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Smart Sensors and Standard-Based Interoperability in Smart Grids

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Abstract

Smart grids (SGs) are electrical power grids that apply information, advanced networking, and real-time monitoring and control technologies to lower costs, save energy, and improve security, interoperability, and reliability. Smart sensors (SSs) can provide real-time data and status of the grids for real-time monitoring, protection, and control of grid operations. Sensor data exchange and interoperability are major challenges for the SGs. This paper describes sensing, timing, intelligence, and communication requirements of sensors for the SGs and proposes a general model of the SSs for SGs based on these requirements. Then it illustrates, how the model works with phasor measurement unit (PMU)- and merging unit-based SSs deployed in the SGs with standardized interfaces to support the interoperability of the SSs. Furthermore, to address the interoperability issues, this paper describes sensor interface standards used in the SGs and the need for interoperability testing, and proposes a passive interoperability test method for the SSs to achieve and assure sensor data interoperability. To verify this test method, an interoperability test system for the PMU-based SSs was developed and presented. Interoperability test results of eight commercial PMU-based SSs are provided to show that the proposed interoperability test method works.

Keywords

Interface standards; interoperability test; phasor measurement unit (PMU); merging unit (MU); smart grid (SG); smart sensor (SS)

I. INTRODUCTION

SMART grids (SGs) are electrical power grids that apply information, advanced networking, and real-time monitoring, and control technologies to lower costs, save energy, and improve security, interoperability, and reliability. A comparison of SG and traditional grid is shown in Figure 1. It is adapted from the Electric Power Research Institute (EPRI) presentation given

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Commercial equipment and software, many of which are either registered or trademarked, are identified to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose. The associate editor coordinating the review of this paper and approving it for publication was Dr. Rosario Morello.

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at the National Institute of Standards and Technology (NIST) Standards Workshop held on April 28, 2008 [1]. The traditional power grid has a central power plant that produces electricity and transmits it over long distances on transmission lines to substations, as shown in Figure 1(a). From the substation, the power is distributed by both overhead and underground power lines to residential or commercial customers. This involves one way power flow and simple interactions. Traditional generation is inefficient, converting only about one-third of fuel energy into electricity, without recovering the waste heat, and almost 8 % of its electric power is lost along transmission lines. Additionally, 20 % of its generation capacity exists to meet peak demand only (i.e., it delivers power to the grid only 5 % of the time) [2]. Power outages cost Americans more than $150 billion per year, and it is estimated that 90 % of these outages occur on distribution grids [3], [4]. Due to the lack of real-time monitoring and control, distribution grids are not optimized and their efficiencies are not well established. Many components remain in use until they fail or cause an outage. SGs, as illustrated in Figure 1(b), entail two-way power flows, multi-stakeholder interactions, and can address and mitigate the problems mentioned above. Some characteristics and benefits of SGs are described in [5] and [6].

The idea behind SGs is that they will automatically and dynamically respond to changes in grid conditions, which will require sensors to provide real-time information and status. Sensors enable the grids to be “smarter” [7] and could play a critical role in real-time monitoring and control of power transmission and distribution systems and in maintaining grid health and stability. Grid control relies heavily on the measurement and monitoring of electrical parameters in the transmission and distribution networks [8]. Sensors are used to measure a wide variety of physical parameters in power generation, transmission lines, substations, distribution lines, energy storage, and customers. These include current transformers (CTs), voltage transformers (VTs), phasor measurement units (PMUs), merging units (MUs), smart meters, temperature sensors, humidity sensors, accelerometers, rain gauges, internet protocol (IP) network cameras, pyranometers and pyrheliometers (solar irradiance), weather stations, sonic anemometers, partial discharge sensors, gas sensors, ultrasound and ultra-high frequency sensors, torque sensors, discharge rate sensors, load leveling sensors, occupancy sensors, and power quality monitors [9], [10].

Increasing amounts of distributed energy resources (DERs) located on the customer side of the meter represent both a challenge and an opportunity for grid operators [11]. The technical challenges faced are protection of power equipment, integration of energy resources, load control and stability. Ultimately, SGs enable full integration of energy resources and efficiently deliver sustainable, economic and secure electricity [12]. The SG’s measurement, communication, and control technologies support system operators in maintaining a real-time balance between electrical generation and loads. The large-scale and geographically dispersed deployments of sensing and measurement devices pose great challenges to the underlying communication infrastructure that delivers the measurements and control commands, in terms of scalability, availability, network latency, and interoperability [13]. The Grid Modernization Initiative (GMI) of the U.S. Department of Energy (DOE) focuses on the development of new architectural concepts, tools, and technologies that measure, analyze, predict, protect, and control power grids of the future [14]. The Grid Modernization Laboratory Consortium (GMLC) was established as a strategic partnership between DOE and its national laboratories to collaborate on modernizing the nation's power grids [15]. The GMLC will support the developments of new sensor, monitoring, data processing, and control technologies [16].

This paper proposes a general model of smart sensors (SSs) for SGs. Section II depicts related work on SSs and the general model is proposed in Section III. Section IV describes some SS examples while the interface standards of SSs are addressed in Section V. In Section VI, interoperability test methods for SSs is proposed and interoperability test results for PMU-based SSs, an example of a SS, is provided. Section VII provides a summary.

II. RELATED WORK IN SMART SENSORS

A sensor is a device that generates an electrical signal that is proportional to a physical quantity. The output signal could be in analog (continuous) or digital (discrete) form. Digital sensors typically have more capabilities than analog sensors, such as signal conditioning, analog-to-digital conversion, and data processing capability, and digital signal output. To some degree, digital sensors have some "smart" capabilities.

SSs are digital sensors having integrated microprocessors, include some logic functions, and/or can make some types of decisions [17], [18]. SSs are defined as sensors that can manipulate and compute sensor-derived data and communicate the data through a bidirectional digital bus to users via a communication interface [19], [20], [21].

The Technical Committee on Sensor Technology (TC-9) of the IEEE Instrumentation and Measurement Society defined smart transducers (sensors and actuators) that provide functions beyond those necessary for generating an accurate representation of a sensed quantity in IEEE 1451 that is a family of Smart Transducer Interface Standards for Sensors and Actuators. This functionality typically simplifies the integration of the transducers into applications in a networked environment [22]. This definition emphasizes self-identification and self-description, and networkability of smart sensors, as is done, for example, with IEEE 1451-based smart transducers [23].

III. A GENERAL MODEL OF SMART SENSORS FOR SMART GRIDS

A. Sensor Requirements of Smart Grids

Integrated distribution grid monitoring systems will require various types of sensors and transducers to build smart or intelligent capabilities. IEEE C37.118 defines a transmission format for reporting synchronized phasor measurements in power systems. Accurate and precise timestamping of sensor captured data is critical. As an example, for IEEE C37.118-based PMUs, the timing reference and signal must be traceable and aligned to Coordinated Universal Time (UTC) with an uncertainty of less than 1 μs [24]. The other important requirement for the sensor is the need for a network communication interface to transport the data to a data repository and management system. Monitoring and control applications require different types of information for optimizing distribution network operations. Therefore, sensor data output requirements should meet the anticipated future monitoring and control applications of SGs. Some requirements of sensors for SGs are summarized as follows:

- High-accuracy timing and time synchronization to UTC.
- High-speed data processing and intelligent algorithms (e.g., producing synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from measured voltage and current signals along with time synchronizing signals.) [25].
- High measurement accuracy and sensitivity, such as for current and voltage magnitudes and phase angle [26].
- High-speed, secure, and reliable network communications and standards-based data transmission.
- Standardized interfaces and test methods to help achieve SS interoperability and plug-and-play capability.
- A wide range of sensors with high bandwidth/dynamic range, such as measuring voltage from 600 V to 69 kV of medium voltage (MV), current from amperes to kiloamperes, frequencies from 50 Hz to 5 MHz [27].
- Multiple sensing capabilities of electrical and physical parameters including voltage, current, power flow, temperature, weather, and climate.
- Intelligent capabilities for sensors, such as self-identification, self-localization, self-awareness, self-diagnostics, and self-calibration [27].

B. A General Model of Smart Sensors for Smart Grids

Based on the above requirements for SGs, we propose a general model of SSs, which is shown in Figure 2. A SS consists of a set of sensors, a processing module with an internal clock connected with an optional external time reference, and a network communication module. The SS has four basic capabilities: 1) sensing by means of sensors, 2) analog signal conditioning, analog-to-digital conversion (ADC), and sensor data processing in processing module, 3) timing and synchronization by an internal clock with optional external time reference, and 4) network communications with the outside world through a network communication module. The sensors produce electrical signals based on physical phenomena they measure, such as voltage and current of power lines in microgrids. The internal clock can generate the timestamp for sensor data and synchronize with the external time references, such as Global Positioning System (GPS), one pulse-per-second (1PPS), inter-range instrumentation group-B (IRIG-B), IEEE 1588 Precision Time Protocol (PTP), or Network Time Protocol (NTP). After the analog signals are scaled and conditioned in the processing module, an analog-to-digital converter (ADC) converts the signals into digital form, and the processing module processes the data based on the metadata and the application’s intelligent algorithms, along with time synchronized to improve sensing and measurement accuracy. A network communication module is used to communicate with the outside world, such as sensor applications via wired (serial or Ethernet) or wireless (IEEE

802.11a/b/g/n, Worldwide Interoperability for Microwave Access (WiMAX) or 3G/4G/ Long-Term Evolution (LTE)/5G cellular networks.

In addition to the four basic capabilities, SSs for SGs should have additional intelligent capabilities, which depend on the requirements for specific sensors and applications [28]:

- Self-description [22]: The description about the sensor itself contained in a transducer electronic data sheet (TEDS) or configuration file.
- Self-identification [22], [23]: The sensor identification information stored in electronic metadata in the sensor itself.
- Self-diagnostics [20]: The process of diagnosing or identifying conditions and errors performed by the sensor itself.
- Self-calibration [18], [20]: The calibration of the sensor performed by itself without using an external reference.
- Self-testing [19]: Automatic testing performed by the sensor on itself. The sensor built-in test is a mechanism that permits a sensor to test itself.
- Self-validation: Automatic validation performed by a sensor on data to ensure that it is valid always and reports errors when detected. Self-adaptation [29]: Automatic adaptation to changes in the operating environment by a sensor.
- Location-awareness: Self-awareness of the physical placement of the sensor.
- Self-compensation [20]: Automatic compensation of outputs due to temperature and environment changes in time.
- Multi-sensing and data fusion [18], [20]: sensing multiple phenomena using different sensing elements and performing data fusion automatically.

IV. SMART SENSORS IN SMART GRIDS

SSs are sensors with built-in intelligence deployed in power grids, which include temperature sensors, pressure sensors, humidity sensors, weather stations, current sensors, and voltage sensors, etc. SSs may communicate with the outside world using standardized communication protocols, such as, IEEE 1451 family of Smart Transducer Interface Standards, IEEE 1815 Standard for Electric Power Systems Communications - Distributed Network Protocol (DNP3), IEEE C37.238 PTP Power Profile, and others. Descriptions of sensing functions, applications, and network communications for some specific SSs (e.g., PMU- and MU-based SSs) are given in the following subsections.

A. PMU-Based Smart Sensors

A phasor is the complex representation of a simple sinusoidal quantity composed of the magnitude and the phase angle components. A synchronized phasor is a phasor calculated from sampled waveform data with a standardized time stamp as the reference for the measurement. A PMU is a device that produces synchronized phasor, frequency, and ROCOF estimates from the input voltage and/or current signals together with a time synchronizing reference signal [30]. PMUs provide real-time synchrophasor data for advanced applications, such as wide-area situational awareness, state estimation, monitoring system dynamics, and validating system models.

Figure 3 shows a block diagram of a PMU-based SS that consists of a PMU and a set of current and voltage sensors connected with the PMU. A PMU consists of a processing module with an internal clock connected to an external time reference (e.g., GPS), and a network communication module. A PMU-based SS has the following capabilities [24], [30]:

- Current and voltage sensors provide the analog inputs for the PMU. They can be used to measure 50/60 Hz alternating current (AC) voltage and current waveforms. PMUs typically sample current and voltage phases at a rate of 48 samples per cycle using a common time source for synchronization.
- The internal clock timestamps each sample and time synchronizes within 1 μs accuracy using a phase-locked oscillator with a UTC source as a common time reference.
- The processing module performs signal conditioning using an anti-aliasing filter, converts analog signals into digital form with timestamps by means of a phase-locked oscillator and aligns phase data based on the GPS time reference or external network time reference, and then computes the voltage and current phasors and produces synchronized phasor, frequency, and ROCOF estimates.
- The network communication module can be used to output synchrophasor data to applications (e.g., a phasor data concentrator (PDC)) using the IEEE C37.118.2–2011 standard protocol.

B. MU-Based Smart Sensors

MUs sample AC signals in one or multiple phases and convert these analog voltage and current signals to digital values, merge (align) multiple phases together based on time synchronization and transmit the sampled values (SVs) to protection relays through networks based on the International Electrotechnical Commission (IEC) 61850–9-2 standard protocol. MUs provide real-time status of power grids.

A MU-based SS, shown in Figure 4, consists of a MU and CTs and VTs connected to the MU. The MU consists of a processing module with an internal clock connecting with an external time reference and a network communication module. MU-based SSs have the following capabilities:

- CTs and VTs provide analog current and voltage of power grids, respectively, to MUs.
- The internal clock can timestamp each sample and time synchronize with an external UTC source as a common time reference.
- The processing module performs signal amplification and conditioning, converts analog signals to digital form based on the 1PPS signal from the GPS receiver or external network time reference. It produces the three timealigned phases of voltages and currents by means of a merging or alignment algorithm.

- The network communication module can be used to communicate with intelligent electronic devices (IEDs) or applications using the IEC 61850–9-2 standard protocol [31], [32].

The functions of a MU-based SS include sensing, signal conditioning, analog-to-digital conversion, data merging and processing, and network communications. The data merging process can be found in reference [33], [34]. MU-based SSs are used in substation automation systems for collecting and forwarding voltage and current data to multiple IEDs for protection and control applications.

V. INTERFACE STANDARDS FOR SMART SENSORS IN SMART GRIDS

There may be hundreds or thousands of SSs made by different vendors deployed in electrical power grids. A key challenge facing electrical grids is communication interoperability of these SSs. A set of existing standard communication protocols for PMU- and MU-based SSs, and SSs in general are listed in Table I.

A. IEEE C37.118 Standard for PMU-Based Smart Sensors

The first standard for synchrophasors was IEEE 1344–1995 [35], which defined three messages: data frames, header frames, and configuration messages, was replaced by IEEE C37.118–2005 that included both measurement and real-time data transfer requirements [36]. IEEE C37.118–2005 was split into two standards: IEEE C37.118.1–2011 for synchrophasor measurement requirements, and IEEE C37.118.2–2011 for synchrophasor data transfer requirements [29]. A new CFG-3 message and a time quality field in the SYNC word were added in the IEEE C37.118.2–2011. As shown in Figure 5, the IEEE C37.118.2–2011 standard describes a set of message types related to the configuration and transfer of real-time data from a PMU and PDC. The PDC sends commands to PMU to request information and/or control data. Then the PMU replies with data, the configuration, and the header.

B. IEC 61850–9-2 and 61869–9 Standards for MU-Based Smart Sensors

The IEC standards for MU-based SSs include IEC 61850–9-2 and IEC 61869–9. The objectives of the two standards are to provide a process bus for SVs and a digital interface for instrument transformers.

1) IEC 61850–9-2: The IEC 61850–9-2 standard defines the Specific Communication Service Mapping (SCSM) for the transmission of SVs, based on the abstract specification defined in IEC 61850–7-2 [37]. As shown in Figure 6, IEC 61850–9-2 conformance includes the two communication profiles: client/server services based on Multimedia Messaging Service (MMS) in accordance to IEC 61850–8-1 [38] and SV services based on data link layer.

Client/Server A-Profile is connection-oriented session, presentation, and MMS application. T-Profile is Transmission Control Protocol/Internet Protocol (TCP/IP) over Ethernet. This client/server service profile shall be used to access the sampled values control block (SVCB) via a client. In this profile, there exists mappings of IEC 61850–7-2 Classes and Services to

SV. If a client/server association based on MMS is used in addition to the transmission of SV data sets, the definitions of IEC 61850–8-1 apply for the following data classes of the IEC 61850–7-2 server class, association, logical device, logical node, data class and data set class model. For the transmission of sampled values, the data sets are defined in logical node “LLN0”. All sampled values data sets specification is part of the IED Configuration Description (ICD), except the universal data set, which is fixed and defined in IEC 61850–9-1 [39].

SV A-Profile is connection-less session and presentation and SV application. SV T-Profile is User Datagram Protocol/ Internet Protocol (UDP/IP) over Ethernet. In SV service profile, there existed a need of mapping of the model for the transmission of sampled values. The sampled value class model provides reporting of sampled values data sets in an organized and time controlled way, so that transfer is low latency and deterministic. Sampled values control block for unicast and multicast defines the transmission characteristics of the data set they refer to. The publisher shall write the values in a local buffer at the sending side; the subscriber shall read the values from a local buffer at the receiving side.

Figure 6 shows client-server (MMS) and publisher-subscriber (SV) communication processes of IEC 61850–9-2. In publisher-subscriber communication processes, the MU is a SV publisher, and the protection relay is a SV subscriber. In client-server communication processes, the MU is a MMS server and the protection relay is a MMS client.

2) IEC 61869–9: IEC 60044–8 applies to newly manufactured electronic current transducers having an analog voltage or digital output, for use with electrical measuring instruments and electrical protective devices [40]. IEC 61869 defines the standardization in the field of AC and/or DC current and/or voltage instrument transformers, including their subparts like sensing devices, signal treatment, data conversion, and analog or digital interfacing, which is a transition from IEC 60044–8. The IEC 61869–9 defines a method for digital communications of instrument transformer measurements [41], which is based on the IEC 61850 series of standards and IEC 60044–8. The IEC 61869–9 communications profiles are a selected subset of the IEC 61850 series of standards, which include IEC 61850–9-2:2011 for sampled values specific communication service mapping (SCSM) and IEC 61850–8-1 for client/server SCSM.

C. IEEE 1815 Standard for Smart Sensors

IEEE 1815–2012 (DNP3) is a set of communications protocols used among components in process automation systems. DNP3 was developed for communications between various types of data acquisition and control equipment. DNP3 plays a crucial role in a supervisory control and data acquisition (SCADA) system, which consists of a master station and remote substations [42]. As shown in Figure 7, the DNP3 protocol is over TCP/IP and UDP/IP. Figure 7 shows DNP3 master-outstation communication process. The Master is a SS client and the outstation is SS (slave). DNP3 defines four level subsets: DNP3-L1 for sensors and actuators, inputs/outputs (I/Os), MUs, and IEDs; DNP3-L2 for large IEDs and PMUs; DNP3-L3 for substation devices; and DNP3-L4 for master stations and SCADA devices.

D. IEEE 1451 Standard for Smart Sensors

The IEEE 1451-based smart transducers, which include SSs and smart actuators, are shown in Figure 8. Some IEEE 1451.x standards have been adopted as International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC)/IEEE 21451-x standards. However, IEEE 1451.0 was adopted as ISO/IEC/IEEE 21450. These adopted standards are technically identical to the original IEEE standards. The IEEE P21451–1, designated with a "P" as in the process of being revised, defines a set of common network services (CNSs) for smart transducers, such as discovery services, transducer access services, TEDS access services, event notification services, and transducer management services. The P21451–1 standard and other standards in [43]–[45] provide means for smart transducers to achieve sensor data interoperability in the network level.

The IEEE 1451.0 standard defines a set of common functions, commands, and TEDS for the entire family of IEEE 1451 smart transducer standards. It operates under either a client-server or request-response protocol, which is independent of the physical communication media. Basic functions include reading from and writing to transducer channels, reading and writing TEDS, and sending configuration, control, and operation commands [22]. The key feature of IEEE 1451 smart transducer is TEDS that store transducer identification, calibration, correction data, measurement range, and manufacturer-related information. IEEE 1451.0 was designed to facilitate interoperability and compatibility among the family of IEEE 1451 standards when multiple wired and wireless sensor networks are connected to form a system of networks. The IEEE 21451–001 standard defines a set of signal treatment services in terms of sensor signal processing algorithms applied to smart transducers [46].

VI. INTEROPERABILITY TESTING OF SMART SENSORS

One of solutions to achieve and assure interoperability is to conduct interoperability test [47]. Interoperability testing is used to verify if two or more implementations (i.e. two devices or systems) based on the same standard can interoperate [48]. As shown in Figure 9, the interoperability testing of SSs is proposed as an activity to verify if two independent implementations of SSs (device under test, DUT) and the SS client (SS tester, or SST) are compatible with each other based on the same SS communication protocol. This also checks if the DUT (server, SS) can interoperate with the SS tester (client). SS tester is a client implementation of SS communication protocol and whereas DUT is a server implementation of SS communication protocol. The interoperability testing process includes to see if the communication process between client and server is interactive and collaborative, and checking to see if the command messages from client to server and the response messages from server to client are compatible with the SS communication protocol.

A. Interoperability Test Method for Smart Sensors

The architecture of a passive interoperability test method for SSs is proposed and shown in Figure 10. The SST and SS (DUT) are connected through a network switch and communicate with each other based on the SS protocol. The network sniffer is connected to the switch to monitor the communications and capture all network packets between the SST and DUT. The SS interoperability analyzer (SSIA) (e.g., a human being or an application program), analyzes the SS interoperability status based on the SS protocol (SSP) and generates a test report to support SS interoperability certification.

B. Interoperability Test System for Smart Sensors

An interoperability test system of IEEE C37.118–2005 standard-based SSs, in this case, PMU-based SSs, is shown in Figure 11. This test system consists of a PMU Connection Tester** (SS tester), eight commercial PMU-based SSs (DUTs), a network switch, a network sniffer, and a PMU interoperability analyzer [47].

The PMU Connection Tester, a stand-alone open-source project [49], supports the phasor data protocols and can be used to verify that the data stream from any known phasor measurement device based on IEEE C37.118–2005. It can also be used to test the communication with different PMU-based SSs by sending different commands via the network switch. The network sniffer is Wireshark, which is a free and open-source packet analyzer [50]. It could be used for network troubleshooting and packet analysis, as well as software and communications protocol development and testing. Wireshark captures packets and store them in packet capture (PCAP) files. Five interoperability test cases of eight commercial PMU-based SSs from different vendors were conducted. All network packets between PMU-based SS and PMU Tester for each test case were captured and analyzed for interoperability status. The details of the interoperability analysis are described in [47]. Table II shows interoperability test results for eight commercial PMU-based SSs. The results indicate that all PMU-based SSs passed the interoperability test except one, which had an interoperability issue with the Send Header Frame test.

VII. SUMMARY AND CONCLUSION

This paper proposes a general model of SSs for SGs based on requirements of SGs. In this model, a SS has four basic capabilities: sensing, signal and data processing (intelligence), timing and time synchronization with an internal clock and/or external time reference, and network communication via a network interface. PMU- and MU-based SSs used in SGs are presented to illustrate how they work with the model proposed. This paper also addresses the challenges of SS interfaces standardization and interoperability in SGs. An interoperability test method for SSs is proposed to achieve and assure SS interoperability, which mainly uses a network sniffer to listen, capture, and store the network packet data between the SS tester and SS being tested. It also uses a SS Interoperability Analyzer to analyze the interoperability of the SS based on the packet data collected. An interoperability test system for PMU-based SSs was developed and testing was conducted. The test results not only show the interoperability of commercial PMU-based SSs, but also verify that the proposed interoperability test method and system for SSs work.

Our future plans are to further explore SS interoperability issues in the power industry and propose the SS model to IEEE in consideration for standardization.

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Biography

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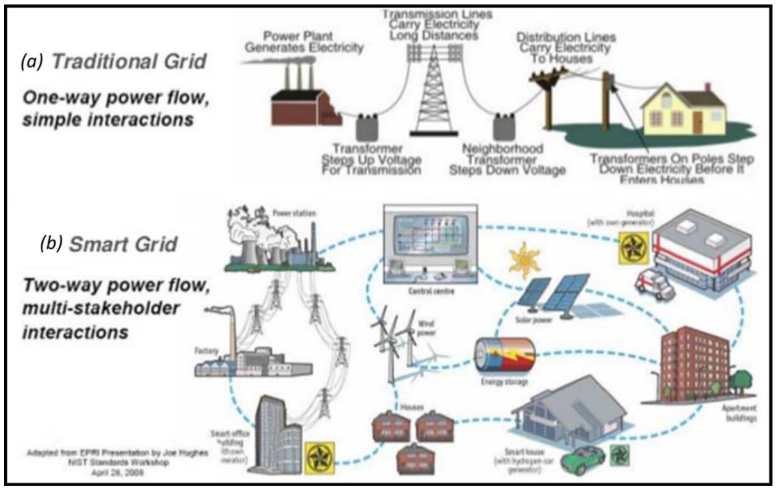

Fig. 1.
The traditional and smart grids [1].

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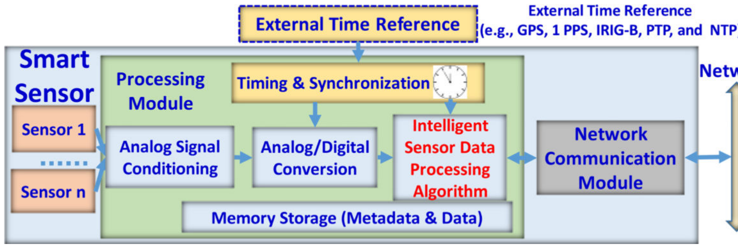

Fig. 2.
A general model for a SS for SGs.

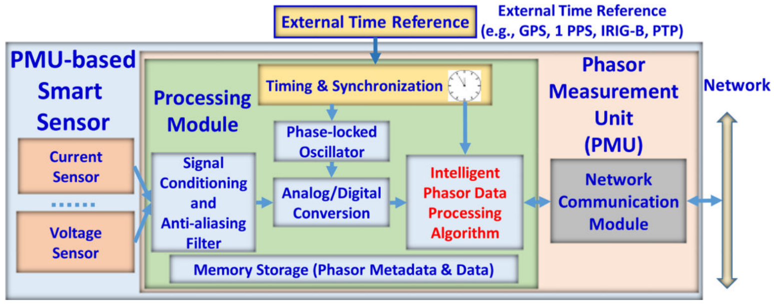

Fig. 3.
Block diagram of PMU-based SS.

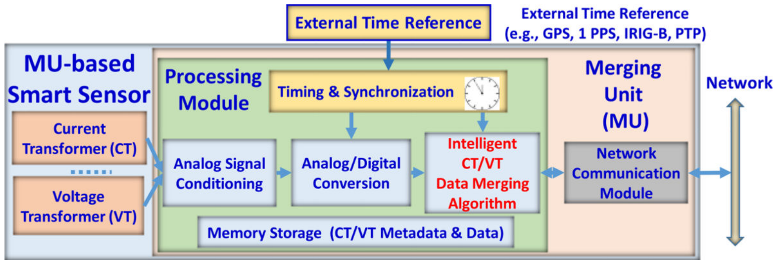

Fig. 4.
Block diagram of MU-based SS.

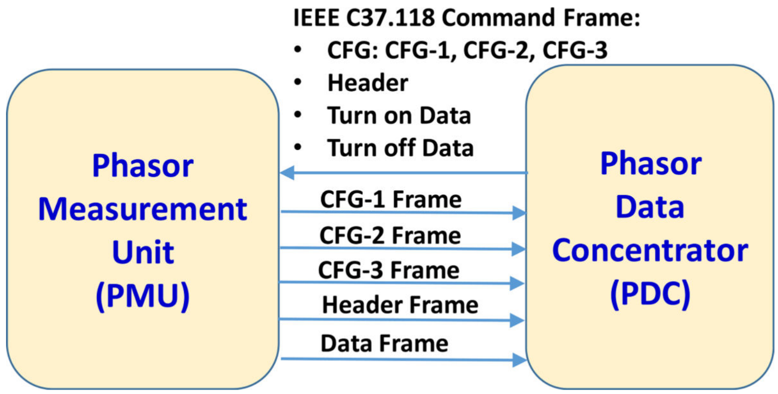

Fig. 5.
IEEE C37.118.2 for PMU-based SSs.

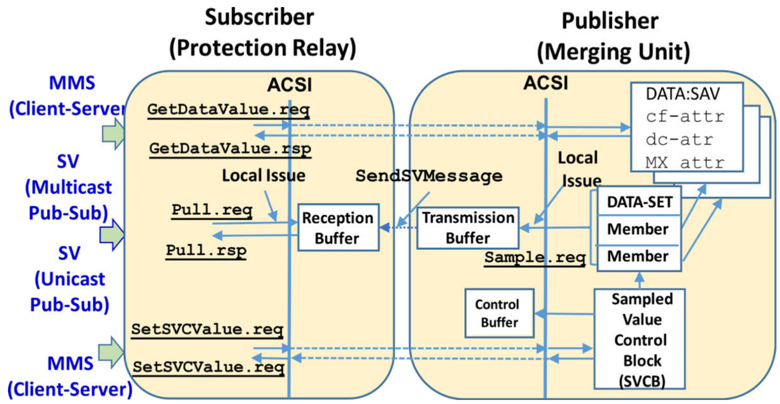

Fig. 6.

IEC 61850–9-2 for MU-based SSs.

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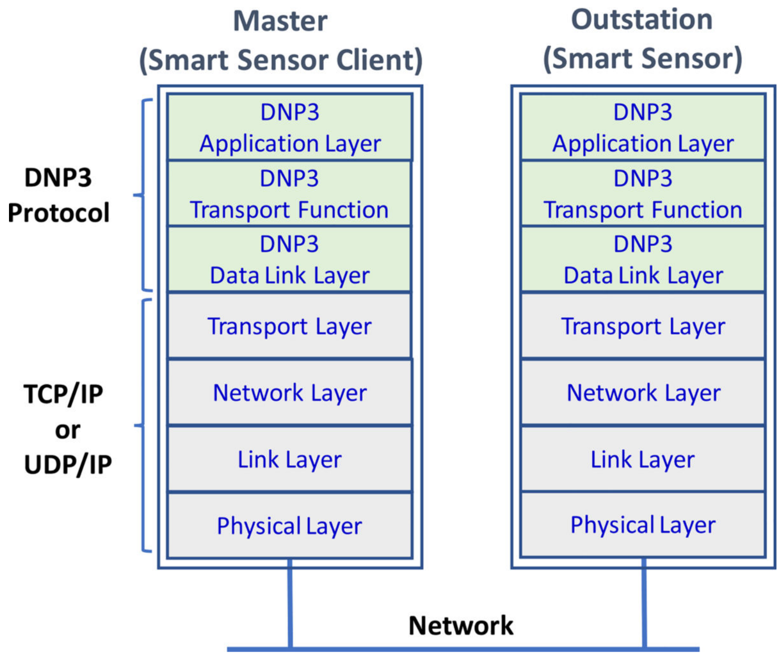

Fig. 7.
IEEE 1815 (DNP3) for SSs.

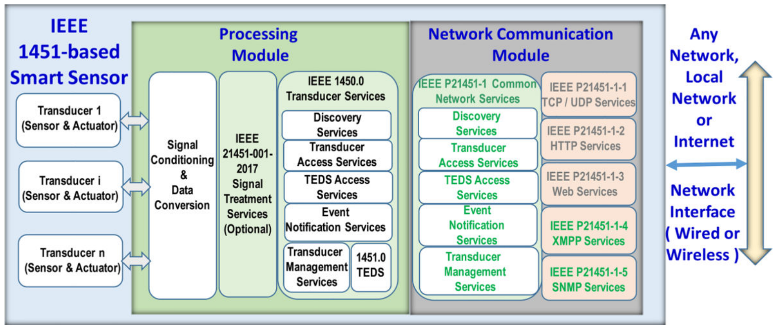

Fig. 8.
IEEE 1451 standard-based SS.

Fig. 9.
Interoperability testing of SSs.

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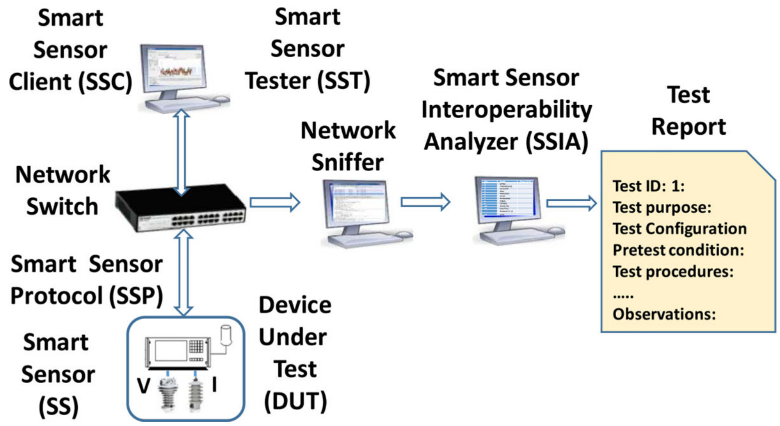

Fig. 10.
Interoperability test method of SSs.

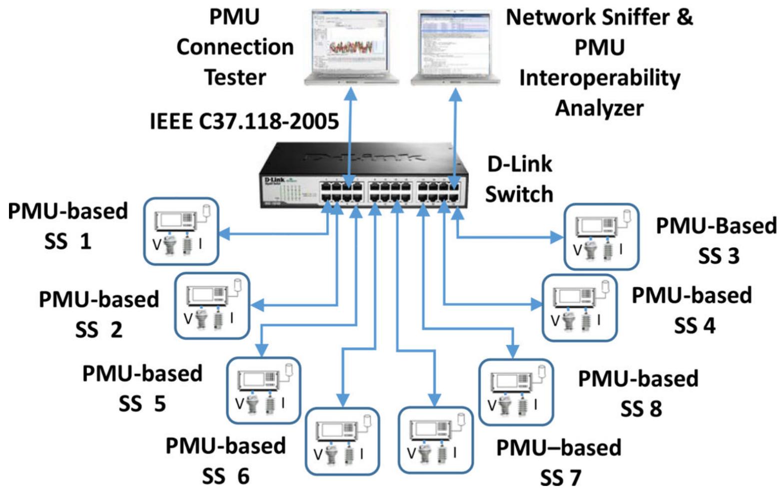

Fig. 11.

Test system of commercial PMU-based SSs.

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TABLE I

SSs and Interface Standard Protocols

Smart Sensors	Interface Standards	Network Connections	
		Wired	**Wireless**
PMU-based SSs	•IEEE 1344 •IEEEC37.118.2 •IEC 61850–90-5	•TCP/IP •UDP/IP •RS232 •Optical	•3G/4G/LTE Cellular •WiFi •WiMAX
MU-based SSs	•IEC 60044–8 •IEC 61869–9 •IEC 61850–9-2	•TCP/IP •UDP/IP •Optical	•3G/4G/LTE Cellular •WiFi
SSs in general (Current, Voltage, Temperature, etc.)	•IEEE 1815 •IEEE 1815.1 •IEEE 1451	•TCP/IP •UDP/IP •RS232 •Optical	•3G/4G/LTE Cellular •WiFi •WiMAX •ZigBee •6LowPAN

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TABLE II

Test Results for Eight Commercial PMU-Based SSs

Interoperability Test		PMU1 (TCP)	PMU2 (TCP)	PMU3 (TCP)	PMU4 (TCP)	PMU5 (UDP)	PMU6 (TCP)	PMU7 (TCP)	PMU8 (TCP)
Turn Off	Procedures	P	P	P	P	P	P	P	P
	Command	P	P	P	P	P	P	P	P
	Response	P	P	P	P	P	P	P	P
Turn On	Procedures	P	P	P	P	P	P	P	P
	Command	P	P	P	P	P	P	P	P
	Response	P	P	P	P	P	P	P	P
Header	Procedures	P	P	P	P	P	F	P	P
	Command	P	P	P	P	P	P	P	P
	Response	P	P	P	P	P	F	P	P
CFG-1	Procedures	P	P	P	P	P	P	P	P
	Command	P	P	P	P	P	P	P	P
	Response	P	P	P	P	P	P	P	P
CFG-2	Procedures	P	P	P	P	P	P	P	P
	Command	P	P	P	P	P	P	P	P
	Response	P	P	P	P	P	P	P	P
Overall		P	P	P	P	P	P(80%)	P	P