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Relay Protection Simulation and Testing of Online Setting Value Modification Based on RTDS

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ABSTRACT Analyzing the feasibility of modifying setting values on the condition of the running line without exiting the protection function is of great importance for 110 kV substations. A system-level test of settings modification is proposed to verify that the values are correctly modified during the process and the protection function is still in effect. A cyber-physical automatic test bed using a real-time digital simulator (RTDS) is developed for relay protection to modify settings online, which distinctly improves work efficiency. Based on actual power grid parameters, a full-process closed-loop RTDS automatic control system is applied for performance testing when setting groups are changed. The experiments are focused on blocking time tests, setting groups switch and coverage tests, DC power supply intermittent tests, unwanted operations in setting value, changing load and protection starting tests, short-circuit fault tests and power system frequency oscillation tests. The results of the trial indicate that the automatic test bed is an effective technology for checking and verifying the reliability of modifying setting values online. In addition, 36 line protection devices from 12 relay protection manufacturers are tested. The reliability of each test item is analyzed and the relay performance is evaluated using a comprehensive method. The test bed provides reliable technical support for the design, engineering, commissioning and substation operation of online setting modification.

INDEX TERMS Real-time digital simulator (RTDS), setting value, cyber-physical automatic test bed, relay protection.

I. INTRODUCTION

Relay protection can be achieved via the setting value when power system failure occurs. The protection setting value is modified with increasing frequency as the grid scale expands. In recent years, the operating mode of the Inner Mongolia power grid has been increasing. Thus, the protection setting value is adjusted via the operation mode [1].

Traditionally, modification of the setting value requires power line outage and exit of the corresponding protection equipment. A dual-protected configuration is used for power systems with voltage levels of 220 kV and above whereas a single-protection system is usually configured with voltage levels of 110 kV and below [2]. The settings of the 110kV substation in the Inner Mongolia power grid were modified 2,000 times per year. Therefore, a setting value for voltage levels of 110 kV and below with a blackout cannot meet the requirements of power supply reliability. The associated system involves a large workload and low efficiency. Moreover, the benefits and people's satisfaction are reduced due to blackouts.

With the implementation of power grid technology reform and relay protection, nine standards have been unified and grid automation has been improved. It is necessary to modify setting values online without a blackout. Some power supply companies and electric power research institutes have carried out online modifications. They have researched and applied online relay protection setting with respect to the equipment configuration, control model, setting system, and online management scheme [3]–[6]. However, no tests or studies indicate that online modification of settings is absolutely safe. The conditions for verifying the safety of changing device setting values are not available at a substation without power. Thus, this technology is not widely used because the protection

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equipment should be tested for reliability. Such equipment should not be tripped incorrectly when the setting value is modified. Therefore, it is necessary to carry out dynamic simulation tests.

The real-time dynamic simulation technology for testing relay protection equipment is mainly divided into physical simulation, all-digital simulation and digital-physical mixed simulation technology [7]–[9]. Physical simulation is mainly used for equipment-level simulation and testing. The corresponding model is complex and strongly influenced by the simulation scale. All-digital simulation technology such as the latest Advanced Digital Power System Simulator (ADPSS) simulator offers significant advantages of real-time simulation speed, accuracy and simulation scale [10]. Digital-physical mixed simulation technology is capable of real-time digital simulation and has the advantage of connecting to an external protection device. In this regard, the RTDS simulator shows outstanding performance [11], [12]. RTDS has been widely used in the last 10 to 15 years. The RTDS environment was developed [13] to solve the protection problem of ultrahigh-voltage power systems. RTDS was extended [14], [15] to test the security and stability of control systems. Protection algorithms were verified effectively [16] for centralized protection and control systems.

The remainder of this paper is organized as follows. Section 2 constructs the overall framework of the relay protection simulation system with RTDS. Then, the automatic test bed is developed. Section 3 analyzes the scheme for online setting value modification and modeling. Section 4 describes the experiments to verify the reliability of the protection equipment. In Section 5, line protection equipment from 12 manufacturers are tested and a comparison and statistical analysis are carried out. The evaluation method of test results is described. Finally, concluding remarks are made in Section 6.

II. THE AUTOMATIC TEST BED OF RELAY PROTECTION

Cyber-physical systems (CPSs) are intelligent integrations of computation, control and physical processes [17]–[20]. In this paper, a cyber-physical automatic test bed with RTDS is developed for setting modification. The overall architecture of the automatic test bed of relay protection is shown in Figure 1.

A. CYBER-PHYSICAL SYSTEMS

The test bed of the physical system is used as a system-level test. It consists of four main components: the RTDS simulator, intermediate processing devices, relay protection equipment and a system simulation workstation.

Protective relays and substation supervision systems are used with IEC 61850 [21], which is a basic cyber system used by some utilities. The manufacturing message specification (MMS) main-station communicates with each protection device through the network of the station layer. The protection device features an Intelligent Electronic Device (IED) model that should comply with MMS. The MMS program sends and receives data packets that can interact with electric power data networks in real time. The setting value can also be uploaded and downloaded by the MMS program to enable remote modification.

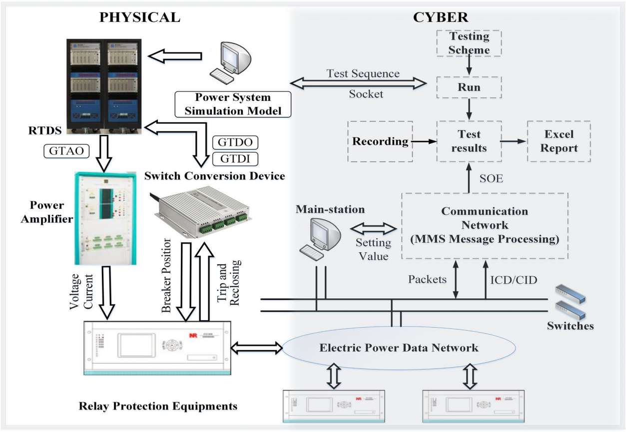


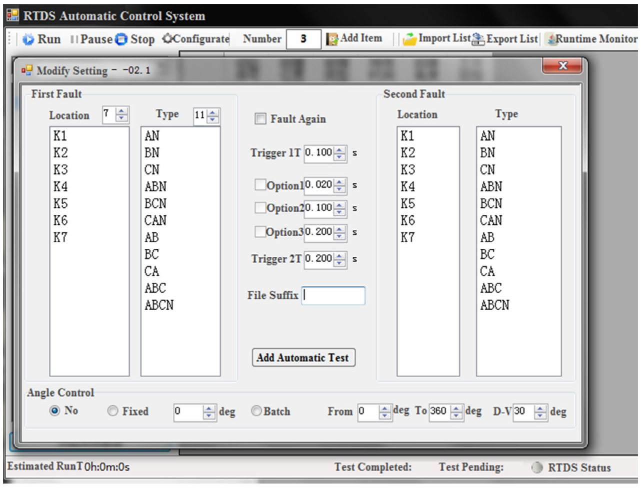
FIGURE 1. The overall architecture of the automatic test bed of relay protection.

B. AUTOMATIC CONTROL SYSTEM

The core of a cyber-physical system lies in the control system. In this paper, an automatic control system for testing online setting modification is proposed. The previous real-time platform used to test the performance of developments needs to operate each test manually or by writing a complicated script. Our system allows for batch automated operation of the test and flexible customization of the list of test items. The work efficiency is improved and equipment utilization is increased. The purpose of automatic control is to effectively intervene in and control the RTDS simulation system test process. The automatic control system consists of three modules: a test scheme configuration module, an RTDS control module, and an information collection module.

1. Test scheme configuration module. Detailed test items are configured through this module. The visual operation interface setting includes a fault point, fault type and fault time to customize the test project, as shown in Figure 2.

2. RTDS control module. The purpose of the control module is to automatically load the test sequence into the RUNTIME interface of the RTDS. During the running phase of the automatic control system, simulation commands including parameter classes, variable classes and instruction classes are initially mapped to RTDS-recognizable sequences; additionally, a socket is used to send command statements from the automatic control system. Finally, command lines interact between the RTDS and the control system according to certain test sequences. The system is executed in the following order: initialization of the model and setting of the fault point, fault type, fault time, breaker status, and other electrical primary system states; the electrical primary system simulation is triggered to fault automatically, and the waveform is recorded synchronously.



Number 3

First Fault: Location 7, Type 11

☐ Fault Again

Trigger 1T 0. 100 s

☐ Option1 0. 020 s

☐ Option2 0. 100 s

☐ Option3 0. 200 s

Trigger 2T 0. 200 s

File Suffix

Angle Control: ● No ○ Fixed 0 deg ○ Batch From 0 deg To 360 deg D-V 30 deg

Estimated RunT 0h:0m:0s Test Completed: Test Pending: RTDS Status

FIGURE 2. The visual test interface of the automatic control system.

3. Information collection module. One function of this module is to record the test details, including the operator, test time, SOE, detected equipment, and test project. Another function is to collect feedback from protection devices. Fault trip signals, breaker position signals and transient fault records, etc., are incorporated into the test results.

III. ONLINE SETTING VALUE MODIFICATION ANALYSIS AND MODELING

The design and formulation of the testing project is the key of this paper. Unlike the general relay protection test, it focuses on the protection behavior during the process of setting value modification.

A. SETTING MODIFICATION THEORETICAL ANALYSIS

When the modified setting confirmation key is pressed, the data are calculated and processed according to the internal underlying program of the protection device. The locking time of the relay device is triggered when a setting value is written to the protection board, which allows for the primary equipment of the grid to operate unprotected. Therefore, the first analysis is to detect the solidification time and blocked time of the device.

The underlying design of the protection device is not uniform due to the varying technologies used by manufacturers. There are many ways to modify settings, such as through WEB-HMI or IPC, but the process and logic of modifying the settings are consistent. The process is summarized in the flow chart shown in Figure 3.

The new value is sent to the protection board by the management board. The operation of the main program is required to block the device. The device needs to self-check after restarting. Therefore, the solidification time includes the main program and the self-check time. The first step in this paper is to calculate the blocked time and solidification time, which have not been clarified in previous studies.

According to the above analysis, the blocking time is essentially the time when the protection exits the operation.

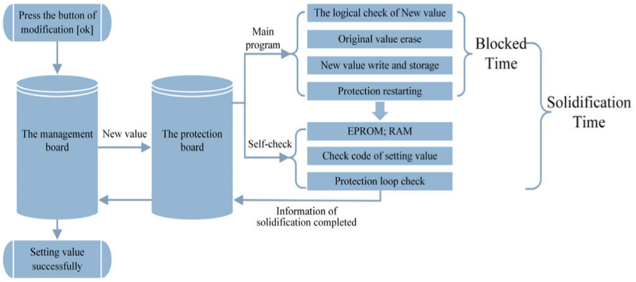


FIGURE 3. The flow of underlying design during setting value modification.

Using the permanent short-circuit fault in the protected area as an example for calculation, the device inputs only the distance II, and the solidification time T_S and the blocking time T_B are calculated by modifying the impedance value. Through the RUNTIME interface of RTDS, the remote modification setting and triggering fault buttons are configured as the same control button. Pressing the control button calculates T_S and T_B as follows:

$$T_S = T_1 - T_0 \tag{1}$$

$$T_B = T_{trip} - T_0 - T_{II} - T_{delay} \tag{2}$$

where T_1 represents the solidification completion time in the device alarm information, T_0 is the moment when the modification button is pressed, T_F is the moment of a fault, the shaded area indicates the fault duration, T_{trip} represents the protection trip time, T_{delay} represents the device delay time and T_{II} represents the impedance of the distance II. In this test, T_0 is equal to T_F.

B. TEST ITEMS OF SETTING MODIFICATION

The operator of the substation modifies the settings without a blackout, usually under the condition that the line runs stably. However, our tests consider whether the line can be correctly modified under special working conditions. Therefore, seven items are used to test and qualitatively evaluate the setting modification. The quantitative results are based on qualitative analysis. Satisfaction is defined as 1, general satisfaction is defined as 0.5, and dissatisfaction is defined as 0. The detailed analysis is as follows.

1. Setting groups switch and coverage tests. This item is specially formulated for power grid dispatching, substation operation and maintenance. The main test is whether the settings can be modified in the no-running group and the new values copied to the running group. In this process, the running group is guaranteed to remain unchanged. Thus, with the above function, x_1 is equal to 1, otherwise x_1 is equal to 0.5.

2. DC power supply intermittent tests. The device suddenly loses the DC or voltage fluctuation (80% rated voltage to 115% rated voltage) during the process of online setting value modification. At this time, the inspection device uses the original value or the new value. Thus, if the setting is wrong,

then x_2 is equal to 0. If the setting has not changed, x_2 is equal to 0.5. If the setting is a new value, x_2 is equal to 1.

3. Unwanted operation tests of online setting of values. This is an innovative testing item that has not been applied in dynamic tests of protective products [1], [2], [22]. The item can guide substation protection technicians to modify the settings. When the setting is abnormal, it is necessary to check whether the behavior of the protection device can be blocked correctly without incorrect operation. Four typical unwanted operations are selected for testing: distance II time > distance III time; distance II impedance > distance III impedance; zero sequence overcurrent setting decreases 10 times; and a setting outside the range. Thus, in the function of checking for unwanted operation, x_3 is equal to 1, otherwise x_3 is equal to 0.5; if the device trips during operation, x_3 is equal to 0.

4. Load changing tests. In the substation of the wind power collection area, load and power fluctuations often occur. To simulate the rapid switching of the load and the nonlinear slow change process, the inertia link and the transfer switch are designed into the power control module of the RTDS. Our work focuses on whether the setting can be correctly modified in this case. Thus, if the setting is modified successfully during the load changing, x_4 is equal to 1, otherwise x_4 is equal to 0.

5. Protection starting tests and frequency oscillation tests. These are special tests that must be performed by a power grid dispatching control center because the device is started frequently when the setting is low or the sensitivity of the protection is high. In this case, the setting should be modified in a timely manner. The protection device is required to operate reliably in the event of grid oscillations. Therefore, in the function of modifying the value during the protection starting process, x_5 is equal to 1, otherwise x_5 is equal to 0. If the setting is modified successfully during the oscillation, x_6 is equal to 1; if the device trips during modification, x_6 is equal to 0.

6. Short-circuit fault tests. These tests are different from the conventional dynamic short-circuit fault tests. These tests focus on the protection behavior while changing setting values. The purpose of these tests is to verify that the device is using a new or original value when a short-circuit fault occurs, which is important for accident analysis and processing. In general, the period of this time is very short; during this period, line faults occur. The relationship between the aforementioned period and line faults is shown in Figure 4.

In the figure, the shaded area indicates the fault duration. Based on the differences in the solidification time and the point of triggering failure, the faults can be divided into the following five situations. The purpose of this test is to verify whether the device is using a new or original value when a short-circuit fault occurs, which is important for accident analysis and processing.

The theoretical analysis is as follows. In timeline A, it is obvious that the device uses a new setting. In timeline B, a fault occurs during the period of solidification, and the protection delay action follows the new setting value. In timeline C, the solidification time is too long (more than 1 s); thus, the backup protection of the superior line is tripped and removes the faulty line. In comparison, timeline D indicates that the sensitivity of the superior protection or reach of protection is insufficient, and the faulty line is not tripped in time; the line protection of this level operates according to the new value. Timeline E represents a situation in which the device operates according to the original value. Therefore, in the above case, if the setting is modified successfully and the device is tripped correctly, then x_7 is equal to 1. If the device is tripped incorrectly or refused, x_7 is equal to 0. If the device is tripped after a delay and the delay time is longer than the blocked time, then x_7 is equal to 0.5.

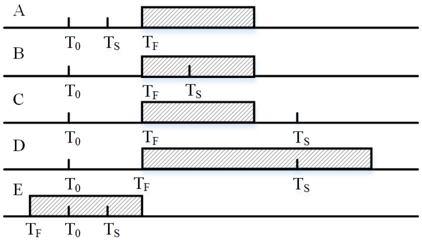


FIGURE 4. The relationship between the setting modification period and line faults.

The evaluation of the test results is based on a comprehensive method that combines subjective and objective weighting methods. The weight of each test item can be calculated as follows:

$$w_i = k_1 a_i + k_2 b_i \quad (i = 1, 2, \ldots, 7) \tag{3}$$

where a_i represents the weight determined by experts and b_i represents the weight calculated by the information entropy method. The entropy for each test item is calculated using the following equations.

If a test report has m test items and n devices are detected, the data of item k is defined as $[x_{k1}, x_{k2}, \cdots, x_{kn}]$, where x'_{ij} represents a normalized value.

$$H_i = -\frac{1}{lnn} \sum_{j=1}^{n} \frac{x'_{ij}}{\sum_{j=1}^{n} x'_{ij}} ln \frac{x'_{ij}}{\sum_{j=1}^{n} x'_{ij}} \tag{4}$$

$$b_i = \frac{1 - H_i}{\sum_{i=1}^{m} (1 - H_i)} \tag{5}$$

C. BUILDING A DIGITAL MODEL OF RTDS

According to the above analysis, we take a typical power plant transmission line in Inner Mongolia as an example to test the performance of the setting value modification. The electrical primary system of RUNTIME is shown in Figure 5. The simulated system parameters under a voltage of 110 kV based on the actual operating values are shown in Table 1. In the model, the load and generator output can be adjusted,

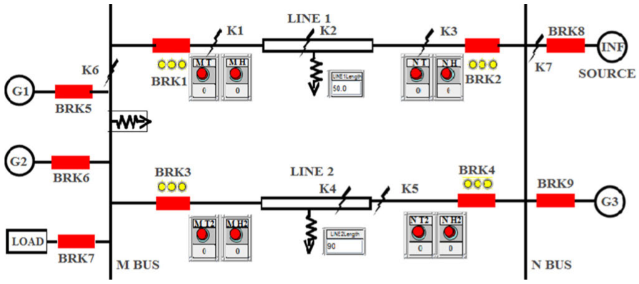


FIGURE 5. Electrical primary system of RUNTIME.

TABLE 1. System parameters for the digital model based on actual operating values.

Name	Parameter	Value
Infinite-bus System Equivalent Parameter	Capacity /MW	500
	Frequency /Hz	50
	M Side System Maximum X1 /p.u	0.0703
	M Side System Maximum X0 /p.u	0.0599
Each Generator	Capacity/MW	100
	Rated Voltage /kV	110
	R D-axis Xd /p.u	0.93
	R Q-axis Xq /p.u	0.69
	Trans.R Xd' Xq' /p.u	0.302/0.29
	Sub-Trans.R Xd"Xq"/p.u	0.171/0.27
	Power Factor	0.90
Load	Capacity /MW	300
110kV Transmission Line	Positive Sequence Resistance /Ω/km	0.0656
	Positive Sequence Reactance /Ω/km	0.3185
	Zero Sequence Resistance /Ω/km	0.0656
	Zero Sequence Reactance /Ω/km	0.3185
	Length /km	4.32
Current Transformer	Ratio /p.u	240
Potential Transformer	Ratio /p.u	1100

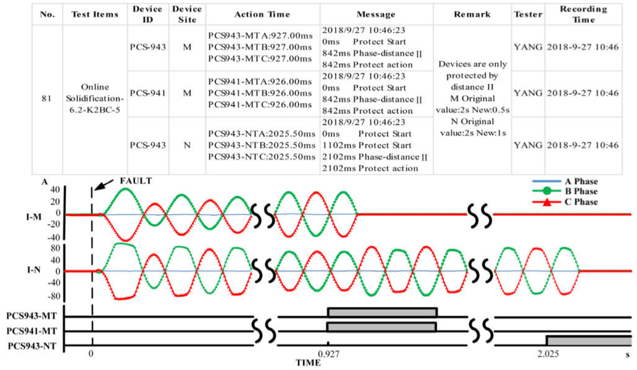
an infinite source is suitable for the maximum operation mode and minimum operation mode of the power system, manual procedures for the closing and tripping of breakers are written in DRAFT, and the locations of faults K2 and K4 are moved flexibly according to the line setting. The parameters of the excitation control system and power system stabilizer (PSS) are obtained by actual excitation tests performed at the test site.

Equipment from 12 relay protection manufacturers was tested. Each system includes 2 fiber optic differential protection devices and 1 distance protection device. To perform the contrast test at the same time, the differential protection devices (i.e., NR-943) were disposed on the M side and the N side, and the distance protection device (i.e., NR-941) was disposed on the M side.

IV. SIMULATION EXPERIMENTS AND RESULTS

The simulation experiments and tests are based on technical codes in the literature [22]. The test results are as follows.

1. Short-circuit fault test. Under the various conditions of setting fixation and line faults analyzed in Figure 4, 50 tests were performed with the automatic control system, with each automatic test lasting 40 s. Seven fault points (K1-K7) were detected in turn; thus, 350 trials were conducted. Similarly, 350 switching setting groups trials were performed. This test was performed over approximately 8 hours. Through the automatic test system, the workload of the experimenter was greatly reduced.



No.	Test Items	Device ID	Device Site	Action Time	Message	Remark	Tester	Recording Time
81	Online Solidification-6.2-K2BC-5	PCS-943	M	PCS943-MTA:927.00ms PCS943-MTB:927.00ms PCS943-MTC:927.00ms	2018/9/27 10:46:23 0ms Protect Start 842ms Phase-distance II 842ms Protect action	Devices are only protected by distance II M Original value:2s New:0.5s N Original value:2s New:1s	YANG	2018-9-27 10:46
		PCS-941	M	PCS941-MTA:926.00ms PCS941-MTB:926.00ms PCS941-MTC:926.00ms	2018/9/27 10:46:23 0ms Protect Start 842ms Phase-distance II 842ms Protect action		YANG	2018-9-27 10:46
		PCS-943	N	PCS943-NTA:2025.50ms PCS943-NTB:2025.50ms PCS943-NTC:2025.50ms	2018/9/27 10:46:23 0ms Protect Start 1102ms Protect Start 2102ms Phase-distance II 2102ms Protect action		YANG	2018-9-27 10:46

FIGURE 6. The record of a K2 phase fault saved by the automatic control system.

To provide an example, the setting value was modified while a phase fault occurred in K2, and the record saved by the automatic control system is shown in Figure 6. It was performed under the condition of exiting differential protection and distance I. The delay time is measured by the action of distance II and distance III. The setting values of the M side devices are written together by a remote MMS master station, and T_0 is equal to T_F. The setting value of the N-side device is written by an adjustor, and T_0 is later than T_F. In the protection message of the M side, the action time of 842 ms includes a blocking time of 342 ms and a new value setting time 0.5 s. The trip times of 927 ms and 926 ms represent the actual moments when breaker M is triggered, as indicated in the record figure. In the protection message of the N side, protection is started twice because T_0 is later than T_F. Therefore, the action time of 2102 ms includes the second start time of 1102 ms and the new value setting time of 1 s. In the record figure, 2025 ms is the trip time of breaker N. From the current waveform, we also observe a transient saturation phenomenon of the N-side short-circuit current. The results show that the protection devices operated correctly according to the new online modification procedure.

2. Power system frequency oscillation test. The purpose of this test is to modify the setting value during the oscillation process simulated by static stability, and the dynamic stability of the system is destroyed. There are two ways to simulate oscillation: one is to adjust the generator active power and turn the PSS on or off, which causes the system to oscillate synchronously. The other is to adjust the oscillator to make the infinite source lose stability, as shown in Figure 7, which causes the system to oscillate asynchronously. A current sudden-change starting value is modified 0.1 s before triggering the single-phase fault. The oscillator generator is a custom model compiled by our team using the RTDS C BUILDER, which is programmed in C language. The experimental results show that, in the case of system oscillation,

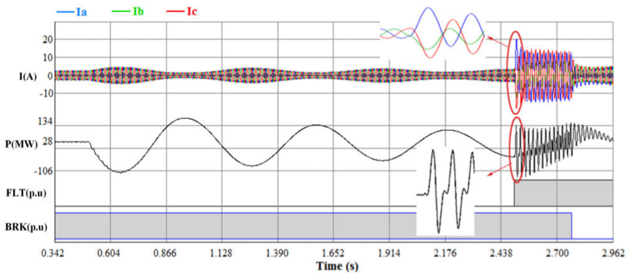


FIGURE 7. Settings modification under asynchronous oscillation and an a-phase ground fault.

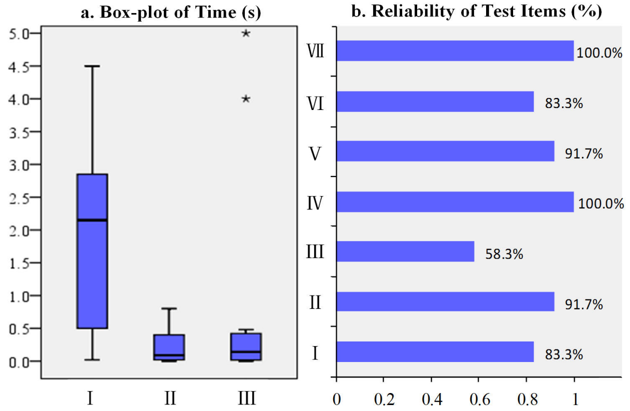


FIGURE 8. Statistical analysis charts of test reports: a. Box-plot of time during modification of the setting value, where I represents the solidification time, II represents the theoretical blocked time, and III represents the real blocked time; b. Reliability of test items. where I represents the setting groups switch and coverage tests, II represents the DC power supply intermittent tests, III represents the unwanted operation of value tests, IV represents the load changing tests, V represents the protection starting tests, VI represents the short-circuit fault tests, and VII represents the system frequency oscillations tests.

the protection device can correctly modify the value and successfully switch the setting groups.

V. DISCUSSION AND EVALUATION

The cyber-physical automatic test bed based on RTDS can simultaneously detect multiple protection devices. Twelve typical domestic line protection manufacturers were selected to test the performance of online setting value modification. This is the first time that this system-level test has been carried out in China. Each system was tested using 2 typical optical fiber differential protection devices and 1 distance protection device, and 36 devices were tested.

The online modification value time of all devices was analyzed using a box-plot, as demonstrated in Figure 8 (a).

The solidification time of each device varies greatly and it takes a long time. Two outliers indicate that relay protections were blocked for too long and therefore could not be operated in time. The detected blocking time was mostly less than 0.5 s. Therefore, during the online modification of the relay production settings, the time that the grid equipment operated unprotected is less than 0.5 s.

Based on the statistics of the 12 test reports, the reliability of seven test items is shown in Figure 8 (b). During the process of online setting modification, the protection devices have the risk of incorrect operation, failure to trip and delay tripping. Therefore, online modifications of the settings of the devices require system-level testing.

VI. CONCLUSION

Based on the RTDS simulator, we solved a practical power system problem—that online modification of setting values cannot be widely applied in substations. In this paper, we reviewed the limitations of modifying settings during a blackout and the feasibility of using RTDS dynamic simulation technology to test online modification.

To test relay protection devices, we developed a cyber-physical automatic test bed with the RTDS. In a physical system, we built a full-process closed-loop test environment. Real-time interaction between the grid simulation and the relay protection was realized. In the cyber system, the MMS virtual master station was used to transmit messages via substation communication networks. The key component of the RTDS cyber-physical test bed is the automatic control system, which we used to test online setting value modification. Automatic control techniques were applied from the test flow to data processing to report generation, which greatly improves the work efficiency.

Using actual power grid parameters, we built a digital simulation model that closely approximates real grid operating conditions. Seven tests were performed to determine whether the relay protection equipment satisfies the reliability requirement for setting value modification. Finally, our test methods and cyber-physical automatic test bed were used to test 45 protective devices from 15 manufacturers, which are the main manufacturers of 110 kV line protection technology in Inner Mongolia.

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