Case Studies: Designing Protection Systems That Minimize Potential Hidden Failures

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Case Studies: Designing Protection Systems That Minimize Potential Hidden Failures

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***Abstract*—Historical data indicate that protection system hidden failures contribute to cascading power system disturbances. There are many types of hidden failures in protection systems, including in instrument transformers, primary equipment such as breakers, secondary system hardware and firmware, and relay settings. Most of the hidden failures can be traced to protection system maintenance issues. With advanced digital relays and communications, protection systems can be designed with much improved mechanisms that monitor protection system conditions and minimize potential hidden failures. This paper analyzes the key requirements of condition-based maintenance for protection systems. The paper proposes a relay supervisory system (RSS) as a part of protection systems to improve condition-based maintenance and mitigate hidden failures. The paper illustrates the structure and functions of the RSS with several real-world projects.**

I. Introduction

Nearly 70 percent of $n - 2$ contingencies are caused by relay misoperations, particularly those due to hidden failures. Maintenance is listed as the leading cause of hidden failures [1]. A hidden failure in a protection system has been defined as "a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event" [2] [3]. The major objective of protective relay maintenance testing is to maximize the availability of protection and minimize the risk of relay misoperation [4].

Digital relays have been widely used around the world since the 1980s. Philosophies of routine maintenance testing for these digital relays have changed [4]. Considerable work has been done to optimize routine maintenance tests because digital relays include self-test and self-monitor functions. Reference [5] analyzes the routine test interval for protective relays with and without self-test capabilities based on a Markov model. Reference [6] illustrates the self-test effectiveness of digital relays associated with routine relay maintenance. Reference [7] discusses the detailed 17-state model for protection associated with an optimal routine test. Reference [8] proposes an alternative method for testing relays. Reference [9] recommends a power system monitor to quickly restore the malfunctioning components to proper operation.

Digital relay self-tests verify relay integrity by detecting the out-of-tolerance conditions of relay components. Field data indicate that self-test effectiveness is around 80 percent because the self-test does not cover the input/output contact section or part of the analog input section [5]. In addition to undetected component failures, hidden failures also come from improper relay settings, protection functions unsuitable for evolving system configurations, and increasingly involved communications networks. Relying on relay self-tests and routine maintenance tests to reduce hidden failures is still a challenge facing utilities.

Aside from generating the final outputs of protection functions, modern digital relays offer many other intermediate logic outputs and status indications. This abundance of information, plus routinely available programmable logic controller (PLC) functions in relays and the IEC 61850 standardized communications architecture, provides an opportunity for a condition-based maintenance solution for protection systems. This paper proposes a relay supervisory system (RSS) that takes advantage of the extensive protection, monitor, and control functions of modern relays to improve condition-based maintenance and reduce the possibility of hidden failures. Several real-world projects illustrate the structure and function of the RSS.

The North American Electric Reliability Corporation (NERC) PRC-005-2 draft defines protection systems as including the following components:

- Protective relays, which respond to electrical quantities.
- Communications systems, which are necessary for the correct operation of protection functions.
- Voltage- and current-sensing devices and their circuits, which provide inputs to protective relays.
- Station dc supply, which is associated with protection functions.
- Control circuitry, which is associated with protection functions through the trip coil(s) of the circuit breakers and other interrupting devices.

As part of the PRC-005-1 reliability standard, NERC requires generation and transmission owners to maintain documented test results for maintenance testing procedures, testing intervals, and each of these components [10].

II. Features of Modern Digital Relaying

A. Protection System

As mentioned previously, a protection system consists of transducer inputs [current transformers (CTs) and potential transformers (PTs)], communication, protective relays, output circuits (breakers), and batteries [11]. The schematic diagram of a line protection system is shown in Fig. 1.

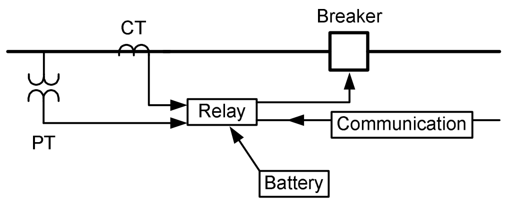

Fig. 1. Schematic diagram of protection system.

The analog input section consists of signal connections, isolation transformers, low-pass filters, one or more multiplexers, and an analog-to-digital (A/D) converter. A digital relay self-test partially monitors the analog input section.

Digital relays have a self-test function that monitors hardware and firmware operating conditions. Protective relaying also includes relay settings and configurations associated with various applications. However, the self-test function of digital relays does not cover relay settings and configurations. We need to rely on rigorous system studies to derive proper relay settings and configurations.

Relay output contacts interface with the tripping and closing circuits of circuit breakers. When a relay does not operate for a long period of time, we need to verify that relay output and input contacts work appropriately with a routine maintenance test. Modern digital relays provide various methods to facilitate this verification.

Because the self-test does not include the entire analog input section of a digital relay, utilities need to use additional monitoring functions, such as a metering command in a relay, to detect failures in the analog input section. Routine metering checks and comparisons with other intelligent electronic devices (IEDs) on the same circuit augment the relay self-test well.

B. The Architecture of a Digital Relay

The block diagram in Fig. 2 shows the major subsystems of a digital relay. Digital relays use a microprocessor, an analog signal acquisition system, memory components containing relay algorithms, contact inputs to control the relay, and contact outputs to control other equipment. As the center of a digital relay, the microprocessor is responsible for the execution of protection algorithms, maintenance of various timing functions, and communication with its peripheral equipment. The algorithms and settings contained in the relay memory define the protection characteristics.

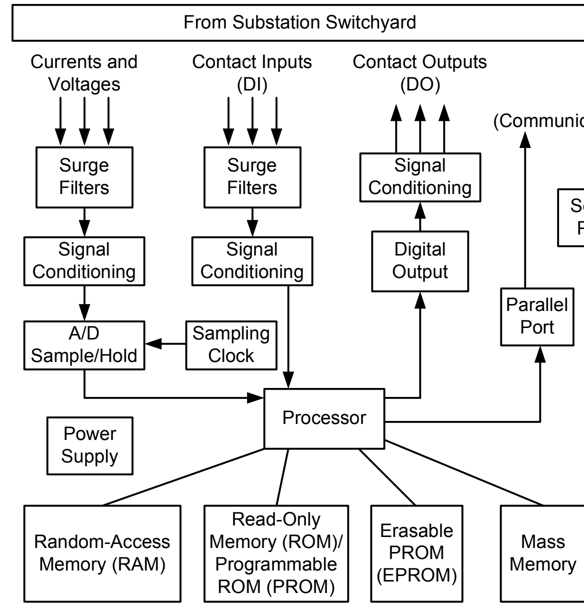

Fig. 2. The architecture of digital relaying.

Digital relays replace the induction disks of electromechanical relays and the logical circuits of static relays with implicit digital signal processing in a microprocessor. From a practical point of view, digital relays tend to be "black boxes," meaning that it is hard to analyze the behavior of digital relays with traditional relay visualization provided by electromechanical and solid-state relays.

C. Configuration Functions of Digital Relays

IEC 61850 defines the logical node (LN) as a basic element of numerous real devices and functions in a substation. The logical architecture of IEC 61850 permits LNs to be distributed in multiple physical devices throughout a substation. In order to interconnect these distributed LNs, a fast and reliable delivery mechanism is needed. One solution to meet the identified requirements is known as Generic Object-Oriented Substation Event (GOOSE). Using GOOSE to exchange information among LNs, the conventional wired integration of physical devices is replaced with a virtually wired, logical integration of functions, as shown in Fig. 3.

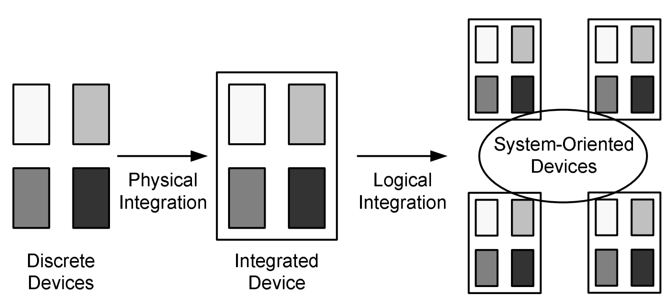

Fig. 3. Logical integration.

The design of modern digital relays is based on the concept of the LN. The internal logical information of relays is mapped into LNs through communications interfaces for analysis. These mapped LNs provide sufficient information for the condition-based maintenance of a protection system.

IEC 61850 makes it possible to freely allocate logical functions to physical devices. This provides the potential for more standardized varieties of IED configurations than was possible with pre-IEC 61850 devices. Flexible integration under the IEC 61850 paradigm tends to reduce the number of physical devices required in a protection system. This reduction of devices can also contribute to an increase in system reliability.

III. The Issue of Relay Maintenance

A. Determination of Routine Maintenance Time

Maintenance is critical for keeping a protection system in good condition. With this in mind, it is necessary to define adequate testing and monitoring practices for digital protective relays, such as secondary wiring and settings values being in accordance with power system growth.

The conventional two-state model shown in Fig. 4 illustrates the reliability of a protection system [12]. In Fig. 4, the model includes an up state and a down state. Up means the element is available or in a service state. Down means the element is unavailable or in an outage state. The symbols μ and λ are called the failure rate and the repair rate, respectively; both can be considered transition probabilities.

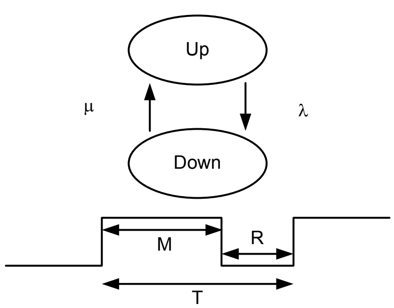

Fig. 4. Two-state reliability model.

M and *R* signify the average times of the up and down states, respectively. *T* denotes a period of time and is equal to *M* plus *R*. The value of *M* is equal to the mean time between failures (MTBF) and that of *R* is the mean time to repair (MTTR). The other relevant parameters are obtained from (1) and (2) as follows:

$$U = \frac{\text{MTTR}}{\text{MTBF} + \text{MTTR}} \quad (1)$$

$$\lambda = \frac{1}{\text{MTBF}} \quad (2)$$

where:

U denotes the unavailability for an element.

Hidden failures contribute to the unavailability of a larger protection system. One of the purposes of routine maintenance, therefore, is to root out possible hidden failures. They extend system downtime (R) and are a major maintenance issue. Relay settings associated with system conditions can contribute to hidden failures and are not part of routine maintenance. The reliability of relays highly depends on the maintenance period. From a Markov model-based analysis, [5] points out that there is an optimal routine maintenance interval for modern digital relays with self-test functions. It is also important for utilities to monitor the alarm contacts of digital relays, conduct simple tests on contact inputs and outputs, and check relay analog input quantities with the metering function.

B. Cost of Routine Maintenance

From a practical point of view, relay maintenance is a low-value activity because it only proves that relays are in good working condition most of the time. Relay maintenance tests occasionally resolve some issues in a protection system.

Also, maintenance activities can introduce human mistakes. These human mistakes, such as forgetting to restore test switches to their original positions or restore correct settings, are another cause of hidden failures.

Another drawback of routine relay maintenance is that utilities may need to put some primary substation equipment out of service for security reasons. However, outages of primary equipment sacrifice the reliability of the power system by weakening the interconnection between grids.

The labor required by routine relay maintenance is another issue to consider. This is especially true when a substation is located in a remote area, which means a long travel time for a routine maintenance test.

Considering the outcomes of routine maintenance tests, the labor involved, and the drawbacks of introducing possible hidden failures, the routine maintenance of relays is a challenging issue for the entire life cycle of a protection system.

C. New Mode of Hidden Failure

As in a conventional digital relay, a permanent defect can arise in three ways for digital relays: a component failure inside a relay, a defect in the connections of the protection system, and incorrect settings. It has been argued that the main cause of hidden failures is relay maintenance and is related to relay settings [13].

An IEC 61850-based digital relay can introduce a new mode of hidden failure. Because the LNs of the relay are associated with a Substation Configuration Description (SCD) file, the interface boundary of conventional digital relays as defined by terminals on relay backplanes becomes a logical interface.

Due to the lack of standardization of input data sets, the IEC 61850 standard directly associates an SCD with the unique data set definitions based on LNs residing in protection and control IEDs. This direct association makes it difficult to manage the boundaries of protection systems because each IED may be unique and the configuration may change. Any changes in an SCD may result in Configured IED Description (CID) changes, increasing the possibility of hidden failures. A configuration tool can associate protection functions to IED input and output terminals and isolate the impact of SCD changes to the CID.

IV. Main Considerations of Condition-Based Maintenance

A. Eliminate Blind Spots of Supervision Systems

The architecture of IEC 61850 makes it possible to acquire sufficient information for supervising relay behavior through either the station or process bus, such as current and voltage, internal information of relays, and circuit breaker information, as shown in Fig. 5.

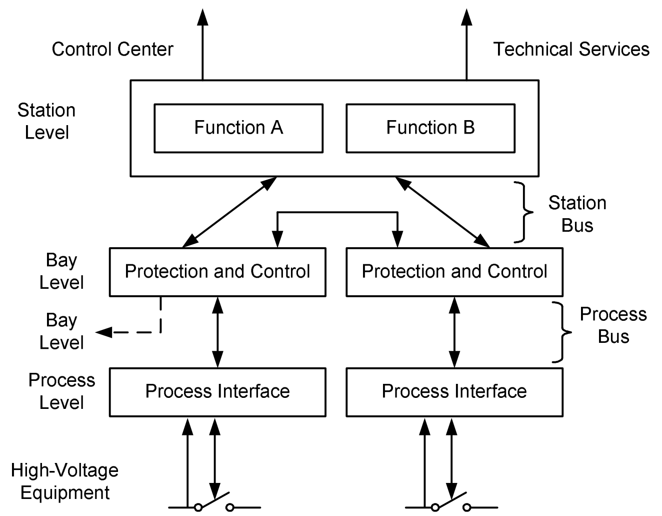

Fig. 5. Structure of substation automation system (SAS).

Fig. 6 shows the main functions of the RSS. The RSS will issue an alarm in case there is anything wrong with the protection system under supervision.

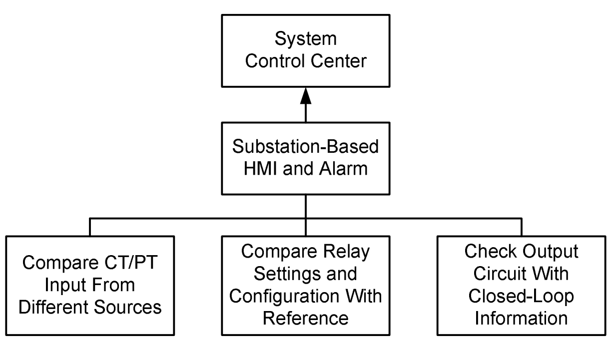

Fig. 6. RSS functional diagram.

B. Visualize Behaviors of Protection Functions

IEC 61850 models numerous physical devices and functions found in substations. These models and functions are organized into LNs. A specific protection function is then modeled through logical connections between the LNs that exist throughout a substation.

An important characteristic of IEC 61850 is the free allocation of subfunctions to any physical device. As a result, it is possible to organize the LNs of relays in the RSS to illustrate the functional behaviors of relay hardware and firmware in a customized visualization setup. Graphical functions aid in this visualization and extend it across several physical devices.

Emerging flexible human-machine interface (HMI) capabilities allow a choice of substation-based HMIs, which integrate the operator information of front-panel HMIs of decentralized IEDs that are installed in switchyards in harsh physical and electrical environments [14]. It is anticipated that RSS applications will expand the content of the integrated HMI to include real-time, protection system analytics for review, archive, and ad-hoc audits. This greatly improves the value of the RSS.

C. Routine System Operations Are Part of a Routine Test

One aspect of a routine maintenance test is to check secondary wiring and settings according to a maintenance schedule.

The manufacturing message specification (MMS) of IEC 61850 defines the virtual manufacturing device (VMD), which describes the external behaviors of physical equipment [15]. Using the IED PLC functions to emulate the trip and close operations of circuit breakers as enabled by the VMD, we check the health of protection secondary circuits by adding a small signal online or from the routine operations of breakers.

Utilities normally exercise substation breakers from time to time through bus reconfiguration procedures. Online monitoring that coordinates with each breaker operation can replace this procedure and avoid unnecessary maintenance to save labor costs.

V. Development of a Substation Automation System With RSS

A. General Trend of SASs

Fig. 7 shows the evolving trend of SASs, with optical fiber and network switches replacing copper cable connections between IEDs. The performance of IED functions increasingly depends on the reliability of intranet networks inside substations.

This future trend of SASs raises some concerns regarding the reliability of protection systems. The protection reliability of this architecture tends to be reduced because of the heavy dependence on communications networks. In addition, communications networks become more and more complicated because of the need to process an increasing number of protection messages and the need for redundant network designs.

B. IEC 61850 Impact on Hidden Failures

The application of the IEC 61850 standard generates some new concerns for hidden failures.

Any change of an SCD design will probably result in changes in the CIDs of IEDs. Any change in a CID indicates that the relay performance could be different and that the virtual wiring to other IEDs via GOOSE may be different. The application of an SCD may increase the probability of hidden failures in protection systems.

Replacing copper conductors with fiber optics results in the logical connection of IEDs via digital communications-based virtual wires. Unlike the conventional copper point-to-point connections, it is not straightforward to check the logical connections. Because the data set of a GOOSE message may be received by several IEDs and used for several different applications, it is important that a conventional test mode for each application be used to verify the correctness of IED connections.

Peer-to-peer communications make IEDs connected on a network less secure. The IEC 61850 standard does not address the network security issue. However, this is addressed in IEC 62351, which is under development [16]. The critical nature of the process and station buses in the IEC 61850 layout may make it necessary to take some actions concerning information security for reliable protection systems. Network design must ensure the security and dependability of data delivery to ensure the security, dependability, and reliability of the communications-assisted automation and protection schemes. For cybersecurity, the boundaries of the station and process buses must be secured so that digital communications can be published within this private network without fear of compromise. Further, the privacy of the network is necessary to permit data exchange without encryption, which causes latency and network burden. Encryption and other security applications are added to messages that leave the network, as described in IEC 62351.

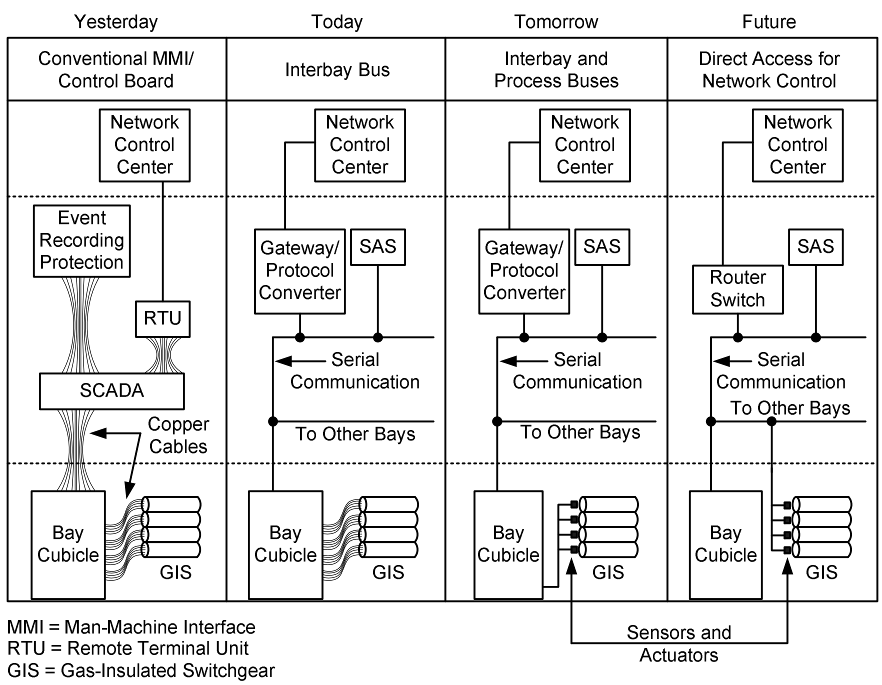

Fig. 7. The developing trend of SASs.

C. *Innovative RSS Structure*

The IEC 61850 standard provides technical methods that are needed for the RSS to mitigate the hidden failures of protection systems. Fig. 8 shows a layout of a protection system with an RSS function. The RSS has connections to both the process and station buses. In this configuration, the process level information is shared through a network of Ethernet switches. The RSS easily acquires the complete information about the protection system from the Ethernet network switches on the process bus.

Protection and control IEDs provide internal diagnostic and all other information to the RSS through the process bus interface. The RSS prevents nonsecure access to IEDs from the substation communications network.

The main RSS functions are as follows:

- Supervision of the secondary control circuits of protection systems.
- Management of IED CID files.
- Provision of traceable causes to protection outputs.
- Margin analysis of primary and backup protection functions.
- Prevention of unauthorized access to IEDs from the substation communications network.

D. *Online Alarm Scheme*

Modern digital relays are complex due to the increased protection and control functions that are included in one IED. This abundance of functions plus programmable capabilities makes the relay flexible for configurations associated with various applications. At the same time, however, the flexibility also leaves room for possible configuration errors and hidden failures.

As mentioned previously, IEC 61850 introduces the concepts of SCDs and CIDs. The management of CIDs has become an issue for substation designs under the IEC 61850 architecture. Without suitable design software that manages and coordinates with changes and version controls of SCDs and CIDs, it is possible to introduce hidden failures. By tracking the CIDs and checking the substation communications network, the RSS provides online alarms in case of inconsistencies between CIDs and SCDs.

Equipped with complete information from protection and control IEDs in the substation, the RSS monitors the intermediate outputs of the internal logic of these IEDs. With the aid of substation HMIs, the RSS clearly indicates what has led to the final decisions of the protection system, allowing system operators and protection engineers to understand the logistics of each operation and to find any potential problems that may lead to a hidden failure.

The RSS constantly monitors substation configuration changes and checks the health of the secondary control circuits through each system operation. The results of RSS supervision and monitoring provide a basis for condition-based online maintenance programs.

The RSS communicates with system control centers. When any supervised condition exceeds the set RSS supervision limit, the RSS issues an alarm locally or to remote system operators through the station bus of the substation communications network.

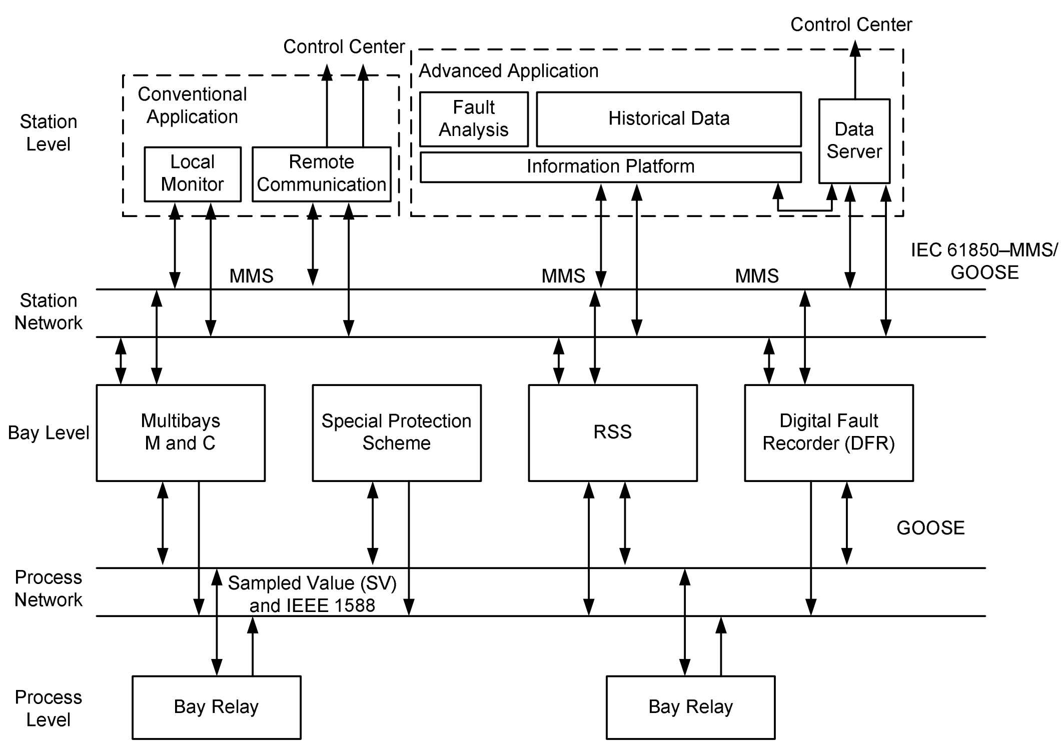

Fig. 8. Innovative RSS architecture based on IEC 61850.

E. Remote Event Analysis

One of the functions of the RSS is remote event analysis and maintenance.

The RSS communicates with remote control centers through the station bus defined under the IEC 61850 structure. Utility operators access the analysis results and alarm information from the RSS through remote operations of the system. Functioning as a data concentrator, the RSS allows operators to remotely retrieve event reports and Sequential Events Recorder (SER) data from all substation IEDs for further analysis of critical system events. This remote operation of the RSS provides low-cost condition-based maintenance that reduces the impact of hidden failures.

F. Adaptive Special Protection Scheme

Adaptive relaying is a protection philosophy that allows and makes adjustments to various protection and control functions in order to make the protection system more attuned to the prevailing power system conditions [17] [18] [19]. This adaptive protection from individual substations becomes a part of a special protection scheme for the entire region of power systems operated by a utility.

Adaptive relaying implies that relays must change their settings according to changing system conditions based on the information acquired from the local power system. The RSS obtains system information directly from the process bus. Together with the settings and protection logic information from the protective IEDs in the substation, the RSS validates each operation of the protection system. In addition, the RSS checks the operating margins of the protection elements that operated or did not operate. From these operating margin checks, it is possible for the RSS to adaptively tune the relay settings according to the changing system configurations.

VI. Real-World Cases

We introduce three real-world projects in this section to demonstrate the implementation and effectiveness of an RSS in SASs.

A. 110 kV Xining Steel Plant Project

This project was implemented at a steel plant located in Qinghai province, China, in 2005 [20]. The project included two 110 kV substations and several 35 kV and 10 kV substations. Modern digital relays with programmable logic capabilities were used in this project. It has been routine for Chinese utilities to use a breaker operating unit between the relay output and the breakers. The main contribution of this project is to replace the conventional breaker operating units of protection systems. Fig. 9 shows the main logic of the breaker operating unit that is replaced by the PLC function in the relays. Implementing the breaker operating function with programmable logic makes it possible to monitor this part of the secondary wiring system online.

Monitoring the critical parts of output circuits extends the monitoring function beyond the relay self-test itself. At the same time, the input circuit monitors the relay programmable logic as well.

On August 20, 2007, the RSS detected abnormal voltage in the 35 kV PT circuit caused by an incorrect connection and prevented a hidden failure by alerting technicians to correct the connection problem before a malfunction occurred.

B. 220 kV Jin Shuitan Hydropower Project

This project was implemented at the 220 kV Jin Shuitan hydropower plant located in Zhejiang province, China, in 2009. The hydropower plant has six generators. The project involved a total of 31 digital relays. The system control building is 50 kilometers away from the Jin Shuitan hydropower plant. It is time-consuming and costly for daily routine inspections of the protection system.

The main purpose of this project was to visualize the relay functions associated with routine inspections. Digital relays with programmable logic functions were selected as a solution. The RSS was installed in the control building where operators monitor the status of the generator protection system via a fiber-optic connection, as shown in Fig. 10. In this case, the RSS improved the reliability of the generator protection system and saved labor expenses for routine site inspections.

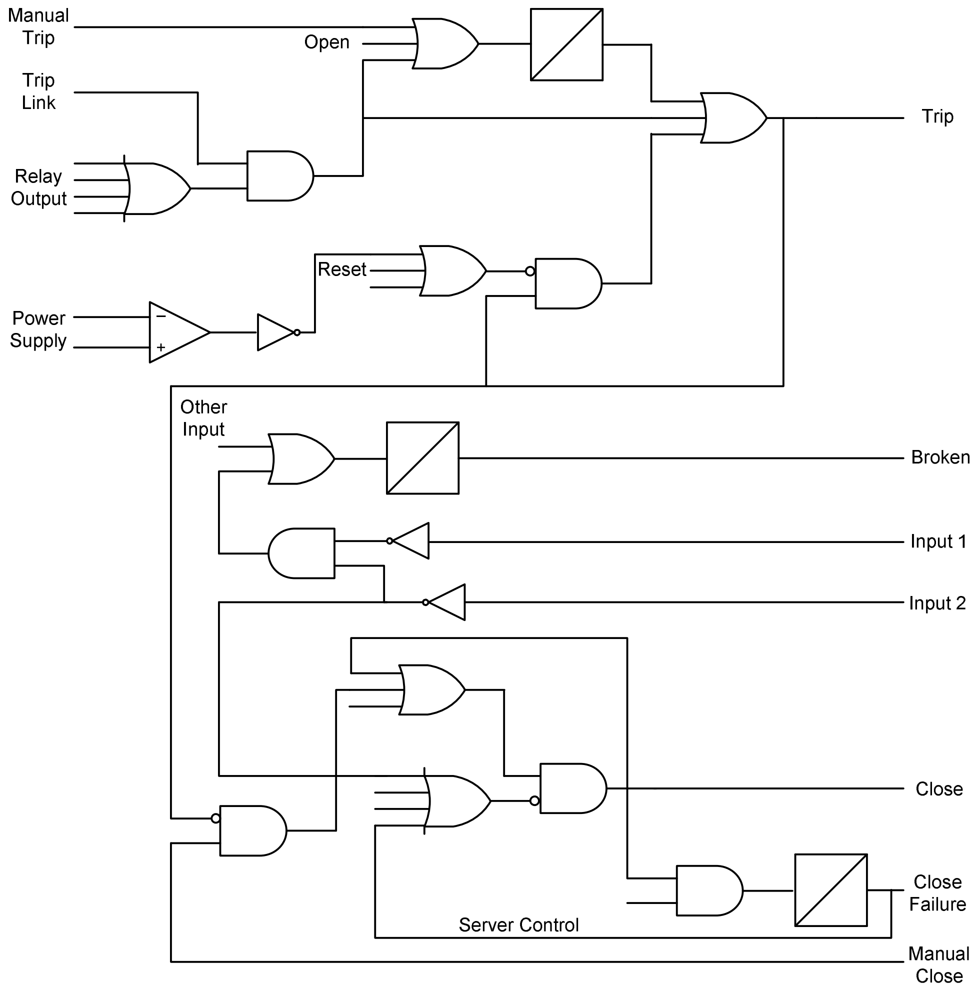

Fig. 9. Programmable output circuit for Xining steel plant project.

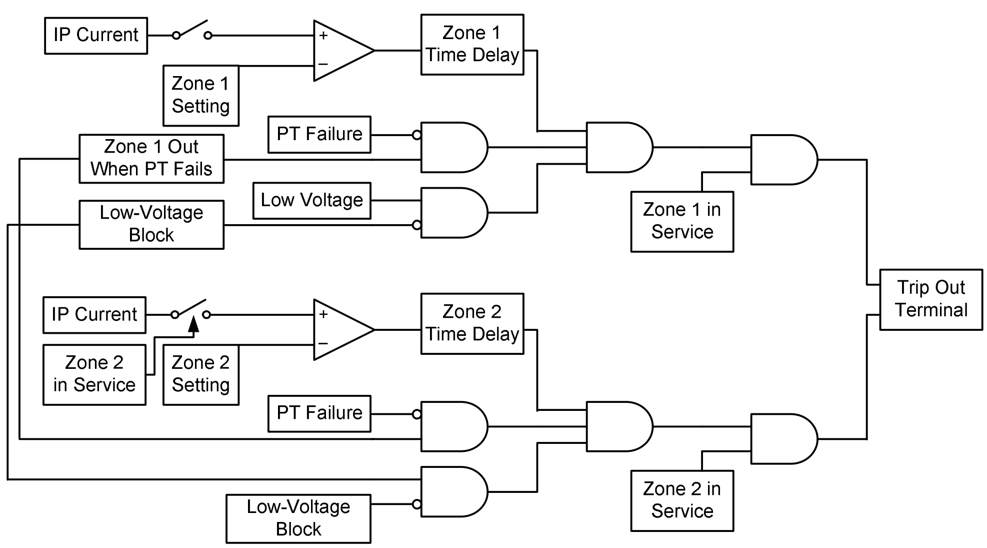

Fig. 10. Visualized relay operation diagram for Jin Shuitan hydropower project.

C. 110 kV Liang Shuijing Substation Project

This project was implemented in Liang Shuijing substation located in Guizhou province, China, in 2011. The main purpose of this project was to design a decentralized SAS with IEC 61850 applications. Modern digital relays are installed inside the cubicles of outdoor gas-insulated switchgear or by the station transformers in the switchyard. One network Ethernet switch is used for process bus information sharing, and another network switch shares the station bus information, as shown in Fig. 11.

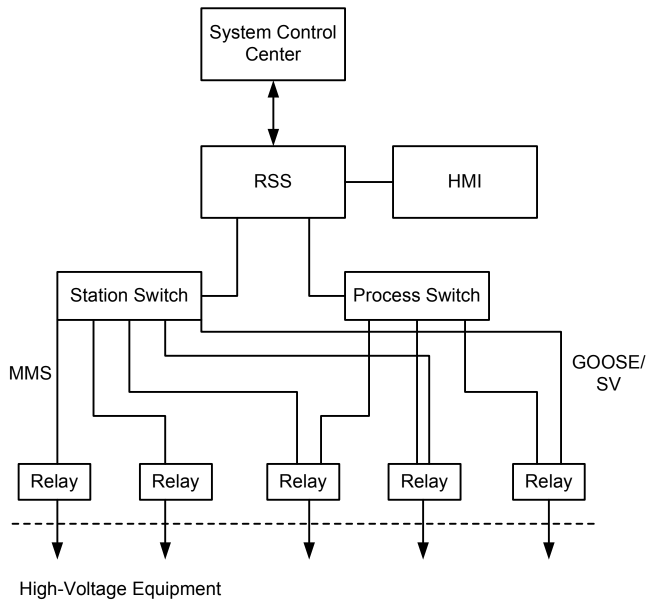

Fig. 11. Decentralized protection system for Liang Shuijing substation project.

The main features of this project are as follows:

- Decentralized allocation of relays inside the cubicle of outdoor gas-insulated switchgear or substation transformers.
- Substantial reduction of copper cables.
- Use of substation-based HMI technology, which displays all functions of the relays installed.
- Use of remote maintenance technology for the purpose of closed-loop testing.

VII. Conclusion

Hidden failures contribute to a large percentage of cascading outages. The IEC 61850-based RSS mitigates or reduces the impact of hidden failures in protection systems. Three implemented projects illustrate the effectiveness of the functions within an RSS. An RSS installed in a substation significantly reduces the possibility of hidden failure occurrences. The RSS contributes to a condition-based maintenance strategy that can reduce the labor costs of routine maintenance. With advances in new tools and technology, such as HMI and IEC 61850, the RSS will play an increased role in the future to make protection systems more reliable.

VIII. Acknowledgment

This paper was based in part on the report "Anatomy of Power System Blackouts and Preventive Strategies by Rational Supervision and Control of Protection Systems" (ORNL/Sub/89-SD630C/1), which was sponsored by Oak Ridge National Laboratory.

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X. Biographies

Xiang Gao received his PhD from Zhejiang University, Hangzhou, China, in 2008. He was a visiting scholar at Virginia Tech in 2011. He is the former Vice Chief Engineer of the Dispatching Center of the East China Electric Grid Limited Corporation and the former General Manager of Shanghai SHR Automation Co. Ltd. He has worked with relay and substation automation systems for more than 20 years. He is an adjunct assistant professor at Virginia Tech.

James S. Thorp was the Hugh P. and Ethel C. Kelley Professor of Electrical and Computer Engineering and Department Head of the Bradley Department of Electrical and Computer Engineering at Virginia Tech from 2004 to 2009. He was the Charles N. Mellowes Professor in Engineering at Cornell University from 1994 to 2004. He was the Director of the Cornell School of Electrical and Computer Engineering from 1994 to 2001, a Faculty Intern, American Electric Power Service Corporation from 1976 to 1977, and an Overseas Fellow, Churchill College, Cambridge University in 1988. He was an Alfred P. Sloan Foundation National Scholar and was elected a Fellow of the IEEE in 1989 and a Member of the National Academy of Engineering in 1996. He received the 2001 Power Engineering Society Career Service award and the 2006 IEEE Outstanding Power Engineering Educator Award and shared the 2007 Benjamin Franklin Medal with A. G. Phadke.

Daqing Hou received BSEE and MSEE degrees at the Northeast University, China, in 1981 and 1984, respectively. He received his PhD in Electrical and Computer Engineering at Washington State University in 1991. Since 1990, he has been with Schweitzer Engineering Laboratories, Inc., where he has held numerous positions, including development engineer, application engineer, research and development manager, and principal research engineer. He is currently the research and development technical director for East Asia. His work includes power system modeling, simulation, signal processing, and advanced protection algorithm design. Daqing holds multiple patents and has authored or coauthored many technical papers. He is a senior member of IEEE.

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