Compatibility and Interoperability Evaluation for All-digital Protection System through Automatic Application Test

Peichao Zhang, Levi Portillo and Mladen Kezunovic, *Fellow, IEEE*

***Abstract*— This paper proposes a methodology of compatibility and interoperability evaluation for all-digital protection system through automatic application testing. The paper starts with the introducing of compatibility and interoperability evaluation issues, explaining the importance of application tests. The paper then defines the performance indices and compatibility indices as well as the evaluation methodology. Making full use of the advantages of IEC 61850, a fully networked and automated application test solution for all-digital protection system is then proposed to calculate these indices. The related IEC 61850 information models and ACSI (Abstract Communication Service Interface) services which contribute to the automatic testing are described. Finally, the hardware architecture and software implementation are proposed in this paper. The framework technology is used to obtain an open software architecture, so that different power network models, transducer models as well as multiple performance evaluation criteria can be added to the system, without altering the overall software structure and control flow of the automatic testing system.**

***Index Terms*— compatibility, interoperability, IEC 61850, performance evaluation, process bus, protective relaying, relay testing.**

I. Introduction

The recent development of optical instrument transformers and the spread of digital relays permit the development of an all-digital protection system. In such system, the output of both the optical current and voltage transformers is a digital signal, which can be connected to digital relays through an IEC 61850-9-2 digital process bus [1].

Compatibility and interoperability are among the main driving forces behind the creation of IEC 61850. Many interoperability tests have been performed in the past few years. Through these tests, the bay level interoperability and the IEC 61850-9-1 interoperability at the process level have been verified. But the all-digital protection system containing different optical instrument transformers connected to different digital relays by an IEC 61850-9-2 process bus was not described in details in the literature yet.

Compatibility and interoperability evaluation of the all-digital protection system requires two kinds of test, namely conformance and performance test. IEC 61850-10 gives guidance for the conformance tests [2]. The conformance tests are only the first step to verify the interoperability. Compared with conformance tests, performance tests allow more extensive assessment and can be used to determine the performance characteristics of the overall system. Thus, performance tests will be as important if not even more so, as than conformance tests [3].

Performance testing of the protection system by itself is not a new topic [4], [5], [6]. All these papers are within the scope of conventional protection system. The evaluation criteria and methodology proposed in these papers are purely for performance evaluation purpose, not for compatibility and interoperability evaluation purpose.

This paper is aimed at proposing a methodology of compatibility and interoperability evaluation for all-digital protection system through automatic application testing. This methodology is now being realized in a PSerc [7] project. The paper is organized as follows. Section II introduces the compatibility and interoperability evaluation issues; Section III defines the performance evaluation criteria and methodology; Section IV discusses the automatic application test; Section V describes the hardware architecture of the application test system; Section VI describes the software implementation.

II. Compatibility and Interoperability Evaluation

A. Compatibility and Interoperability

Compatibility is often understood as the ability of two or more components or devices to perform their functions while sharing a common environment. In the context of 61850, compatibility means the ability of two or more IEDs to perform their intended functions (protection, control, metering, etc) while sharing the IEC 61850 common communication standard. Interoperability according to IEC 61850 means the 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. This is achieved by standardizing the access to data stored in different logical nodes (LN) through the Abstract Communication Service Interface (ACSI) [8].

As a standard of the communication networks and systems for substations, IEC 61850 does not try to specify the actual implementation of a function. Vendors will still use their individual algorithms, which they regard as best suited to perform a certain task. So unlike interoperability, the IEC 61850

This work was supported by PSerc project titled, "Digital Protection System Using Optical Instrument Transformers and Digital Relays Interconnected by an IEC 61850-9-2 Digital Process Bus"

P. Zhang is with the Department of Electrical Engineering, Shanghai Jiaotong University, Shanghai, China (e-mails: pczhang@sjtu.edu.cn). He is now working as a visiting scholar in Texas A&M University. L. Portillo and M. Kezunovic are with the Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843-3128, USA (leviportillo@tamu.edu, kezunov@ece.tamu.edu).

standard was never intended to ensure interchangeability of IEDs [3]. However, interchangeability of the transducer system (comprised of current and/or voltage sensors and merging units) and process bus (also called process LAN, usually 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.

The assessment of the compatibility and interoperability of different IEDs or systems will enhance the practical application of all-digital protection system and make a significant contribution to industry's understanding of the novel system.

B. Conformance Tests and Performance Tests

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. IEC 61850-10 [2] gives guidance on how these conformance tests have to be performed and UCA®International Users Group [9] has authorized KEMA to perform IEC 61850 conformance tests in accordance with the Users Group Assurance Testing Program Procedures.

Performance tests belong to application tests which aim at verifying the behavior of the protection system, the accuracy and operating times under various power network conditions (both faulted and unfaulted conditions) and computer network conditions [10]. When compared with conformance tests, performance tests concentrate on IEDs operation as part of a complete application system, verifying that the performance for a given application is adequate and ensuring that the whole system is as robust and reliable as feasible. For the all-digital protection system, the interests for performance tests are the trip/no trip decisions and the operating times.

These two types of tests have a stronger bind for the all-digital protection system than the conventional one. On the one hand, conformance tests are the basis of performance tests. It means only IEDs which have passed the conformance tests may be connected together to build an application system for performance tests. But it should be noted that the passing of conformance tests does not imply the passing of performance tests. Because of the unanticipated network performance, the complexities of IEC 61850 standard, the multifunction of IEDs, the mission sensitive and time critical features of the protection and control functions, it may happen that IEDs did pass the conformance tests but did not perform the necessary functions when connected together. So passing conformance tests is just a necessary but not a sufficient condition for performance tests success. On the other hand, the passing of performance tests will verify the conformance tests to a great extent. As compared with conformance tests, performance tests allow more extensive assessment and can be used to determine the performance characteristics of the overall system. Thus, the feasibility, applicability and efficiency of the new standard can be tested. So performance tests will be as important as the conformance tests in the future.

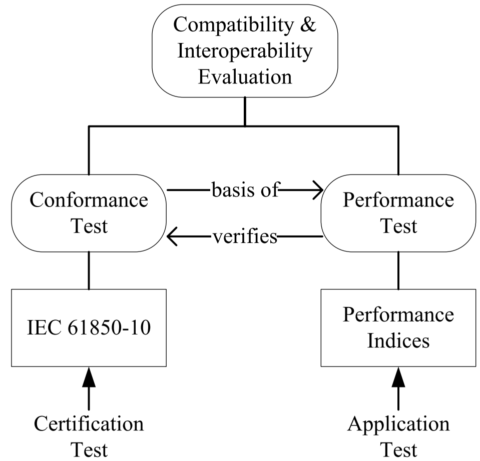

Fig. 1. Compatibility and interoperability evaluation

As a result, both conformance and performance tests play an important role in improving the compatibility and interoperability of the all-digital protection system and minimizing the chance of inter-working problems. Fig. 1 summarizes these tests. This paper will suggest how to evaluate the compatibility and interoperability of all-digital protection system through performance tests. To quantitatively determine the compatibility and interoperability, the evaluation criteria and methodology are defined in the next section.

III. Evaluation criteria and methodology

A. Referent Models

The purpose of the introduction of referent models is to evaluate the performance of the transducer system and the overall protection system automatically. There are two kinds of referent models, namely the transducer system model and the protective relay model.

The referent transducer system model in this paper is regarded as ideal, and therefore, delivers exact signals from the primary side.

The referent protective relay model is a software simulation model of a protective relay. Several protective relay models with different relay principles such as over-current and impedance have been realized [11], [12].

B. Performance Indices

A number of performance indices for evaluation, design and setting optimization of measuring algorithms, operating principles, complete relays and protective systems are defined in details in [5]. This paper adapts some of the performance indices to meet the needs of the all-digital protection system.

Definition 1: A single exposure E is a disturbance which triggers a protection system P to perform certain operations or other signals if called upon [5]. The exposures database EB is a database of exposures collected from the actual system or using simulators. Signal S^t, S^r denote the digital output of the tested and the referent transducer system (with merging unit) respectively. Decision D^t, D^r denote the decision of the tested and the referent protection system respectively.

Definition 2: The performance index of transducer T when fed by exposure E is denoted by TPI_T^E, $E = \{e_1, e_2, e_3, ..., e_n\}$. The average performance index of transducer T is defined as:

$$TPI_T = \frac{1}{N} \sum_{E \in EB} TPI_T^E \tag{1}$$

where N is the number of exposures in the database.

There are two primary types of transducer performance indices calculation methods, namely the time domain method and frequency domain method respectively. For the time domain:

$$TPI_T^E = \sqrt{\sum_{i=1}^{n} (S_i^t - S_i^r)^2 / \sum_{i=1}^{n} (S_i^r)^2} \tag{2}$$

For the frequency domain:

$$TPI_T^E = \sqrt{\sum_{j=1}^{m} (F_j^t - F_j^r)^2 / \sum_{j=1}^{m} (F_j^r)^2} \tag{3}$$

where F_j^t, F_j^r stand for the FFT coefficients of S_i^t, S_i^r respectively.

Definition 3: 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:

$$PPI_P = \frac{1}{N} \sum_{E \in EB} PPI_P^E \tag{4}$$

where N is the number of exposures in the database.

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:

$$PPI_P^E = |D^t - D^r| \tag{5}$$

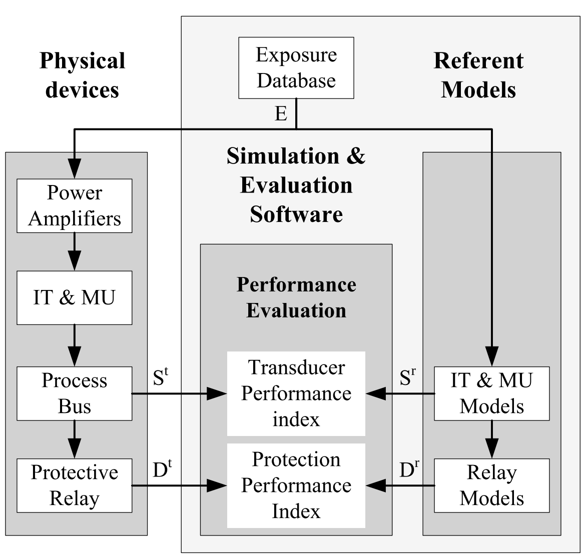

Fig. 2. Performance indices calculation

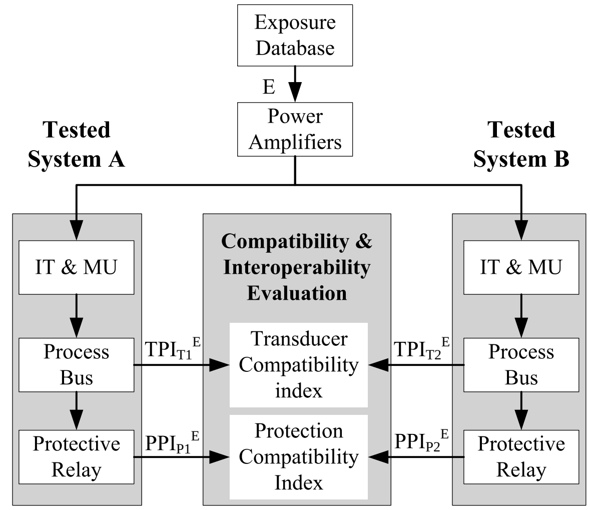

Fig. 3. Compatibility indices calculation

where:

$$D^t, D^r = \begin{cases} 1 & \text{if relay trips} \\ 0 & \text{otherwise} \end{cases}$$

For the trip time method:

$$PPI_P^E = D^t - D^r \tag{6}$$

where D^t, D^r stand for the trip time of the tested and the referent protection system respectively.

C. Compatibility Indices

The evaluation methodology is described in Fig. 3. It will be explained by the following definitions.

Definition 4: The compatibility index of transducer $T1$ and $T2$ when fed by the same test signal E is defined as:

$$TCI_{T1,T2}^E = |TPI_{T1}^E - TPI_{T2}^E| \tag{7}$$

The average compatibility index of transducer $T1$ and $T2$ is defined as:

$$TCI_{T1,T2} = \frac{1}{N} \sum_{E \in EB} |TPI_{T1}^E - TPI_{T2}^E| \tag{8}$$

In this paper, the transducer system includes the optical sensors and merging unit. By the definition, the smaller TCI, the better compatibility and interoperability.

Definition 5: The compatibility index of protection system $P1$ and $P2$ when fed by the same test signal E is defined as:

$$PCI_{P1,P2}^E = |PPI_{P1}^E - PPI_{P2}^E| \tag{9}$$

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

$$PCI_{P1,P2} = \frac{1}{N} \sum_{E \in EB} |PPI_{P1}^E - PPI_{P2}^E| \tag{10}$$

In this paper, the protection system includes the transducer system, the process bus (the Ethernet LAN) and the protective relay. By the definition, the smaller PCI, the better compatibility and interoperability.

In table I, The symbol T, B and P stand for the transducer system, the process bus and the protective relay respectively.

TABLE I

TEST CASES AND COMBINATIONS OF PROTECTION SYSTEMS

Case	P1			P2		
	T	**B**	**R**	**T**	**B**	**R**
1	*T1*	B1	R1	*T2*	B1	R1
	T1	B1	R2	*T2*	B1	R2
2	T1	B1	*R1*	T1	B1	*R2*
	T2	B1	*R1*	T2	B1	*R2*
3	T1	*B1*	R1	T1	*B2*	R1

To calculate the PCI, we combine the T, B and P in different ways to assemble different protection systems.

There are three test cases listed in the table.

1) In case 1, same protective relay but different transducers are used to assemble a protection system. The purpose is to evaluate both the interoperability between the transducers and IEDs and the interchangeability between the transducers.
2) In case 2, same transducer but different protective relays are used to assemble a protection system. Because of the fact of different operation characteristics of relays, only the interoperability between the transducers and relays is evaluated.
3) In case 3, same transducer and relay but different Ethernet LANs are used to assemble a protection system. Ethernet switches with different traffic load will be simulated to evaluate the performance of the all-protection system during network overload and the reaction of all-digital protection system during Ethernet failure will be inspected.

Since there is a large number of tests to be performed, the automatic application testing is indeed necessary. The introduction of IEC 61850 makes the automatic testing possible, which will be demonstrated in the next section.

IV. AUTOMATIC APPLICATION TESTING

For the conventional protection system, the application test cannot be automated for the following reasons:

1) The IEDs have no self-description capability. The technical manuals from different vendors are in free format, which prevents the application test software from selecting the proper test cases and scenarios automatically according to the system configuration and IEDs capabilities.
2) There are no common configuration tools for the IEDs. The IEDs from different vendors provide their configuration data in their own proprietary format and use multiple standardized or proprietary communication protocols. This prevents the application test software from configuring the IEDs automatically according to the selected test cases.
3) Hard wired tripping signals do not carry with them any information related to their origin and meaning. Event reports generated by protection devices do provide the meaning but they are usually originated in proprietary form.
4) A third party digital fault recorder or high precision oscilloscope may be needed to record the disturbance data. Only the possibility of recording disturbance data in COMTRADE files brings some form of standardization. However, only IEC 61850, because of its nature and the way it has been conceptualized, could offer complete real time-data acquisition standardization.

With the introduction of IEC 61850, the data acquisition and description methods are standardized. Both the application system and the application test system will benefit from the standardization. From the application test perspective, the standard will provide the possibility of automatic testing. The automatic testing feature and technology for all-digital protection system are described next.

A. Automatic Test Scenario Configuring

IEC 61850 uses SCL (Substation Configuration description Language) which is based on XML to describe both the IED capabilities and the system configuration. Besides, it provides some ACSI (Abstract Communication Service Interface) services to extract configuration information from IEDs at runtime. Thus, the application test software can use the SCL file as a test specification for automatic testing.

From the application test perspective, the IEDs capabilities and configuration of interest involve the types, zones and operating characteristics of relays, the services the relays support and the communication links between the optical transducers and relays. The application test software will then automatically configure the test cases and scenarios according to the tested protection system. The test cases and scenarios for relay testing used in this paper are described in details in [4], [6].

B. Automatic Configuring of a Relay

The configuration of the protection system being tested is a critical step in the application test. The main problem with the advancements in the functionality of modern protective relays is the increased complexity of the setting of the IEDs. The protection engineer has to configure hundreds of settings. Another problem is that when using devices from different vendors, models or types the engineers have to usually configure them using different software tools. IEC 61850 makes a significant improvement in that process, defining standard object models and a configuration language that will allow automatic processing. Ongoing work in IEC and IEEE working groups will result in a standard IED configuration file format based on the object models and SCL (Substation Configuration Language) defined in IEC 61850 [13], which will further simply the configuration tasks.

The SCL concept promises many advantages, such as consistent description of the device and substation configuration and the possibility to use vendor independent configuration tools.

From the application test perspective, the main configuration tasks involve relay setting and GOOSE (Generic Object Oriented Substation Event) configuration. For the relay setting, IEC 61850 provides SGCB (Setting Group Control Block) services to fulfill the task. For the GOOSE configuration, IEC 61850 provides GoCB (GOOSE Control Block) services to fulfill the tasks.

C. Automatic Processing of a Tripping Message

GOOSE is used to replace the hard wired control signal exchange between IED's for interlocking and protection purposes [8]. Status information like trip commands is transmitted via GOOSE messages. The GOOSE messages defined in IEC 61850 allow the IEDs to multicast change of state information to other IEDs connected to the substation LAN.

The test device has to monitor the outputs of the relay under test in order to change the states of the simulation and to evaluate the performance of the relay under test. In the all-digital protection test system, the test device can subscribe and analyze the GOOSE message sent by the relay to get the trip decision and trip time of the relay.

D. Automatic Recording of Disturbance

The disturbance data should be recorded to calculate the transducer performance indices and compatibility indices. In the all-digital protection system, the merging unit will multicast the samples of currents and voltages over the IEC 61850-9-2 process bus. The multi-use of these data will serve not only the protection but also the application test device. The test device will subscribe to the sampled value using the Sampled Value service provided by IEC 61850.

E. Overall Information Model

As described in the above, IEC 61850 defines standardized access to all data and resources, which makes the fully networked, automatic relay testing possible. IEC 61850 defines not only the object models of IEDs and functions in a substation automation system, but also the semantics of the communications between the components of the system and the different system requirements.

The basic functional elements defined in IED 61850 are the Logical Nodes. A Logical Node is "the smallest part of a function that exchanges data". The information model of the test system is showed in Fig. 4. The related data model and services are summarized in table II.

In the new generation test system, the test devices will act as IEC 61850 clients, which will be connected with the IEDs being tested which act as IEC 61850 servers.

F. Procedure of Application Test

Fig. 5 is the sequence diagram of the application test system.

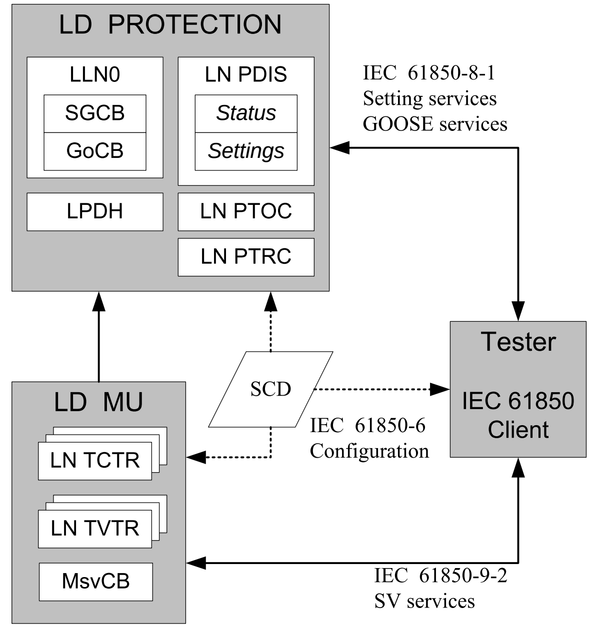

Fig. 4. LNs and related ACSI services used in application test system

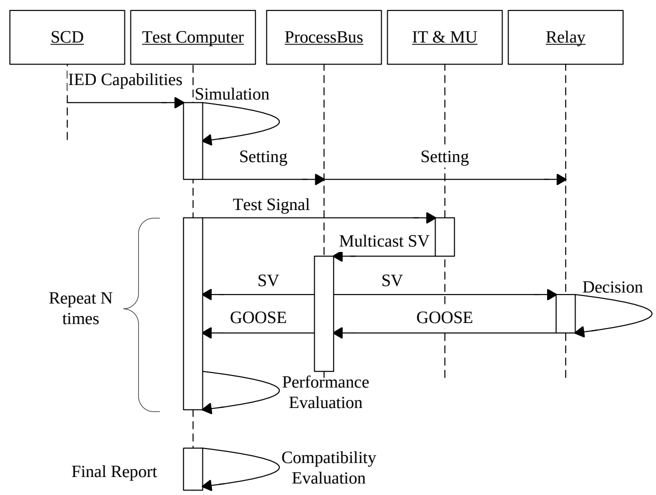

Fig. 5. Test sequence of the automatic application test system

V. HARDWARE ARCHITECTURE

The hardware architecture of the automatic application test system is described in Fig. 6.

The simulation computer will generate the exposures according to the selected test scenarios which will be fed to the optical transducers. A test switch is used to select the active transducer system. The merging unit will then multicast the sampled values over an IEC 61850-9-2 process bus.

When the protective relay with the tested function operates, it will send GOOSE messages. The test computer will subscribe and capture these messages to get the trip decision and trip time of the relay. Meanwhile, the test computer will subscribe and capture the sampled values to get the disturbance fed to the relay. The use of modern Ethernet switch technology allows the merging of the station bus (IEC 61850-8 for GOOSE and configuration services) and process bus (IEC

TABLE II
DATA MODEL AND ACSI SERVICES USED IN TEST SYSTEM

Catalog	Item	Description
LN	LLN0	LOGICAL-NODE-ZERO
	PDIS, PTOC, PTRC	LNs for protection functions
	TCTR, TVTR	LNs for transducer functions
Control Block	SGCB	Setting Group Control Block
	GoCB	GOOSE Control Block
	MsvCB	Multicast Sampled Value Control Block
ACSI	SelectActiveSG, SelectEditSG, SelectSGValues, ConfirmEditSGValues, GetSGValues, GetSGCBValues	setting related services
	SendMSVMessage, GetMSVCBValues, SetMSVCBValues	sampled value related services
	SendGOOSEMessage, GetGoCBValues, GetGOCBValues, ...	GOOSE related services

61850-9-2 for sampled value service) to one communication network, without affecting the performance of the whole system.

A GPS receiver is used to properly synchronize the different devices. This will ensure that all events or disturbance records are time-stamped with sufficient accuracy.

Multiple merging units and protective relays can be interconnected by a single IEC 61850-9-2 process bus. The communication links between the merging units and the relays can be reconfigured. Thus, the compatibility and interoperability of the all-digital protection system can be evaluated.

Compared with the conventional test system, the hardware architecture described in the above is a fully networked test system, which eliminates the hard-wired interface.

VI. SOFTWARE IMPLEMENTATION

A. Variability in the Application Test System

The automatic application test system should be designed for general purpose, not for specific IEDs from specific vendors. From the software implementation perspective, the variability in the requirement is a challenge to the software design. The main variants contained in this system involve:

1) Power system models. Different power system models should be provided for different test cases and scenarios;
2) Referent models. Different referent models (including transducer models and protective relay models) should be provided to simulate devices with different operation characteristics;
3) Evaluation criteria. Different evaluation algorithms (including performance evaluation and compatibility evaluation algorithms) should be provided to support different evaluation criteria.

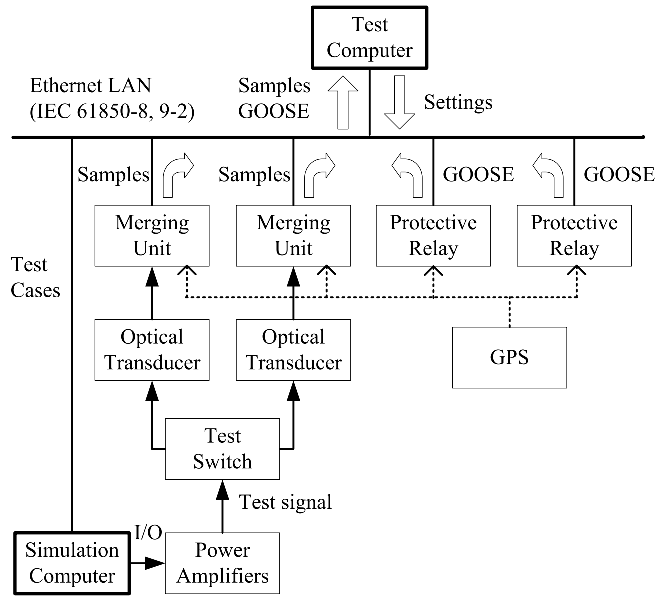

Fig. 6. Hardware architecture of fully networked test system

To fulfill the automatic application test, the software system should have the ability to be varied with different models and criteria as described in the above. The framework design technology is used to obtain an open software architecture, so that different models and criteria can be added to the system, without altering the overall software structure and control flow of the automatic test system.

B. Framework

Framework is a set of cooperating classes that makes up a reusable design for a particular kind of application [14]. A framework provides architectural guidance by partitioning the design into abstract classes and defining their responsibilities and collaborations. The basic properties of a framework involve modularity, reusability, extensibility and ease of change.

One import idea in the framework design is to identify commonality and variability among a particular kind of applications. Once identified, the variant aspects of the system will be encapsulated and localized in so called ’hotspots’ or ’extension points’. Thus, all the variants in the system will be predicted, planned and controlled.

C. Class Design

Fig. 7 is the UML (Unified Modeling Language) [15] classes of the simulation subsystem. Fig. 8 shows the UML classes of the test subsystem.

In the class diagrams, the classes in white box model the common parts of the system, whereas the classes in grey box model the variants in the system. The common parts and the variable parts of the system are divided by the classes marked as ’abstract’. As described in the above, the classes in grey box are the ’hotspots’ where we can extend or change the system.

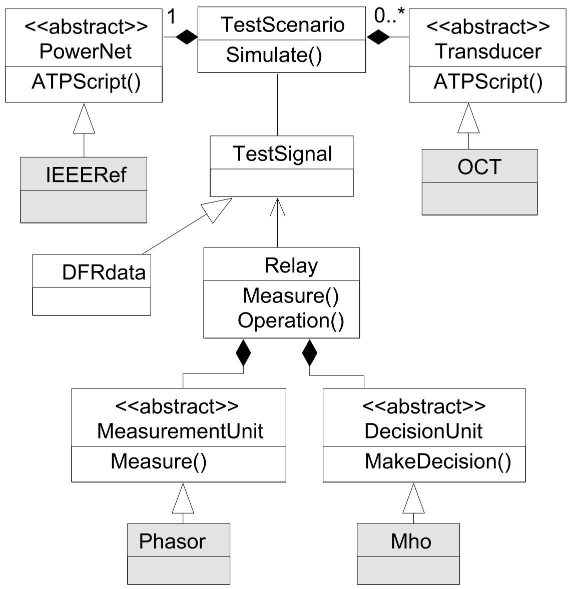

Fig. 7. UML classes of the simulation subsystem

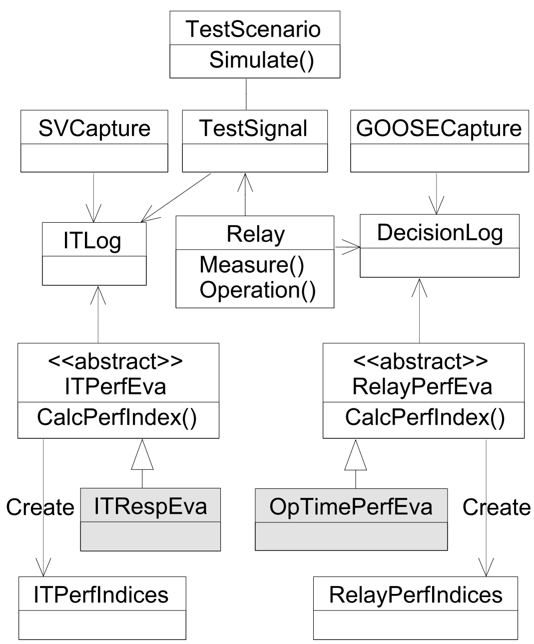

Fig. 8. UML classes of the test subsystem

VII. Conclusion

This paper is aimed at proposing a methodology for compatibility and interoperability evaluation of all-digital protection system through automatic application testing. The proposed methodology is now being realized in a PSerc project.

The importance of application test for the compatibility and interoperability evaluation is discussed. A number of performance indices and compatibility indices are defined to fulfil the evaluation.

The necessity and possibility of automatic application testing for an all-digital protection system are discussed. The hardware architecture as well as the software implementation are proposed.

References

[1] *Communication networks and systems in substation-Part 9-2: Specific communication service mapping(SCSM)- Sampled analogue values over ISO 8802-3*, IEC Std. 61 850.

[2] *Communication networks and systems in substation-Part 10: Conformance testing*, IEC Std. 61 850.

[3] D. Dolezilek. (2005) IEC 61850: What you need to know about functionality and practical implementation. [Online]. Available: http://www.selinc.com/techpprs/SEL_Dolezilek_IEC61850_6170.pdf

[4] M. Kezunovic and T. Popovic, "Assessing application features of protective relays and systems through automated testing using fault transients," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, vol. 3, Yokohama, Japan, Oct. 2002, pp. 1742–1767.

[5] M. Kezunovic and B. Kasztenny, "Design optimization and performance evaluation of the relaying algorithms, relays and protective systems using advanced testing tools," *IEEE Trans. Power Delivery*, vol. 15, no. 4, pp. 1129–1135, Oct. 2000.

[6] M. Kezunovic, T. Popovic, S. Donald, and D. Hyder, "Transient testing of protection relays: Results, methodology and tools," in *International Conference on Power Systems Transients (IPST)*, New Orleans, USA, 2003.

[7] The Power Systems Engineering Research Center (PSerc) website. [Online]. Available: http://www.pserc.org/

[8] *Communication networks and systems in substation-Part 7-2: Basic communication structure for substation and feeder equipment - Abstract communication service interface (ACSI)*, IEC Std. 61 850.

[9] The Utility Communications Architecture (UCA) International Users Group website. [Online]. Available: http://www.61850.com/uca_group.html

[10] M. Achterkamp, R. W. P. Cremers, A. F. Valdivielso, E. C. Navarro, and F. D. O. Carvalho, "Power system protection relay testing moving from certification testing to application testing," in *Eighth IEE International Conference on Developments in Power System Protection*, vol. 1, Amsterdam, Netherlands, Apr. 2004, pp. 248–251.

[11] M. Kezunovic, "User-friendly, open-system software for teaching protective relaying application and design concepts," *IEEE Trans. Power Syst.*, vol. 18, no. 3, pp. 986–992, Aug. 2003.

[12] M. Kezunovic, A. Abur, and G. Huang, "MERIT 2000 - a new concept in power engineering education," in *Proceedings of International Conference on Energy Management and Power Delivery: EMPD '98*, vol. 1, Singapore, Mar. 54-59.

[13] A. Apostolov, D. Tholomier, and S. Richards, "Simplifying the configuration of multifunctional protection relays," in *2005 58th Annual Conference for Protective Relay Engineers*, vol. 1, College Station, TX, USA, Apr. 2005, pp. 281–286.

[14] M. E. Fayad, D. C. Schmidt, and R. E. Johnson, *Building Application Frameworks*. Addison-Wesley, 1999.

[15] C. Larman, *Applying UML and Patterns: An Introduction to Object-Oriented Analysis and Design and Iterative Development, 3rd Edition*. Prentice Hall, 2004.

[16] B. Vandiver, "Testing of UCA based microprocessor based protective relays," in *IEEE Power Engineering Society Summer Meeting*, vol. 1, Chicago, IL, USA, July 2002, pp. 294–296.

[17] A. Apostolov and B. Vandiver, "Functional testing of IEC 61850 based IEDs and systems," in *Power Systems Conference and Exposition, 2004. IEEE PES*, vol. 2, New York, NY, USA, Oct. 2004, pp. 640–645.

Peichao Zhang was born in 1970 in Jiangsu province, China. He received his M.S. and Ph.D. degrees from Shanghai Jiao Tong University, all in electrical engineering, in 1996 and 2004, respectively. Dr. Peichao ZHANG is an associate professor in Shanghai Jiao Tong University. His main research interests are power system protection, system-wide disturbances, as well as signal processing and artificial intelligence applications in power systems. He is now working as a visiting scholar in Texas A&M University. Email: pczhang@sjtu.edu.cn.

Levi Portillo was born in 1979 in the state of Zulia, Venezuela. He received his B.S. in Electrical Engineering from Zulia University in 2000. He is currently pursuing the M.S. degree in the Department of Electrical Engineering, Texas A &M University, College Station. Email: leviportillo@tamu.edu.

Mladen Kezunovic (S'77, M'80, SM'85, F'99) has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators as well as application of intelligent methods to control, protection and monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of the IEEE.