System-Level Field Test Platform Development for Secondary System in Smart Substation

Qiang-chao XU¹,* and Yang LIU²

¹Guangzhou Power Supply Bureau, Guangdong Power Grid Corporation, Guangzhou, China, 510620
²Electric Power Dispatching & Communication Center of Guangdong Power Grid Corporation, Guangzhou, China, 510600
*Corresponding author

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Abstract. At present, secondary system in smart substation lacks field test way. This paper proposes the implementation scheme of system-level field test system. System feasibility, test platform architecture, testing process, principle of the algorithm, software and hardware design and testing system application are presented in the paper. It systematically demonstrates the design idea and the design detail of the platform. The promotion of system-level field test platform can improve efficiency of test for secondary system in a valid way and current limitations of depending on integration testing in commissioning. What is more, it proposes a new idea of operating maintenance and corrective maintenance under the environment of using the platform.

Introduction

As smart substation increasingly depend on sharing Information, the interaction of all kinds of information in substation secondary system will become more complicated, the security risks of information and equipment are growing, the substation secondary system will face unprecedented challenges, the security and stability issues in secondary system have become restriction factors in develop process of smart substation. Secondary system test is an important means to eliminate the hidden dangers, the development and innovation of its technique concept as well as its working style have significance in further development of smart substation.

In the traditional sense, smart substation secondary system test is an intensive calibration work of equipment and system, which verified by equipment integrator before secondary system puts into operation, the test includes factory acceptance and joint debugging, individual equipment debugging, partial system debugging, system debugging and loading test. Secondary system test can guarantee the function and performance of system and equipment to satisfy the requests, to some extent, also verify compatibility and interoperability problem in smart substation secondary system among different manufacturers and equipment.

However, although equipment integrator tests and checks secondary system systematically and normatively before it puts into operation system, secondary system has frequent failure in actual construction and in the operation of substation, the failure covers various aspects such as secondary equipment, secondary circuit and protocol compatibility and so on. The main reason is that:

(1) The bad establishing environment in worksite. Integrator testing is finished in specialized testing center, no matter establishing system technology or establishing environment are better than the establishing environment in worksite.

(2) The uneven staff technique quality. The difference of technique principle and working system between testing staffs and operating maintenance staffs can cause operating maintenance staffs to fail to repair system failures and abnormalities at level of equipment principle and technology after equipment put into operation.
(3) Uncontrollable equipment quality in long-time running. The power system secondary equipment between different manufacturers have difference in operational stability and quality, so factory acceptance can only ensure the stable operation of the equipment in a certain time, working reliability of the equipment for a long time cannot be guaranteed.

So, the smart substation secondary system test method and test system mentioned in this paper are necessary. This paper describes system-level testing platform test method and result evaluation and studies in system-level testing platform simulation theory and algorithmic design from testing platform and testing concept. At last, this paper gives hardware of testing platform, software design method, to form a complete system design plan.

The Feasibility of the System Level Testing Platform

The Application of IEC 61850 Standard

The application of IEC 61850 standard in smart substation provides a better technology platform and protocol support for developing of system level testing technology, and it is reflected in following point: 1) Applying of many digital equipment and electronic equipment. In substation, the traditional electromagnetic transformer is replaced by electronic transformer, the electric signal transmission is replaced by optical signal exchanging, that extends the range of information sharing and using. 2) Interoperating between equipment. Equipment use the same modeling standard and design specification, the different type smart devices from different manufacturers can interoperate without restriction and do not depend on protocol converter. 3) Cable connection is replaced by network transmission. The way that establishing network in process level to replace traditional cable connection overcomes difficulties in network connection and the problem of low level information sharing. 4) Using unified engineering configuration language. IEC61850 uses substation configuration language (SCL) based XML including four substation configuration, such as SCD, SSD, providing unified and standard description and management.

The Increasing Mature Test Standards

With smart substation construction and popularization, smart substation secondary system test flow and test technology develop and regulate constantly, secondary system testing system and standard is increasing mature. Literature[15] according to the way which injecting signal through cable in substation, digital relay protection tester has been produced, it will rich testing way of single equipment; Zhejiang Province has built a centralized testing base, it has secondary system dynamic simulation test which uses practical equipment to simulate primary equipment, that riches testing contest and enlarges testing range; State Grid published the installing and acceptance inspection specification of relaying and secondary circuit in 2014, further detailed testing contest and testing link. Increasing mature secondary system testing technology and specification provide strong technical supports and specific technical requirements for designing system-level testing system, also provide guidance of contest and direction to further applying of testing system.

System-Level Testing Platform and Its Testing Flow

Systematic Framework

Figure 1 shows the total framework of system-level testing device in smart substation, the device mainly includes graphical interfaces unit, model and parameter management unit, real-time digital simulation unit, analyzing collected data unit, converting emulational data unit.

Each part function of system-level testing device in smart substation is as follow:

(1) Graphical interfaces unit; providing graphical modeling tool of power system, that will be used in editing primary electric wiring diagram, setting component parameter, operational control and so on;
(2) Model and parameter management unit: it is used for managing model and its parameter in power system electric wiring diagram.

(3) Real-time digital simulation unit: it is based on the model that has existed and simulates operation in power system by real-time computing, outputs real-time simulation data, detects feedback information from system under test to update simulate data.

(4) Analyzing collected data unit: it analyses collected data and transforms format which is need by relevant status information in model, then sends it to real-time digital simulation unit.

(5) Converting emulational data unit: it transforms emulational data produced by real-time digital simulation unit to the format which is need by output data.

(6) Virtual switch box: it can replace intelligent terminal and breaker to participate in the test. The virtual breaker in virtual switch box equals to major system, corresponds to total station simulation system of system-level tester, needs break time and the split phase switch. The converting unit of digital value and switch value to transform GOOSE to analog switch to control virtual breaker on and off, meanwhile, it can transform virtual breaker position to GOOSE messages and send it to the Internet.

Figure 1. Devices structure of system-level panoramic test in smart substation.

**Testing Method**

The testing steps of system-level testing device in smart substation are as follow:

(1) Setting primary model. Setting primary equipment and its topology connection, meanwhile, setting fault location and fault type, calculating primary analog quantity and switching value;

(2) Setting secondary model. Setting secondary equipment connected relation and information subscription connection.

(3) Starting system-level testing, mutual inductor outputs voltage and current information in FT3 or IEC61850-9-2, outputs switch position in GOOSE messages.

(4) System receives GOOSE and MMS messages, analyses protective action signal, updates switch position information, further regenerates topology, back to step 1), to be a closed loop test.
Simulation Theory and Algorithm Design

To simulate parameter in primary system steady state and transient state is the core of secondary system-level whole environment simulation in smart substation, it can package SV messages according to practical voltage and current value, and further trigger smart terminal and protective action which is analyzed and showed by human-computer interactive interface of system-level tester.

System-level testing device has primary system simulation and display function, its simulation uses primary system simulated calculation model, not only needs to consider the model accuracy but also model calculation, relevant velocity, refresh cycle. As Table 1 shows, this thesis gives the component model used by primary system simulation.

<table>
<thead>
<tr>
<th>Component</th>
<th>Equivalent model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power line</td>
<td>π Equivalent model</td>
</tr>
<tr>
<td>Transformer</td>
<td>π Equivalent model</td>
</tr>
<tr>
<td>Generator</td>
<td>Power source and resistance series model</td>
</tr>
<tr>
<td>Capacitor</td>
<td>Capacitor</td>
</tr>
<tr>
<td>Reactor</td>
<td>Reactor</td>
</tr>
</tbody>
</table>

Table 2. Calculation model.

<table>
<thead>
<tr>
<th>Calculation model</th>
<th>Mathematical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load flow calculation</td>
<td>Newton-Raphson method</td>
</tr>
<tr>
<td>Short circuit calculation</td>
<td>Superposition method</td>
</tr>
<tr>
<td>Output value calculation</td>
<td>Further symmetrical component method</td>
</tr>
</tbody>
</table>

As Table 2 shows, the primary system simulation of system-level panoramic testing in smart substation involves load flow calculation, short circuit calculation, output value calculation. Load flow calculation uses Newton-Raphson method which is widely used in power system, so this paper will not explain it in detail. This section mainly researches mathematical model of short circuit calculation and actual output value calculation.

Testing Short Circuit Calculation Model

Panoramic simulation software in substation is based on load flow short circuit calculation method and superposition method, can accurately calculate the state of power network in short circuit state. The schematic diagram is shown in Figure 2:

(a) The schematic diagram when short circuit occurs
The schematic diagram when short circuit current is replaced by current source

The schematic diagram when current in current source is zero

The power network schematic diagram when potential source is zero

Figure 2. Schematic diagram of panoramic the simulation calculation of substation.

In Figure 2(a), short circuit situation equals to breaker shown in the figure is on, and under the effect of the original potential source in the network, the short circuit current $I_k$ is generated in short circuit point. According to substitution principle, that is equal to additional insert current source valued $I_k$ in short circuit point as Figure 2(b) shows. The state of network is a consequence of original potential source and insert current source. According to superposition principle, Figure 2(b) can be decomposed into Figure 2(c) and Figure 2(d) and in Figure 2(c), only potential source has function, just like the normal operation state in the network before the short circuit occurs, we can know the network status by calculating the load flow; in Figure 2(d), only current source $I_k$ works, the original potential source in network will be set to zero, the network now is turn to be a passive network.

According to the above analysis, the Short circuit calculation based on load flow can be divided into three steps:

1. Calculating network status before short circuit occurs, the process is load flow calculation
2. Calculating short circuit current after short circuit occurs, then calculating the network status when the constant current source inserts into passive network.
3. To add up the above results, then we can get the network status after short circuit occurs.

The Calculation Model of Actual Output Value

System-level panoramic simulation system in smart substation needs to output phase voltage of potential transformer (PT) and threefold zero-sequence voltage, phase current of current transformer (CT) and threefold zero-sequence current. By using symmetrical component method, we can work out phase voltage of each calculating node and phase current of each component, phase current in fault point. The value worked out is just basic value, to be marked as $V_a$, $V_b$, $V_c$, $I_a$, $I_b$, $I_c$, the actual phase voltage of calculation node, phase current of component and phase current of fault point can refer to Table 3.

The phase voltage of PT is equal to phase voltage of connecting calculating node, threefold zero-sequence voltage is the sum of phase voltages. The phase current of CT is calculated as following flow:

1. To treat CT as a component, regenerating calculating node, that equals to add some calculating nodes in original calculating nodes.
(2) Scanning all of calculating nodes, if the calculating node only connects a unknown CT (it has not worked out the current of CT yet), then the current of unknown CT is equal to the sum of component current of calculating node, current of fault point, known current of CT. There are some CT to work out to be known CT in each scan, and also maybe have nothing.

(3) Rescanning all of calculating nodes, repeating that step until it can’t work out current of CT.

(4) Scanning all of calculating nodes, formulating current equation of calculating nodes connected to CT, and to get the equation that the current of CT is unknown, the element of coefficient matrix can only be -1, 0, 1. Using Gauss elimination method to solve, the type of coefficient is integer. When choosing pivot element, if it is found that all elements are zero, then deleting this row or rank and all the rows or ranks after it, meanwhile, deleting the unknown value corresponding to the deleted rank, the unknown is set to zero. If there is no new rank and row needs to be solved, deleting the unknown corresponding to all of unsolved rank and row, the value of unknown is set to zero. Calculating the rest matrix, we can get the other unknown value.

Table 3. Calculation of actual transmission voltage and current.

<table>
<thead>
<tr>
<th>Type</th>
<th>Actual value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B phase ground</td>
<td>( V_a = V_a' \angle 120^\circ )  ( I_a = I_a' \angle 120^\circ )</td>
</tr>
<tr>
<td>CA interphase short circuit</td>
<td>( V_a = V_a' \angle -120^\circ )  ( I_a = I_a' \angle -120^\circ )</td>
</tr>
<tr>
<td>CA phases ground</td>
<td>( V_a = V_a' \angle 120^\circ )  ( I_a = I_a' \angle 120^\circ )</td>
</tr>
<tr>
<td>C phase ground</td>
<td>( V_a = V_a' \angle 120^\circ )  ( I_a = I_a' \angle 120^\circ )</td>
</tr>
<tr>
<td>AB interphase short circuit</td>
<td>( V_a = V_a' \angle 120^\circ )  ( I_a = I_a' \angle 120^\circ )</td>
</tr>
<tr>
<td>AB phases ground</td>
<td>( V_a = V_a' \angle 120^\circ )  ( I_a = I_a' \angle 120^\circ )</td>
</tr>
<tr>
<td>Fault-free</td>
<td>( V_a = V_a' )  ( V_b = V_b )  ( V_c = V_c' )</td>
</tr>
<tr>
<td>Three-phase short circuit</td>
<td>( I_a = I_a' )  ( I_b = I_b' )  ( I_c = I_c' )</td>
</tr>
<tr>
<td>A phase short circuit</td>
<td>( I_a = I_a' )  ( I_b = I_b' )  ( I_c = I_c' )</td>
</tr>
<tr>
<td>BC interphase short circuit</td>
<td>( I_a = I_a' )  ( I_b = I_b' )  ( I_c = I_c' )</td>
</tr>
<tr>
<td>BC phases ground</td>
<td>( I_a = I_a' )  ( I_b = I_b' )  ( I_c = I_c' )</td>
</tr>
</tbody>
</table>

Development of System-Level Testing Platform

Hardware Design

The standard metal case of system-level testing device hardware platform is about 6U 19 inches, backboard of metal case uses technical grade high-speed PCIE bus plate, has one power plugboard, one CPU plugboard, one switching value plugboard and several optical network plugboard. System plugboard configuration is shown in Figure 3.

By using high-speed PCIE bus and independent IO, the CPU connects the other plugboard, the structure is shown in Figure 4.

Unit device is the operative part in the system, which make connection and basic process to all kinds of incoming and outcoming signals. In addition, the unite devise interchanges datum with the upper computer under the control of the local administrative unite. Unit device is composed primarily of core module, including embedded RTOS vxWorks, high-performance PowerPC, massive FPGA, interface circuits and peripheral chips. The structure is shown in Figure 5.
The core module is made up of high-performance PowerPC with PowerPC in it. Running the embedded RTOS vxWorks on it is to compute the real time data, receive and dispatch datum and massages, control experiment process, time, compare the time, correspond with the upper compute and DUTs. Interface circuits are designed by module and board card according to the signal type, and expand interfaces by PFGA. PFGA and CPU are connected via super-speed data bus, with data exchanging between them.

Every interface support the interface-boards bellows:
1) input hard contact tip interface module.
2) output hard contact tip interface module.
3) analog quantity input interface module: collecting and processing all kinds of analog signal.
4) analog quantity output interface module: outputting all kinds of analog signal.
5) optical network internet access module: optical fiber ethernet connection.
6) light serial port module: connecting serial signals transmitted by optical fiber.
7) clock interface module: input all sorts of time synchronization signals.

**Software Design**

Figure 6 is the constitution of system-level testing platform. Functions of software components to intelligent substation system-level testing platform can be divided into three parts like plug-in manager module, computation module and communication module.

![Software architecture of test platform.](image)

The function of each part described below:

1) Plug-in manager module: plug-in manager module mainly responsible for creating figure and property. It is responsible for loading components, creating graphic element and providing information of registered components.

2) Computation module: computation module obtain connection status formation in the current view, update voltage classes according to settings. It need to checkout whether the model of figure meets the requirement of load flow calculation. Only meeting calculation requirement can pass the examination and then enter the communication module of lower computer.

3) Communication module: communication module is responsible for converting figures to XML, and send to the lower computer via TCP protocol and receive replies. For example, the lower computer reports GOOSE deflection to the communication module, than the change reflect on figures eventually.

**Development Application of Test System**

System-level testing platform covering individual equipment testing, interoperability testing, system linkage testing at all levels, test content also covers the protection logic testing, the testing for remote functions, soft plate testing, pressure of network testing and other types testing.

Intelligent substation secondary system testing platform can be divided into secondary system periodic detection and secondary system break maintenance by application context. The differences between them are test requirements, test procedures and test criteria. Periodic detection requires the testing range includes that the test criteria specified, while break maintenance pays more attention to the accuracy, rapidity and reliability of the test results. Different testing requirements determine the system-level tests criteria and leaving a broad space to application study in various applications.
Conclusion
To test the correctness of secondary system function is the core work in the intelligent substation construction project. The overall functional tests of communication network and status of equipment can be covered by using the secondary system-level test platform of intelligent substation, the testing efficiency of secondary system is effectively increased by graphical simulation of the primary system and local-liking test styles, which improve the imbalance that the excessive dependence on integrating tests before the system start to work and the severe shortage of field test skills. The flexible test method and extensive application prospects of the secondary system-level test platform can efficiently adapt the secondary system test requirement and provides a new idea for operating maintenance and corrective maintenance under the application environment.

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References
