Visual Online Debugging and Diagnosis System for Substation Secondary Equipment

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Abstract. Firstly, based on the demand of substation "operation and maintenance integration", this paper describes the necessity of constructing an efficient, flexible and reliable remote operation and maintenance system. Then, the realization architecture, characteristics and key technologies of the visual online debugging and diagnosis system with flexible configuration are proposed. The system realizes the remote operation and maintenance services such as remote debugging of secondary equipment, intelligent diagnosis, health status assessment and status prediction by using container technology, video processing technology, virtual liquid crystal technology, etc. The application practice shows that the visual online debugging and diagnosis system improves the standardization management and visualization of secondary equipment and optimizes the remote operation and maintenance mode.

1. Introduction
In recent years, the concepts of "Internet+" and "Energy Internet" have been vigorously promoted. The State Council and the National Development and Reform Commission have successively issued "Several Opinions on Further Deepening the Reform of the Power System", "Guiding Opinions on Promoting the Development of "Internet+" Smart Energy" and other documents to guide the reform of the power system. The State Grid Corporation has held relevant meetings to fully deploy the construction of energy internet. How to improve the level of power grid management and realize integrated operation and maintenance with the help of cloud computing, big data analysis, advanced communication technology and other technologies is the focus and difficulty of current research.

With the large amount of new substations put into operation, the promotion of unattended substations [1-2], and the implementation of dispatching and control scheme, the data collected into the dispatch automation system has increased significantly, which will inevitably increase the operation and maintenance workload of the dispatching center. Literature [3-4] proposed a new generation dispatching and control system that combines the “Internet+” concept and the “Internet of Things technology”. It has balanced the decision analysis task in several different decision-making centers, optimized the power grid management mode, but failed to provide effective remote operation and maintenance methods. Literature [5] proposed the system architecture of intelligent operation and maintenance of the secondary equipment of the smart grid, and studied the key technologies of secondary equipment visual operation and maintenance, intelligent warning, and fault diagnosis and so on. Among them, the visual operation and maintenance focuses on the research of graphical display technology, without mentioning the visual control of the equipment. The automatic generation and online checking technology proposed in literature [6-7] guarantee the accuracy of the remote operation and maintenance system. The substation remote operation and maintenance system proposed in literature [8-9] has realized the functions such as remote monitoring of equipment status, remote
inspection, remote fault processing, remote intelligent diagnosis, and remote testing. The secondary equipment diagnosis mode has changed from "local diagnosis" to "remote diagnosis". Literature [10] puts forward the overall solution of "integrated operation and maintenance", and introduces hardware structure, monitoring and early warning, fault processing and other key technology supporting the integrated operation and maintenance. The above researches mainly involve substation operation status monitoring, intelligent alarm, fault location and processing functions, or auxiliary operation and maintenance means such as remote testing and self-checking, which have improved the level of grid intelligence to a certain extent. However, the interaction level between the master station and substations, and the interaction level between substation equipment have not been improved. Moreover, the existing remote operation and maintenance system has many deficiencies in visualization level, expansibility and intelligence, so it is urgent to study a more efficient, flexible and reliable remote operation and maintenance system.

In order to realize the requirement of "operation and maintenance integration" in substations, this paper studies remote management of substation secondary equipment, status assessment, fault prediction and alarm, visual operation and maintenance, and designs a flexible and configurable visual online diagnosis and debugging system based on graphical programming ideas. The system improves the efficiency of substation operation and maintenance, improves the flexibility of grid management means, and promotes the development of the grid operation and maintenance management mode towards "operation and maintenance integration", intelligence, and automation.

2. Overall Implementation Ideas

In order to realize the visual remote operation and maintenance of secondary equipment in the substation, this paper proposes the visual online debugging and diagnosis system shown in figure 1. The online debugging and diagnosis system includes sub-station system and master station system. The sub-station system is deployed in the substation or power plant IPC (Industrial Personal Computer), and the master station system is deployed in the dispatching center or centralized control station IPC. The sub-station system realizes the functions of data information collection and display, device status evaluation and alarm, device management and control, and version management in the sub-station through online diagnosis app, remote operation and maintenance app, visual human-computer interaction and other modules. In addition to the above functions, the master station system can realize regional equipment information management and resource optimization and integration. The system has the following characteristics:

(1) Online diagnosis system based on expert database

The system collects real-time operation data, equipment parameters, equipment temperature and other global data of measuring and control device, protective device, PMU (phase measurement unit) and other secondary equipment. In addition to monitoring the status of substation equipment and processing system warnings, off-limit alarms, and remote status information, the system uses collected global data to build an expert diagnosis system to realize secondary equipment operation status monitoring and early warning, equipment health status assessment, fault location, system operating status trend prediction and other advanced application functions.

(2) Intelligent remote operation and maintenance system

In response to the lack of remote operation and maintenance means of secondary equipment, an intelligent remote operation and maintenance system is developed based on Remote Desktop Manager. Through edge computing, container technology, video processing technology, virtual LCD (liquid crystal display) technology, etc., the operation and maintenance staffs can remotely realize the operation of version control, program upgrade, configuration modification, backup and recovery of on-site secondary equipment. So, commissioning work concerning secondary equipment can be carried out directly in the master station or substation monitoring room, reducing the work time which the operation and maintenance staffs uses to and from the site, significantly shortening the project commissioning time, and improving the efficiency of substation operation and maintenance.

(3) Visual human computer interaction system

At present, the human-computer interaction system displayed on the remote operation and maintenance platform mainly has the function of displaying real-time operation data, alarm and fault
information. The user’s personalized requirements must be submitted to the R&D personnel before the system is developed, which is not flexible. This system is developed with reference to the idea of graphical programming. Users can configure various types of inputs on the human-computer interaction interface to realize device status prediction, fault prediction, and provide optimization plans and other specific functions. The graphical and configurable human-computer interaction system improves the visibility of the operation and maintenance management and control, and has the characteristics of "convenient, efficient, easy to expand, and strong openness", and improves the level of visual operation and maintenance.

3. Visual Online Debugging and Diagnosis System

3.1. Online Diagnosis System Based on Expert Database

The online diagnosis system based on the expert database collects multi-dimensional data such as power grid operation data and equipment status information. Then, by means of normalized data processing, expert database, it can realize power grid operation status monitoring, status assessment, situation prediction and other advanced functions. So that, the operation and maintenance staffs can have a more comprehensive understanding of the operation status of the power grid, grasp the operation risks of power grid in advance, thereby improving the online diagnosis level of the power grid. The detailed technical route is shown in figure 2.

3.1.1. Multi-dimensional data collection. The user can determine the data acquisition boundary according to the actual demand. The system collects the real-time data of the measurement and control device, protection device, PMU, fault recorder device and other devices within the data boundary.
range, dynamically monitors the operation status of power grid, and timely alarms. It collects device file data and historical data at the same time, such information includes the description of each node and historical diagnostic data. It can assist the online diagnostic system to realize comprehensive applications such as dynamic trend prediction, fault location, and status assessment.

3.1.2. Analysis and processing. The information collected by online diagnosis system involves operating state variables, device status and alarms. The variable type, unit and dimension are different. In order to realize the standardization of the uploaded data, the data processing methods selected according to the characteristics are also different.

(1) The voltage, current and other state information collected by the device are sent to the system directly to display the operation status of power grid.

(2) BOOL type variables are sent directly.

(3) Continuous variables such as device operating voltage, device temperature, and fiber interface power need to be normalized, see table 1 for details [11].

Table 1. Analytical processing of continuous variable

| continuous variable          | Processing methods                      |
|-----------------------------|-----------------------------------------|
| device operating voltage    | current value-rated value               |
| device temperature          | current value-rated value               |
| fiber interface power       | good value of luminous intensity-current value |
|                             | good value of luminous intensity-allowed minimum value |

3.1.3. Online diagnosis. In addition to the operation status monitoring and abnormal information alarm, different types of expert databases can be built for fault diagnosis, status assessment and trend prediction. After the analysis and processing data are matched with the expert database, the corresponding functions are realized.

(1) Operation status monitoring and early warning: According to the user's requirements, the system operation status, equipment self-inspection information, equipment alarm information and equipment fault information are displayed in groups. In this way, the dispatchers, operators and maintenance staffs can independently select the information type for operation status monitoring, and extract the key index data in the group. When the data changes abnormally, the data abnormal alarm is given to remind the operation and maintenance staffs to pay attention to it.

(2) Fault diagnosis: The online diagnosis system collects the comprehensive operation status information, equipment fault signals, warnings and communication condition of each substation. Taking the digital backup automatic device as an example, the operation status includes device working voltage, device temperature, fiber interface power, device fault and abnormal operation. The device fault signals include CPU plug-in abnormal, warnings include time synchronization abnormality, double AD inconsistency, etc. Communication conditions include SV sampling data abnormality, SV sampling link interruption, GOOSE data abnormality, GOOSE link interruption, etc. Among them, the device fault, CPU plug-in abnormal, SV sampling data abnormal and warnings are fatal alarms. Once such information is alarmed, the device fault is judged; the time synchronization abnormality is dangerous alarm; continuous variables such as device working voltage, device temperature, and optical fiber interface power are processed according to table 1 and then brought into formula (1).

$$F = \sum_{i=1}^{m} X_i + \sum_{i=m+1}^{m+n} \alpha Y_i + \sum_{i=m+n+1}^{N} |Z_i|$$  \hspace{1cm} (1)

Where, $X$ is the fatal alarm variable, $m$ is its quantity; $Y$ is the dangerous alarm variable, $n$ is its quantity; $\alpha$ is the danger coefficient, the range is 0–1; $Z$ is a normalized technical index; $N$ is the number of factors that affect the state of the equipment. Table 2 shows the result of fault diagnosis and recommended solutions.
Table 2. Result of Fault Diagnosis

| Assessment results (F) | Processing methods                                      |
|------------------------|----------------------------------------------------------|
| F ≥ 1                  | The device is abnormal and needs to be dealt with immediately by the operation and maintenance staffs |
| 0.7 ≤ F < 1           | The operation and maintenance staffs need to focus on this device                                    |
| F < 0.7                | The device is operating normally                        |

3) Equipment health status assessment: Combined with the current equipment fault diagnosis results and historical diagnosis results, the secondary equipment health status is quantified to provide reference for operation and maintenance. The specific algorithm of secondary equipment state assessment is expressed in formula (2):

\[
S = 100 - 100 \times (\omega F_R + (1 - \omega) F_H)
\]

Where, S is the final score, \( F_R \) is the current diagnosis result, \( F_H \) is the historical diagnosis result, \( W \) is the weight ratio coefficient between the current diagnosis result and the historical diagnosis result. According to the final score, the secondary equipment status is divided into four states: normal, attention, abnormal and dangerous, as shown in table 3.

Table 3. Secondary equipment health assessment results

| Working state | Normal  | Attention | Abnormal | Dangerous |
|---------------|---------|-----------|----------|-----------|
| Score         | 90–100  | 75–90     | 60–75    | <60       |

4) Trend prediction: Based on the comprehensive information collection, the system can grasp the operation of each sub-station in the region. For the important nodes, it can calculate and display the power shortage in real time, and carry out hierarchical early warning. When the warning reaches the highest level, users can check whether there is reserve capacity according to the data of neighbour stations. So it can assist users to complete operation decisions, and realize the optimization and integration of regional resources.

3.2. Intelligent Remote Operation and Maintenance System

Based on this intelligent remote operation and maintenance platform, the operation and maintenance staffs can directly use the virtual LCD to remotely display and control the secondary equipment in the control room of the master station or substation, and realize the functions of the acceptance and debugging of the secondary equipment, daily inspection, technical defect elimination and so on. It solves the problem that the secondary equipment maintenance was limited by time and location in the past, and truly realizes the remote operation and maintenance of the secondary equipment. Its functional architecture is shown in figure 3.

![Functional architecture of intelligent remote operation and maintenance system](image1)

![Schematic diagram of remote virtual LCD](image2)
3.2.1. Version control. The equipment version control function is generally divided into vertical control and horizontal control. Vertical control refers to the self-inspection of equipment version, including check code, software and hardware version information, program release time, etc. Compare the above equipment information with the equipment information in the user record library. If the result is inconsistent, the version inconsistency alarm will be given to ensure the consistency and accuracy of the on-site program and the filing program. Horizontal control means that the system performs consistency check on the information of the same type of equipment in the area, ensures that the versions of the same type of equipment in the area are unified, and realizes the standardized management of equipment versions.

In addition, the system also has a version record function, which records in detail the version information and features of each program upgrade and technical deficiencies. The user can read it when necessary to achieve traceability of version control.

3.2.2. Remote debugging. The Remote operation and maintenance of secondary equipment is the core of intelligent remote operation and maintenance system. The traditional remote operation and maintenance system focuses on information collection, operation status monitoring, system fault diagnosis and other application functions. It is limited to simple operations such as equipment value modification and pressure plate switching. In addition, the program configuration upgrade operation of the device is still at the localization level, and the overall package is generally used, which is not flexible and efficient. The new proposed system can realize remote debugging of secondary equipment through key operation and virtual LCD. The specific functions are as follows:

(1) Remote control: Operation and maintenance staffs can directly use the virtualized LCD panel to access the device in the main station or substation control room to realize secondary device status light display, key operation, device status inspection, file download and upload, device debugging and so on. It eliminates the difference between remote operation and local operation, reduce the number of personnel going to and from the site, thereby reducing the debugging workload of engineering personnel and improving the efficiency. Figure 4 shows a remote virtual LCD diagram of the measurement and control device.

(2) Remote upgrade: In the pre-commissioning and countermeasure stage, after the secondary equipment is connected with the master station/substation, the operation and maintenance staffs can realize the download, configuration upgrade, and one-key backup and recovery of the secondary equipment program at a distance through the virtual LCD and key operation operating.

When the user upgrades, system configure the program version self-checking strategy table to automatically search the user’s record database and the version information of the same type of devices. If the program version is inconsistent with the record, the software program does not match the hardware program, or important files are missing, the upgrade is prohibited. The specific process is shown in Figure 5.

```
Click the program upgrade button
Extract the software version and hardware version of the program to be upgraded
Does the filing library have this version information?
Y
N

N
End
Y
Yes the information consistent with the record database?
Y
Exit this upgrade and give a prompt message
Allow upgrade
Allows to upgrade the program and record version information in the record database
```

Figure 5. Remote upgrade process
(3) Equipment log management: After equipment failure or equipment action, the user can remotely access the equipment log, then integrate the log data of other related devices to conduct fault analysis, which improves the diagnosis level.

3.3. Visual Human-Computer Interaction

Visual human-computer interaction is mainly reflected in the visualization of equipment status, visualization of equipment operation and maintenance, and visualization of fault diagnosis.

3.3.1. Visualization of equipment status. The secondary equipment status visualization adopts hierarchical display structure, which is divided into regional level, station level and equipment level.

The regional level focuses on the statistical global information, including network topology, fault information, communication status, and operation status.

At the substation level, the equipment status can be monitored and displayed in real time through video monitoring, inspection robot and other ways. The equipment health can be preliminarily evaluated and timely delivered, so as to improve the accuracy and timeliness of equipment operation and maintenance, and improve the operation and maintenance efficiency.

At the device level, the secondary equipment status is displayed through virtual LCD panel, real-time data, alarm information, self-test information, soft/hard platen status, diagnosis information, etc., which lays a technical foundation for remote operation and maintenance. Figure 6 is an example of visualization of the device layer status of the system.

![Figure 6. Visualization instance of equipment](image)

3.3.2. Visualization of equipment operation and maintenance. Visualization of equipment operation and maintenance refers to the visualization of remote control, debugging and management realized by virtual LCD. See 3.2.2 for details. Through the virtual LCD panel, the remote/local operation can be realized without differentiation, reducing the workload of debugging, operation and maintenance, and inspection, and enhancing the interaction between users and equipment.

3.3.3. Visualization of fault diagnosis. The traditional fault diagnosis system realizes the diagnosis function by means of expert database or fuzzy algorithm, which is a "black box" for operators. If users have personalized requirements, they can only be provided to developers for modification, which has strong lag. In order to realize fault diagnosis more effectively and quickly, the visual online diagnosis system proposed in this paper draws on the idea of graphical programming and has the characteristics of flexibility and configuration.

According to the operation status, hidden dangers and common defects of the equipment, a typical device fault diagnosis model is provided for users. When the user has personalized requirements, the users can configure various types of input and adjust the fault factor and its coefficient in the fault diagnosis model editing interface. It is composed of system library and function editing interface. The system library includes component library and diagnostic model library. The component library
provides operators, relational operators and variables to provide the basis for user independent logic function modules. The diagnostic model library provides typical diagnostic models according to device types, which can be called by users independently and has strong flexibility. In the function editing interface, users can view and modify the diagnosis model, and customize the alarm, diagnosis and evaluation logic according to the regional characteristics. Figure shows the schematic diagram of the device fault diagnosis visualization interface. Figure 7a) is the schematic diagram of the fault model calling and editing interface. The user can adjust the input signal and its weight information. Figure 7b) dynamically displays the evaluation results in chart format.

The graphical and configurable human-computer interaction system can not only meet the sharing and reuse of common modules, but also meet the personalized needs of users. It greatly improves the visualization degree of operation and maintenance management and fault diagnosis functions, and has the characteristics of “convenient, efficient, easy to expand and strong openness”, and improves the level of visual operation and maintenance.

4. Application Effect

4.1. Significantly Shorten the Project Commissioning Time

The commissioning workload of new 220kV digital substation is generally 2 person multiplied by 2 months. In the debugging stage, when the equipment is upgraded and the debugging point-to-point operation is carried out, the debugging personnel need to go back and forth to the site and the monitoring room frequently to check the information and restart the device, which wastes a lot of time. After the application of this system, one debugging personnel can realize equipment information viewing, remote control, device restart and other operations from a distance. The project commissioning cycle can be reduced to 45 days, and the work efficiency is increased by 62.5%.

4.2. Comprehensively Improve the Standardization Control Level of Secondary Equipment

The intelligent remote operation and maintenance system can realize the local/remote operation of equipment without differentiation. Its perfect device version self-check strategy provides guidance for equipment upgrading, which is conducive to the standardization and control of regional equipment.

In 2018, during the field operation of NSR3697 series devices in Hefei Changlinhe substation, PPC monitoring DSP real-time data loss was frequently reported, and some devices reported locking after long-term operation. After the analysis, the R&D personnel found that problem is caused by the mismatch between the underlying platform program and DSP program. If the system is used to upgrade the program, this problem can be identified before the upgrade, which will not lead to on-site problems. If the system is not used in the early stage, when the above problems occur in the follow-up operation, the R&D personnel can also compare the version information of the device with the information of other sub stations in the region to obtain the inconsistent version information, which is convenient for the R&D personnel to locate the problem and greatly improve the operation and maintenance efficiency.
4.3. Realize Full Awareness of Grid Status
Through the online diagnosis system based on expert database, intelligent remote operation and maintenance system and visual human-computer interaction system, the operation and maintenance staffs can fully perceive the operation status of power grid, equipment health status, remote operation and maintenance process, etc. so as to realize the overall management of multi-party resources in the area and optimize the operation and maintenance work mode.

5. Conclusion
Based on the demand of substation operation and maintenance integration, this paper proposes a flexible configuration and visual online debugging and diagnosis system, which realizes the functions of remote control, remote debugging, intelligent diagnosis, health status assessment, state prediction of secondary equipment. It plays a positive role in standardizing management and control of secondary equipment, accelerating the efficiency of fault handling, visualizing remote operation and maintenance, and optimizing the substation operation and maintenance mode.

In the next step, we will gradually carry out the pilot application of visual online debugging and diagnosis system, continue to deepen the application of big data, edge computing, container technology and other technologies, improve the various functional modules, and improve the reliability, security, compatibility and expansibility of the visual online debugging and diagnosis system. So as to comprehensively improve the remote operation and maintenance management and control level of substation secondary equipment, and further promote the "integrated operation and maintenance" of power system.

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