is used to rapidly form prototype, thus reducing the processing time of prototype. Fast, high-precision and high-resolution printing of structures with complex shapes, especially for plastic structural parts, provides strong support for rapid development of products.

3.2. Intelligent Production Scheduling Verification

Scheduling control belongs to the management control of the executive level of manufacturing system, with the basic task of completing real-time information exchange between MES and APS, which connects the planned production scheduling and production scheduling. MES will analyze the data and
provide it to APS, and APS will transfer the reasonable production scheduling to MES system for scheduling, effectively facilitating the data transfer between plan and production and ensuring the rapid response from plan to workshop. Through production scheduling and scheduling of MES system, the workshop can quickly and effectively implement the production plan. Through the collection of production process data, and analysis of data and important production factors such as production equipment, productivity, production order achievement, production capacity and output, the purpose of closed-loop application can be achieved, so as to improve the production management efficiency.

Function can be established according to the performance index of processing cycle for production scheduling, to calculate the optimal production scheduling mode. Calculate the MFT (mean flow time) of operation.

\[
MFT = \frac{\sum_{i=1}^{n} C_i}{n} = \frac{\sum_{i=1}^{n} \omega_i + \sum_{i=1}^{n} t_i}{n}
\]

where: \(C_i\) refers to the completion time of the i-th operation, \(C_i = t_i + \omega_i\), \(\omega_i\) \(t_i\) refers to the waiting time, processing time and line changing time of the i-th operation. Among them, the processing time and line changing time are fixed, so it is mainly the calculation of waiting time for \(\omega_i\).

Make calculation according to the processing and line changing time of n-th operation:

Waiting time of the 2nd operation: \(\omega_2 = t_1\)

Waiting time of the 3rd operation: \(\omega_3 = t_1 + t_2\)

It can be inferred that the total waiting time is:

\[
\sum_{i=1}^{n} \omega_i = t_1 + (t_1 + t_2) + \cdots + (t_1 + t_2 + \cdots + t_{n-1}) = (n - 1)t_1 + (n - 2)t_2 + \cdots + t_{n-1}
\]

According to the principle of the shortest production scheduling time, the reasonable way shall be \(t_1 < t_2 < \cdots < t_{n-1}\).

Based on the above methods, model simulation is used to make preview in advance, so as to improve the production scheduling strategy. Through calculation of order quantity and completion time, the suitable processing batches and the optimal production scheduling sequence are calculated respectively. The order quantity, product type, processing technology, equipment status, and delivery cycle in actual production are very complex and ever-changing, so it is necessary to make weighted correction on the production scheduling strategy according to the actual situation, but the above two major principles shall remain basically unchanged.

3.3. Intelligent Production

Intelligent production is the key link of intelligent manufacturing of power system protection and control equipment. Power system protection and control equipment consists of various functional boards, which have realized automatic or intelligent production from bare PCBs to functional boards through SMT and
THT production lines during manufacturing. However, the testing of these functional boards and devices basically stays at the stage of manual testing or semi-automatic testing, so there is still a long way to go before intelligent testing. The difficulty for boards of the power system protection equipment or the power system protection equipment itself to realize intelligent testing lies in the various kinds of boards and devices and interfaces. Such equipment is a truly niche product compared with household appliances. There are certain difficulties in the realization of intelligent testing in terms of manpower, financial resources, and technical implementation.

Regardless of a single functional board or the complete protection and control equipment, the key technical characteristics of intelligent testing technology for power system protection and control equipment are that the testing system intelligently identifies the tested object, and the machine automatically acquires various attributes of the tested object, including bar code, two-dimensional code or unique code of the device or board, realizes data search through unique identification to inquire relevant details of the device or board, such as composition, order information and production time of the device/board, builds a digital data model of the tested object, intelligently builds a closed-loop testing environment, drives the tester to call up the corresponding functional modules for automatic hardware testing, automatically makes judgment according to the testing results, split the testing environment and automatically transfer it. In terms of technical implementation, it establishes plug-in and single device intelligent testing systems as showing in figure 3 to realize state monitoring of testing system, automatic uploading of the testing report of each board or device and automatic analysis and pushing of the test error report throughout the whole process, as well as the tracking of various test data [5].

Figure 3. General flow of intelligent testing for power equipment.

Single plug-in intelligent testing system is one important link to realize intelligent manufacturing of functional boards of power protection and control equipment. By extending SMT production line, the production/testing mode of functional boards is realized at the end to closely combine the production link with the testing link, thus realizing the integration of production and testing. Specifically, rapid testing and assembly of the board is realized by designing embedded single board testing system at the end of the production line and single board on-line intelligent testing system or single board intelligent testing cabinet.

Figure 4 shows two different design methods of single board intelligent testing system. Scheme A forms a real single board on-line intelligent testing, which extends the SMT production line and makes the board move on the guide rail to enter the working area of single board on-line intelligent testing system, so as to realize that the board clips into the position, and the system scans the code and identifies the board model. The board BOOT and program is download, and the testing system intelligently builds closed-loop testing environment, which realize the function testing, uploading of the testing report to cloud, and the continuous transfer of board along the guide rail and manual assembly and load. In Scheme B, a robot and a single board intelligent testing cabinet are set beside the guide rail, and several
testers are arranged on the testing cabinet. The robot grabs the boards on the SMT production line and puts them on testers. When the testing is completed, the system informs the robot to grab the boards to the assembly line which will transfer them to the manual assembly area. For the above two designs, the former realizes the compact design of the assembly line, and the latter realizes the rapid processing of boards on the assembly line. Real-time monitoring of testing process and real-time uploading of the testing report can realize traceability of the testing results and subsequent quality statistics and analysis.

The device intelligent testing system is an important part of the intelligent manufacturing of power protection and control equipment. Based on figure 3, General Glow of Intelligent Testing for Power Equipment, a set of device intelligent testing system is designed. The detailed system flow is shown in figure 5. Through the complete set of system, information interaction among the robot, testing cabinet, upper computer, PLC, etc. can be realized, the whole process of single device grabbing, sorting, intelligent testing and back flow to the assembly line can be completed, the operation of the equipment can be monitored in real time, and the testing results can be summarized and analyzed.

Figure 4. Single board intelligent testing system.

Figure 5. Device intelligent testing system.
Robot of the system locates the product accurately with the vision system, which realizes automatic grabbing and handling of the product and improves the efficiency of handling. The upper computer system can interact with MES, which makes the assembly station realize BOM visualization, reducing the risk of assembly errors and improving assembly efficiency. The device intelligent testing station adopts a flexible design for functional testing of multiple models of products, solving the problem of frequent line change in traditional test methods, and improving commissioning efficiency. Four flexible device intelligent testing stations are compatible with various low-voltage products and can meet the testing cycle time of the whole system in one minute. The flexible device intelligent testing station adopts the automatic material demand mode, with the products entering the testing station in turn. After the product enters the testing station, the product bar code is scanned. The upper computer analyzes the product according to the Terminal block, and the PLC automatically selects the testing module and the socket sequence for switching according to the analysis results. After the terminal is put into operation, the SmartTester testing software calls the testing program according to the product, and gives feedback of the testing results to the upper computer system.

The flexible device intelligent testing station realizes the automatic selection and switching of testing terminals through communication among the upper computer, PLC and SmartTester testing software. Compared with the traditional testing method, it omits the tedious steps of manual identification of testing lines and testing sockets, as well as product models and voltage levels, manual selection of testing programs, etc., improves commissioning efficiency, reduces the risk of commissioning mistakes and omission, improves product quality, reduces labor cost and working intensity, and increases production capacity by 100% during normal working hours.

The self-developed intelligent high-temperature aging system is responsible for the acquisition and monitoring of the temperature of the high-temperature aging room of the protection and control equipment, which can realize one-click intelligent control. There is no need to manually set the temperature setting value and upper and lower limits during high-temperature aging. The system connects the alarm and locking nodes of the test device to the measurement and control device to automatically monitor the high-temperature aging test process of each device, which can display the monitoring information and device status information through LCD screen and realize automatic voltage regulation and automatic triggering for recording of position, temperature, etc. of the test device. According to the importance of abnormal information, the system sends short messages to the mobile phones of the personnel on duty in real time to realize unattended operation. Through data integration, the system realizes real-time decision-making process of status information, such as automatic monitoring in the background, printing of test reports, storage and uploading of test data, and statistics and on-line analysis of historical data.

4. Life Cycle Management of Protection and Control Equipment
At present, it is of great significance to establish a big data analysis model with self decision-making function in life cycle of power system protection and control equipment. In figure 6, the production cycle is taken as the time axis in the horizontal direction, and the vertical direction is the data application objects, which are divided into three stages for data application excavation. Making use of these data modeling analysis to integrate industrial chain and value chain and realize prediction, warning, auxiliary control and intelligent decision-making of data analysis will produce significant economic benefits.

4.1. APS System
According to various data such as the demand cycle, production cycle and demand device of different types of devices, the production cycle, production mode and reasonable inventory suggestions of different types of devices are analyzed and given feedback to APS system. APS system makes decisions based on data analysis for production scheduling to arrange production for various types of devices according to different production cycles and production modes, so as to optimize the inventory stocking types and reduce inventory.
4.2. SCADA System
By equipment interconnection of production welding, single board commissioning, device commissioning, continuous operation, etc., the overall utilization of equipment and production efficiency can be evaluated and the production time can be mastered, to achieve the highest utilization efficiency of equipment load, and real-time grasping of equipment operation and expected maintenance strategy, so as to realize the highest overall production efficiency.

4.3. Intelligent Quality Control
All process quality data are directly transferred to the maintenance system from surface-mount to shipment, and the system automatically records the abnormal conditions and pushes them to remind the maintenance engineer. By collecting the links, processes, equipment, personnel and materials that generate abnormal data, the system intelligently analyzes the causes, and provides reasonable suggestions on equipment maintenance, personnel training, supplier interviews, etc.

4.4. Intelligent Management
By collecting and analyzing the overall data of the production process, the working hours of processes in each link are detailed, and suggestions on personnel operation level approval and staff allocation are made, which can realize clear overall workshop operation capacity and allocation of resources, establish the scheduling strategy of one person for multiple posts, etc.

4.5. Intelligent Logistics
Logistics map is used to reflect shipping tasks and completion status. Data sources mainly include task orders and status data of logistics companies. The system better displays the in transit orders and delivery completion rate, and realizes the binding of device bar code and shipping order, as well as the traceability of shipment in batches and substations.

4.6. Big Data Analysis
Product information and quality data generated during intelligent manufacturing are used for intelligent operation and maintenance. The site abnormality bubble chart reflects the fault distribution and abnormality law through big data analysis, and the information such as two-dimensional code of the
equipment can also be used to trace backward for the production process data, to determine whether the abnormality is a common problem in batches and improve the technical means of quality inspection in the factory.

5. Engineering Application
On the basis of in-depth study of standards and specifications and intelligent manufacturing development planning of national equipment manufacturing industry, we researched and developed intelligent manufacturing technology for power protection and control equipment and implemented the technology in Nanjing NR Electric Co., Ltd. combining the characteristics of power equipment and its actual production situation, and made a series of technical research and attempts in the following aspects: intelligent design verification and intelligent production scheduling verification of power equipment, intelligent production testing of single board and device, intelligent high-temperature aging and intelligent warehouse management, life cycle management of big data of power equipment, etc.

![Intelligent manufacturing platform for power equipment](image)

**Figure 7. Intelligent manufacturing platform for power equipment.**

On the one hand, an intelligent manufacturing management system for coordinating research and development, manufacturing, engineering, operation and maintenance services, supply chain and enterprise management is being established by continuously deepening the application of and integrating the ERP, MIS, SRM, WMS and other information systems; on the other hand, a new digital, intelligent, networked and integrated manufacturing mode based on functions of SAP, MES, WMS, MIS and other systems is being explored. A new intelligent collaborative manufacturing mode is being formed by integrating production process, enterprise business management and product life cycle management, to improve the management efficiency of lean production. At present, an effective small-scale intelligent manufacturing platform for power protection and control equipment has been formed, as shown in figure 7. The platform improves the production efficiency by over 20% and reduces the consumption rate of energy resources by over 30% in key application areas, with obvious effect.

6. Conclusion
In view of the current manufacturing status and problems of power system protection and control equipment, this paper studies the key technical characteristics of intelligent manufacturing of protection and control equipment for ubiquitous power Internet of things from four aspects: intelligent design, intelligent production scheduling verification, intelligent commissioning, and life cycle data management of power protection and control equipment combining the National Equipment Manufacturing Industry Standardization and Quality Improvement Plan, and develops the technical support system of corresponding production stage based on that.

Characteristics and rapid development of power system protection and control equipment determine
that the refinement of intelligent manufacturing technical standards and technical implementation in power industry cannot be achieved overnight. The implementation, effectiveness verification and promotion of intelligent manufacturing technical standards for power equipment need to be further discussed, which is also the focus of the next research.

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