Compatibility and Interoperability Evaluation of All-digital Protection Systems Based on IEC 61850-9-2 Communication Standard

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***Abstract*-- Recent development of electronic instrument transformers and use of digital relays allow the development of an all-digital protection system, where the traditional analog, hardwired, interface has been replaced with a digital communication link (process bus) based on IEC 61850-9-2 standard. An all-digital system should provide compatibility and interoperability so that different electronic instrument transformers can be connected to different digital relays (under a multi-vendor connection). Since the novel all-digital system composed of IEDs from multiple vendors has never been implemented and/or tested in practice so far, its performance needs to be evaluated. This paper presents a methodology for performance and compatibility evaluation of an all-digital protection system. The test results obtained using a digital simulator test bench and comparison of the compatibility of systems provided by different manufactures are discussed.**

***Index Terms*--compatibility, interoperability, IEC 61850, performance evaluation, process bus, protective relaying, relay testing, optical transformers**

I. Introduction

RELAY testing is a very important issue when applying the protective relays. Vendors need an evaluation tool to validate the design of the relay logic and communication. Utilities need a tool to compare the performance of different relays, calibrate relay settings and perform troubleshooting. The recent development of optical and Hall Effect instrument transformers and the use of digital relays enable the development of an all-digital protection system. Different components of such system communicate using digital communication protocol. The output of the electronic current and voltage transformers are sampled (digital) signals, which after combining in merging units can be connected to digital relays through an IEC 61850-9-2 digital process bus [1]. Compatibility and interoperability are one of the most important features of IEC 61850. Although many interoperability tests have been performed at the bay level and the IEC 61850-9-1 interoperability at the process level, the all-digital protection system containing different electronic instrument transformers connected to different digital relays by an IEC 61850-9-2 process bus was not described in the literature yet. Compatibility and interoperability evaluation of the all-digital protection system assumes two kinds of test, conformance and performance test. IEC 61850-10 gives guidance for the conformance tests of Intelligent Electronic Devices (IEDs) interconnected in an all digital protection systems [2]. The performance tests allow more extensive assessment and can be used to determine the performance characteristics of the overall system [3]. Evaluation of the all-digital system performance is necessary in order to recognize all possible conditions when protection system may miss-operate, or operate with unacceptable performance (reduced selectivity, increased operating time, etc). Identifying these abnormal situations is important for two reasons: a) recognizing possible conditions for incorrect operation, b) proving that the novel implementation will not translate in degrading protection system performance. In [4] authors propose a methodology of compatibility and interoperability evaluation for all-digital protection system through automatic implementation of application testing. This methodology is now used as a base for compatibility and interoperability testing of all digital protection systems composed using components from multiple vendors.

The paper is organized as follows. Section II introduces the compatibility and interoperability evaluation; Section III defines the evaluation methodology; Section IV discusses test results and Section V conclusions.

II. Compatibility and Interoperability

Compatibility means the ability of two or more IEDs to perform requested functions (protection, control, metering, etc) using IEC 61850 standard for communication and data exchange. According to IEC 61850 interoperability is ability of IEDs or substation automation systems from different vendors to execute bi-directional data exchange functions, in a manner that allows them to operate effectively together. Unlike interoperability, the IEC 61850 standard was never intended to ensure interchangeability of IEDs [3]. However, interchangeability of the transducer system (comprised of

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current and/or voltage sensors and merging units) and process bus (made of copper or fiber wires and an Ethernet switch) is not only a possibility but also a highly desirable feature of the all-digital system, allowing utilities to choose between different sensors and fast Ethernet switches without restrictions.

Performing compatibility and interoperability tests gives ability to make conclusion about possible interchangeability between protection systems components made by different vendors. As mentioned, compatibility and interoperability evaluation of the all digital protection system requires two kinds of test, namely conformance and performance test. Conformance tests belong to certification tests which aim at verifying whether an IED satisfies the criteria specified by certain standard or authority. These tests are performed at the vendor's laboratories or at independent test institutes. Criteria for performance evaluation of the protection system are not a new topic and have been investigated in different research efforts [5], [6]. Although they have proven to be effective to evaluate the performance of conventional protection system, they need to be extended to be applicable for all-digital systems. Performance tests belong to application tests which aim at verifying the behavior of the protection system, the accuracy and operating times under various conditions. For the all-digital protection system, the interests for performance tests are the trip/no trip decisions and the operating times.

In [4] authors propose how the compatibility and interoperability evaluation of all-digital protection system is performed through protection system performance tests.

A. Performance Indices

This paper follows selection of the performance indices adopted in [4] to meet the needs of the all-digital protection system. Two kinds of indices are used for performance evaluation:

The performance index of protection system P when fed by exposure E is denoted by PPI_P^E. The average performance index of protection system P is defined as:

$$PPI_P = \frac{1}{N} \sum_{E \in EB} PPI_P^E$$ where N is the number of exposures

There are two types of protection performance indices calculation methods, namely the trip decision method and trip time method respectively. For the trip decision method:

$$PPI_P^E = s = \frac{N_1 + N_0}{N}$$ where N_1 and, N_0 denotes number of correct trip/restraints and N is the total number of exposures

For the trip time method:

$$PPI_P^E = D^t$$ where D^t stand for the trip time of the tested protection system.

B. Compatibility Index

The compatibility index of protection system P1 and P2 when fed by the same test signal E is defined as:

$$PCI_{P1,P2}^E = |PPI_{P1}^E - PPI_{P2}^E|$$

The average compatibility index of protection system P1 and P2 is defined as:

$$PCI_{P1,P2} = \frac{1}{N} \sum_{E \in EB} |PPI_{P1}^E - PPI_{P2}^E|$$

The protection system includes the transducer system (sensor and merging unit), the process bus (the Ethernet LAN) and the protective relay. By definition, the smaller the PCI, the better compatibility and interoperability.

III. Evaluation Methodology

The compatibility indices, defined in the previous section, are calculated by analyzing output signals of IEDs from different manufacturers combined into a test system. Three transducer sets (composed from current sensors and merging units), two 100Mbit/sec Ethernet switches and one digital relay where available for testing. Generic evaluation systems diagram is as shown on Fig 1.

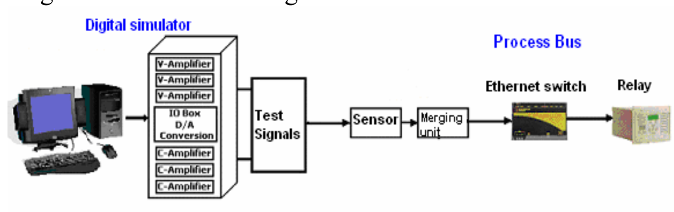

Fig. 1. Generic test evaluation setup

Simulation scenarios define the power system events to be created and replayed into the modeled referent protection systems and the all-digital protection system assembled in the lab. These events are simulated using a sequence of circuit breaker switching corresponding to various power system conditions. Any particular scenario is defined by two parameters: Time at which the event starts and finishes and scenarios shown in table I.

TABLE I. Simulation scenario, overcurrent protection

Fault type	Fault Location [%]	Resistance [Ω]	Inception Angle [deg]
AG	-10, 20, 70	0, 5, 10	0, 30, 60, 90
BC	-10, 20, 70	0, 5, 10	0, 30, 60, 90
BCG	-10, 20, 70	0, 5, 10	0, 30, 60, 90
ABC	-10, 20, 70	0	0, 30, 60, 90

Simulated scenarios are selected to create those power system conditions in which correct operation of the protection system is critical [7]. Voltage sensors were not available from all vendors so scenarios were limited to those that do not require directionality (forward zone 20% and 70%). Overcurrent protection is expected to operate (issuing a trip command) for faults in the forward zone of protection.

Features of the tested overcurrent relay function are:

- Phase time overcurrent protection as backup protection
- Residual time overcurrent protection

Settings of the relays are:

- Nominal input current of relay model is In=5A

- Pickup current is set to 1.5 times the nominal value
    - Very inverse time-current characteristic was used.

This characteristic is defined as:

$$t_{operate} = \frac{13.5\times k}{I_n - 1} \qquad \text{k was chosen as: k=0.025}$$

A total of 120 different exposures (1200 tests since each exposure is replayed 10 times) are generated for the overcurrent protection testing.

Three complete all digital protection systems are composed by interchanging available sensors and Ethernet switches. Electronic transducer sets from NxtPhase, AREVA and Siemens, Ethernet switches from GE Multilin and RuggedSwitch and relay AREVA Micom P441 are used. Test set configuration are shown on Fig 2.

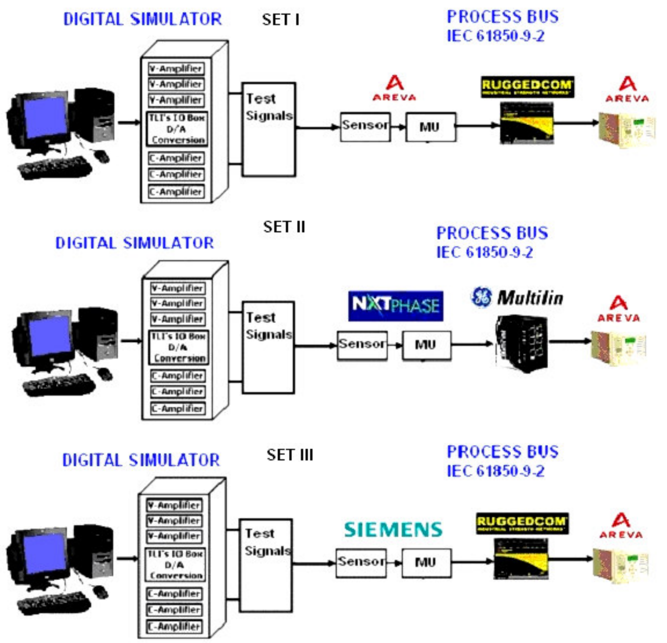

Fig. 2. Test Setup configurations

During the tests all three MUs have been connected to Ethernet network but only one at a time with destination address set that matches relay address. This is used to simulate real conditions when multiple IEDs share the same Ethernet network. In addition, random data packets are generated using PC connected to the same network at the rate of thousand 1500Byte packets per second. This is used to simulate higher network traffic on the process bus.

IV. Test Results

This section presents application of the evaluation methodology. Results are obtained by using simulation and test procedure detailed in the previous chapter. Performance indices for tested all digital protection systems are presented in the form of average values. The test system for performance testing was described in previous section. Interoperability of protection system modules is tested and results are presented.

A. Performance results

Absolute performance indices for all three test setups are presented. All performance indices results shown in Table II, III and IV are obtained following methodology presented in previous section.

TABLE II. Overcurrent performance results, Test setup No1

Fault Type	Fault Location	S	Average t[s]	Average σ[s]
AG	20	1	0.0793	0.002
	70	1	0.3253	0.002
BC	20	1	0.0573	0.002
	70	1	0.1766	0.003
BCG	20	1	0.0503	0.003
	70	1	0.145	0.002
ABC	20	1	0.049	0.002
	70	1	0.121	0.002

TABLE III. Overcurrent performance results, Test setup No2

Fault Type	Fault Location	S	Average t[s]	Average σ[s]
AG	20	1	0.0787	0.002
	70	1	0.3210	0.002
BC	20	1	0.0543	0.001
	70	1	0.1673	0.002
BCG	20	1	0.0480	0.002
	70	1	0.1427	0.003
ABC	20	1	0.0490	0.001
	70	1	0.1200	0.002

TABLE IV. Overcurrent performance results, Test setup No3

Fault Type	Fault Location	S	Average t[s]	Average σ[s]
AG	20	1	0.0750	0.002
	70	1	0.3110	0.003
BC	20	1	0.0580	0.002
	70	1	0.1587	0.002
BCG	20	1	0.0517	0.002
	70	1	0.1377	0.003
ABC	20	1	0.0520	0.001
	70	1	0.1140	0.002

The following conclusions can be made, based on the presented results:

- Selectivity of overcurrent protection function for the tested all-digital protection systems is as expected.
- A comparison of the average tripping times shown in Tables II through IV demonstrates that for all simulated fault types the reaction times of the tested systems are very close to each other.
- Average values for the standard deviation show that there is a high degree of certainty that the tested digital protection system's operating time for any given fault will be consistent.

B. Interoperability results

Compatibility indices which describe interoperability between all three tested protection systems are presented. Indices are calculated as it is described in previous sections. Results for all possible combinations of the tested setups are given in Table V.

TABLE V. COMPATIBILITY INDICES, TEST SETUP NO3

Tests	1st Test Setup (CT+MU - Eth. Switch - Relay)	2nd Test Setup (CT+MU - Eth. Switch - Relay)	Avg. trip time	PCI
I - II	AREVA – RUGGEDCOM – AREVA	NxtPhase – RUGGEDCOM – AREVA	0.1241	0.0024
II - III	NxtPhase – RUGGEDCOM – AREVA	Siemens – GE Multilin – AREVA	0.1212	0.0076
I - III	AREVA – RUGGEDCOM – AREVA	Siemens – GE Multilin – AREVA	0.1226	0.0065

Compatibility indices are calculated following definition shown in section III. The following conclusions can be made, based on the results:

- Comparison between average tripping times for all systems shows that they are very close to each other.
- Compatibility indices which describes performance difference between given systems are relatively small
- Parts of the tested systems can be interchanged without significant effect to system performance.

V. CONCLUSIONS

Methodology and results from the compatibility and interoperability evaluation of an all-digital protection system based on an IEC-61850-9-2 process bus are presented. Testing is performed on three different all digital protection systems assembled in Texas A&M Protection and Control Lab. Results are definitely helpful in gaining understanding on what level of performance and compatibility between systems can be expected from the novel systems, how does the measured performance compares to each other, what elements of the novel system contribute to problematic performance and under what conditions. It was concluded that:

- Performance of the novel system can be regarded as excellent when considering test results for the directional overcurrent protection function. Relevance of this result lies in the fact that these two principles (comparison of the measured quantity versus a threshold and distinction of current flow) are the basis for many other protection functions
- Average values for the standard deviation show that there is a high degree of certainty that the tested protection system's operating time for any given fault will consistently follow the operating time-current characteristic with almost a negligible level of dispersion from the mean trip time - 2 ms.
- Overall protection system performance in not affected by interchange of Ethernet switches. For the present level of traffic load on the process bus and low level of EMI in the lab difference in performance indices are negligible. Ethernet switch interoperability should be further tested in harsh environment with the high level of traffic load.
- Overcurrent performance indices for systems composed by interchanging sensors and merging units are very similar. Testing based on the same input signals and relay settings shows that there is no significant difference in protection system performance.
- Small interoperability indices show that tested protection systems are compatible and can be interchanged without significant effect on protection system performance. Sensors and merging units interchanged during these tests have very similar performance characteristics.

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VIII. BIOGRAPHIES

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