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Towards a standardisation for digital inputs and outputs of protection functions in IEC 60255 series

Volker Leitloff[1], Hao Chen[2*], Dehui Chen[3], Andrea Bonetti[4], Lei Xu[5], Ahmed Mohamed[6] and Carl Byman[7] on behalf of IEC TC95 WG2

Abstract

Fully digitalized substations using IEC 61850 process bus are being introduced all over the world. Numerous utilities have featured pilot projects, demonstrators or even industrial scale deployment of these Fully Digital Protection, Automation and Control Systems (FD-PACS). Product standards such as profiles for Instrument Transformers have been developed and published (IEC 61869-6 and IEC 61869-9 by TC 38—Instrument Transformers). This raises the question about the standards for digitally interfaced protection functions. In 2016, IEC TC 95 (Measuring relays and protection equipment) charged a working group to investigate this subject and to elaborate recommendations concerning requirements and testing of protection IED with digital inputs and outputs for protection standards (IEC 60255-1xx series). For protection functions, publisher/subscriber based data streams are supposed to comply with IEC 61850 and IEC 61869 standards. This holds in particular for Sampled Values (SV) representing energising inputs of the protection function, and is also applicable to Generic Object Oriented Substation Event (GOOSE) which can be used for input or output of protection functions. Quality attributes of published data depend on the operational and connection status of the function and the hosting IED. In addition, protection functions have to take into account the information regarding the time synchronisation of the received SV and other parameters. This paper gives an overview of these features and the proposed way to take them into account in the IEC 60255 standard series. It describes the progress of WG 2 and relates it to existing standardization documents.

Keywords: Process bus, Protection function, Digital interface, SAMU, LPIT, Standards, IEC 61850

1 Introduction

Fully Digital Protection, Automation and Control Systems (FD-PACS) using IEC 61850 are being introduced all over the world. Numerous utilities have featured pilot projects, demonstrators [1, 2] or even industrial scale deployment. Profiles for Instrument Transformers (ITs) have been developed and published by IEC TC 38 (Instrument Transformers), as product standards, and in particular:

- *IEC 61869-6* Additional general requirements for low-power instrument transformers [3].
- *IEC 61869-9* Digital interface for instrument transformers [4].
- *IEC 61869-13* Stand Alone Merging Units [5].

This raises the question about product standards for protection functions digitally interfaced with process interface equipment and with other functions of the PACS.

In 2016, IEC TC 95 (Measuring relays and protection equipment) charged Ad hoc WG 3 (AhWG3), to investigate this subject and to elaborate recommendations for requirements and testing of protection IED with digital

*Correspondence: pingfengma@126.com

[2] State Grid Jiangsu Electric Power Co., Ltd., Nanjing, China
Full list of author information is available at the end of the article

inputs and outputs for protection standards. This concerns IEC 60255, and specifically, the documents mainly dedicated to the functional part, known as IEC 60255-1xx series.

Based on the recommendations given by AhWG3, TC 95 implemented WG 2 "Protection functions with Digital input/output" in 2019. WG 2 is missioned to provide standards and guidelines for this subject and to support the development and review of functional standards for protection functions (IEC 60255-1xx series).

This paper is an overview article describing the progress of the standardization working group. The objective of the document is to describe the subject of the work of WG 2 and to relate it to existing standardization documents. The methodology of work is transparent and corresponds to the development of a Technical Report of the IEC standardisation working group. It is compliant to IEC Directives and includes the circulation of working drafts among National Committees, and modifications and improvements of these documents based on the received comments.

2 Functional protection chain

Published or subscribed data streams of protection functions are required to comply with IEC 61850 and IEC 61869 standards (as seen in Fig. 1). This holds in particular for Sampled Values (SV) representing energising inputs of the protection function, and is also applicable to Generic Object Oriented System Event (GOOSE) which can be used for input (e.g., signals indicating circuit breaker position or circuit breaker failure) or output of protection functions (e.g., trip orders). The value of the data quality attribute of published data depends on the operational status of the protection function, the status of the communication interface and data streams of the function, and the hardware status of the hosting IED. In addition, protection functions may have to take into account the time synchronisation status of the subscribed SV.

Figure 1 shows the functional chain of protection functions interfaced with a digital secondary system, highlighting the different applicable product standards. Although several configurations are possible to interface Instrument Transformers, the characteristics of their digital interface are described by IEC 61869-6 and IEC 61869-9. This interface is common to both of the following units:

- Stand Alone Merging Units (SAMU) connected to Convectional Instrument Transformers,
- Merging Units (MU) associated to Low Power Instrument Transformers (LPIT).

Regarding the fault clearance time, the acquisition time of the Merging Units and the transmission time of SV and GOOSE have to be considered in addition to the time required for the protection algorithm itself and for closing the trip contacts, as seen in Fig. 2. For a conventional PACS with hardwired protection IED, this significantly changes the definition, test and responsibilities for the fault clearing time.

3 Considerations for protection functions interfaced with digital input/output

Analysis of the functional chain of protection functions shows that the following elements also have to be considered [6] as according to Figs. 1 and 2:

- The characteristics and transfer function including anti-aliasing filter and accuracy of the analog data

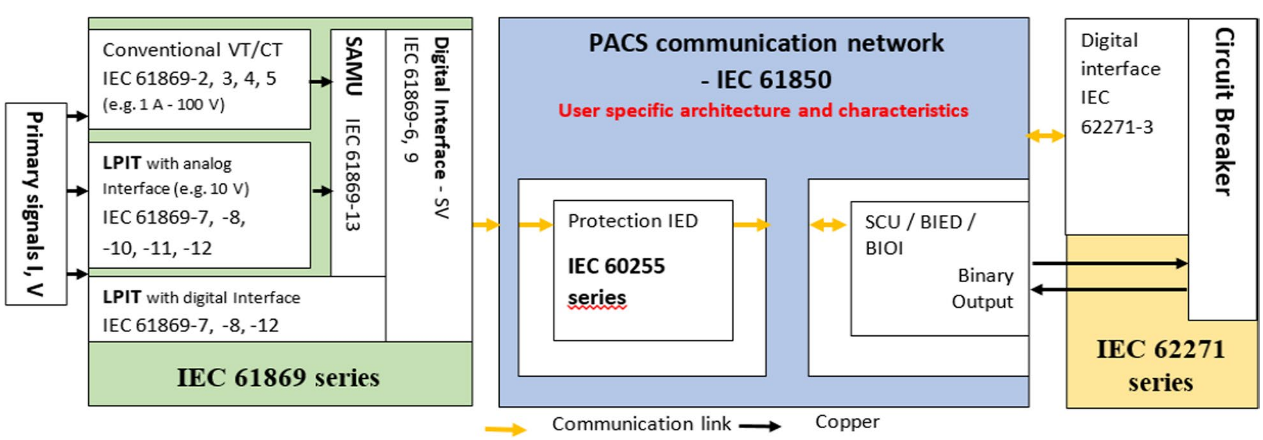

Fig. 1 Functionaal chain of protection functions interfaced with digital secondary system

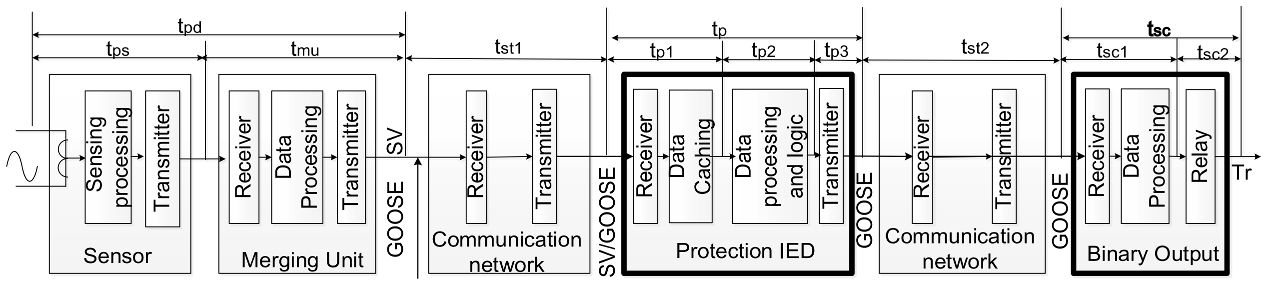

Fig. 2 Operate Time of the functional chain of a protection function (example: LPIT)

(current/voltage) contained in the SV stream are covered by IEC 61869 series (as seen in Fig. 4).

- The overall performance of a functional protection chain depends on the design and the characteristics of the protection itself and the communication network. Even being partially covered by IEC 61850 standards and guidelines or best practices, no general statements over performance of the communication network can be given. A new or extended responsibility of the user and/or integrator for the correct design of the protection schemes has thus to be acknowledged. In the near future, the system integrators may be requested to provide an engineering document addressing the communication network performances, including latency, worst case analysis, reliability etc.
- The expected behaviour of the protection function, if subscribed data or time synchronisation is in a non-nominal state or lost, has to be specified to avoid misunderstanding and minimise tests at commissioning. The corresponding tests have also to be defined.
- No IEC standard currently covers the requirements for binary input / output IED used for interfacing binary inputs and outputs. The devices can be used to interface circuit breakers, disconnectors or other binary inputs (monitoring of auxiliary power supply contacts, etc.), and form part of the functional protection chain when interfaced with a conventional circuit breaker.
- Protection function requirements on Current Transformers (CT), which are mandatory in IEC 60255-1xx relay protection standards, need to be adapted and translated into requirements for Merging Units, publishing the SV streams subscribed by protection functions.

On this base, the recommendations given by AhWG3 [6] can be separated in the following two categories:

1. Recommendations for taking into account digital I/O in IEC 60255 series.
2. Recommendations for clarifications or amendments in IEC 61869 or IEC 61850 standards.

Performance characteristics have to be defined or adapted for protection functions with digital inputs and outputs in the relevant functional standards (IEC 60255-1xx series). In principle, all tests of IEC 60255-1xx series using ideal Instrument Transformers can be performed in a similar way and with the same electrotechnical power system model by injection of SVs. This concerns:

- *Operate time* For a conventional protection IED, the operate time is defined as time between fault inception and relay operation measured on the trip contact. For digitally interfaced protection functions, this corresponds to the instant the SV corresponding to the fault inception is received by the device hosting the protection function, and the moment it publishes the trip GOOSE message.
- *Reset time* The reset time is defined as time interval between the instant the fault disappears from the input signal and the reset of the trip output to normal state.
- Reset ratio, which is the characteristic for the hysteresis between pick-up and reset of the protection function.
- Stability tests, which are required to verify that the protection function does not trip untimely due to signals corresponding to a fault outside the protected zone.
- Steady state accuracy tests for thresholds.

There is an important difference between tests with ideal CTs (and/or VTs) for conventional analog technology and tests with direct primary quantities using SV, as the former tests do include the performances of the analog input module and the internal A/D conversion of the protection IED. The tests using SV injection do not cover this module because it is implemented in the MU. The characteristics of the analog input circuits can be quite important, especially for protection functions that elaborate an instantaneous trip decision (differential protection, zone 1 distance protection, instantaneous overcurrent protection, etc.). Such characteristics have a direct relation with the transient performances of the MUs. The transient performances of the analog input module and internal A/D conversion are already considered in the protection relay algorithms.

For these reasons, the part dedicated to the so called "merging unit requirements" will be a very important aspect for digitally interface protection functions described in IEC 60255-1xx series. Guidelines are required to express the definition of the performances in a standardized way, as it is today done for CTs, shown in Fig. 3 [7, 8]. This approach still needs to be discussed within TC 95.

In order to determine the current transformer requirements for a particular protection function, the IED manufacturers need to perform tests with real Instrument Transformers. At the same time, in order to determine the MU requirements, it is necessary to implement models considering the characteristics of the MUs in the power system network simulator which publish the SV streams used for the test [8, 12, 13].

Another more intuitive difference between the two operate times is that in the first analog situation, the secondary quantities measured by the protection relay are in practice not delayed compared to the corresponding primary quantities. The time required for the A/D conversion of the analog secondary quantities is included in the measurement of the relay operate time. In the IEC 61850 numerical technology, this time is now outside the protection function, as the acquisition is performed by the Merging Unit. For this reason, the operate time measured from when the SV quantities representing the power system fault reach the protection relay, and when the protection relay issues the operate GOOSE message, will be called "operate time of the protection function in the hosting IED" (t_p in Fig. 2). This concept will be described in more detail in Sect. 4.2.

$$E_{alreq} = \frac{I_f}{I_{pr}} \cdot K_{tot} \cdot I_{sr} \left(R_{ct} + R_{ba} \right)$$

Where:

I_f	is the maximum primary steady-state short-circuit CT current for the considered fault case
I_{pr}	is the CT rated primary current
I_{sr}	is the CT rated secondary current
K_{tot}	is the total over-dimensioning factor (including the transient dimensioning factor and the remanence dimensioning factor)
R_{ct}	is the CT secondary winding resistance
R_{ba}	is the total resistive burden, including the secondary wires and all relays in the circuit.

Fig. 3 Example of standardized CT Requirements for the rated equivalent limiting secondary e.m.f. ($_{Ealreq}$) in IEC 60255-121 [9–11]. Copyright © 2014 IEC Geneva, Switzerland. www.iec.ch

4 Requirements regarding subscribed sampled value streams

4.1 Accuracy of the protection function

The accuracy declaration which can be found in IEC 60255-1xx series for protection IED with analog inputs covers the complete functional chain, including:

- Input analog module in the protection device,
- The A/D conversion,
- The protection function itself.

The accuracy declaration for a protection function receiving a SV stream will only cover the protection function itself. In order to indicate the total accuracy, it is thus necessary to consider the requirements on the accuracy class of SAMU or LPIT. In case of SAMU, the accuracy class of the associated conventional Instrument Transformers needs to be considered as well, as this is already the case in protection IED with analog inputs. A correspondence table is provided in IEC 61869-13 [5].

In addition to accuracy requirements, the digitally interfaced protection function is supposed to verify elements that are not available in conventional technology, though, if implemented, will contribute to improve the dependability and security of the protection system. This also enables automatic substation supervision functions, allowing event driven maintenance of FD-PACS with reduced costs for routine maintenance tests. These elements include:

- The synchronisation status of the incoming SV. Depending on the protection function, it may be necessary to suspend the operation of the function if the SV is not globally or locally synchronised. In particular, this is the case for protection functions receiving SV streams from more than one Merging Unit with different time sources.
- The quality data attribute (DA) and the detailed quality of the received SV. The expected behaviour of the protection function in case of non-nominal values of these attributes needs to be specified, and depend on the nature of the protection function. For example, clipping may be tolerable for overcurrent functions but may lead to suspension (blocking) of the operation of differential protection functions, similar to existing system when the communication is lost in line differential protection applications.

- The supervision of the SV stream itself. If loss or jitter of SV exceed tolerable thresholds, the protection function should be blocked to prevent untimely operation.
- The transfer function of the MU publishing the SV stream according to IEC 61869-9 [4] (as shown in Fig. 4).
- In case of SAMU

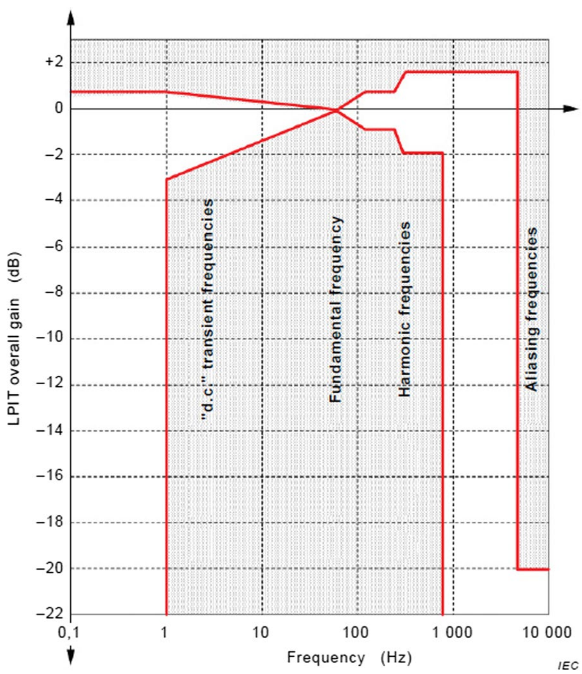

Fig. 4 Example of a MU transfer function for metering accuracy class 1(fr = 60 Hz, fs = 4 800 Hz) according to IEC 61869-6:2016 [3]. Copyright © 2016 IEC Geneva, Switzerland. www.iec.ch

- The saturation characteristics of the conventional current transforms,
- The time constant and transient behaviour of the SAMU, and in particular, its current input circuit [12, 14–16].

As mentioned before, for the characteristics of saturation, remanence and flux, a similar approach as in IEC 60255-1xx series can be taken. In this case, the manufacturers need indicate the required characteristics for the upstream analog acquisition chain for the protection function. The analog acquisition chain has to be verified that the protection function is compatible with the protocol profile of the SV stream (IEC 61869-9 or UCA 9-2LE, as shown in Table 1). It has to be noted that the preferred format of SV according to IEC 61869-9 is 2 ASDU per telegram with a fixed sample frequency of 4.8 kHz.

4.2 Missed samples, time synchronisation, network latency and jitter

Based on the requirements of IEC 61869-9, a jump of SmpCnt is possible if it is related to a resynchronisation. This has to be taken into account by the input processing of SV of the protection functions. It has also to state the acceptable number of consecutive missing or invalid samples.

IEC61869-9 clause 6.902.2 [4] gives the maximum processing delay time limits of MU for publishing the sampled data, and for protection applications, it is 2 ms. As shown in Fig. 2, the delay of the PACS communication network also has to be considered for the maximum time delay of the SV seen by the input port of the protection function.

Table 1 Sampled values protocol profiles according to IEC 61869-9:2016 Table 902. Copyright © 2016 IEC Geneva, Switzerland. www.iec.ch

Digital output sample rates Hz	Number of ASDUs per frame	Digital output publishing rate frames/s	Remarks
4000	1	4000	For use on 50 Hz systems backward compatible with 9-2LE guideline
4800	1	4800	For use on 60 Hz systems backward compatible with 9-2LE guideline, or 50 Hz systems backward compatible with 96 samples per nominal system frequent cycle
4800	2	2400	Preferred rate for general measuring and protective applictaions, regardless of the power system frequency
5760	1	5760	For applications on 60 Hz systems backward compatible with 96 samples per nominal system frequency cycle
12,800	8	1600	Deprecated, only for use on 50 Hz systems
14,400	6	2400	Preferred rate for quality metering applications, regardless of the power system frequency including instrument transformers for tiem critical low bandwidth d.c. control applications
15,360	8	1920	Deprecated, only for use on 60 Hz systems
96,000	1	96,000	Preferred rate for instrument transformers for high bandwidth d.c. control applications

The average transmission time delay and jitter caused by the communication network need to be considered and the values depend on the design of the communication network and the characteristics of the network switches. They can be obtained by communication network system studies as seen in Fig. 2. For protection functions subscribing to one SV stream, the time delay causes a shift of the processing window, and thus impacts on the total trip time. The size of the input alignment table (input buffer) of the protection function is determined by the expected jitter.

For protection functions subscribing to more than one SV stream, the maximum relative time delay between the SV streams also defines the size of its input alignment table as shown in Fig. 5, which constitutes the input buffer for the protection function. The worst case would be a negligible time delay for the communication from one MU and a large transmission time delay for the connection from another MU.

4.3 Meaning of SV values with non-nominal quality attributes

The interpretation given in IEC 61869-9 [4] for the detailed quality attribute is to be applied for protection functions. Table 2 lists the DetailQual attributes as defined in IEC 61850-7-3, the corresponding requirements for SV published by MU according to IEC 61869-9, and the recommended application for protection functions.

Based on Table 2, the value range of analog energising quantities subscribed by protection functions and the associated detailed quality attributes are visualised in Fig. 6. An analog value which is not in line with the

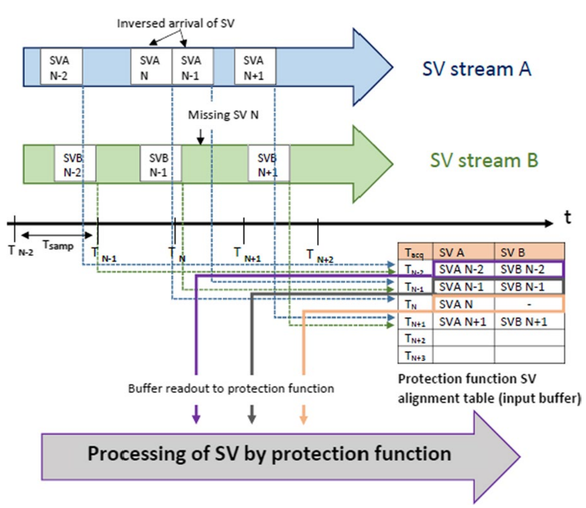

Fig. 5 Operation of SV input alignment table of a protection function

accuracy requirements is published as "questionable". This holds in particular for the case when the analog acquisition circuit saturates and signal clipping occurs.

With reference to Fig. 6, analog values transmitted via SV from a MU designed according to IEC 61869-9 shall not produce invalid data upon any combination of "outOfRange"—"Inaccurate" (as "overflow" is not used in IEC 61869).

Consistent with the behaviour defined in Table 2 and Fig. 6, the expected functional behaviour of a subscribing protection function has to be defined for each subscribed SV stream. This should be done aiming at a globally optimised performance of the PACS. A proper specification and validation of this aspect is a basic requirement for functional interoperability between MUs publishing SV and subscribing protection functions.

The functional interoperability between two or more applications is achieved when they are able to exchange information with each other by using the same communication protocol, and have a common understanding about the exchanged message.

5 Requirements regarding subscribed GOOSE

Protection functions may also use GOOSE messages subscribed by the hosting IED to perform time critical protection tasks, like blocking, acceleration (teleprotection schemes), direct intertrip order or start of breaker failure protection. The requirements and tests for these inputs are similar to those for protection functions with wired binary inputs. IEC 60255-1xx series have already required protection IED manufacturers to publish the protection function operate time for contact output and GOOSE publication, if applicable [8]. However, one big difference is that, for the SV described above, the subscribed GOOSE messages may have a non-nominal quality attribute and is required to specify the behaviour of the protection function. The famous sentence describing this situation is: "I receive a trip order, but the trip order also tells me "I am not sure", so what to do?".

The information "I am not sure" is contained in the quality attribute associated to the trip order, which is a binary signal. In the analog technology, protection engineers are not used to consider binary signals with a quality, i.e., contact open is open, and contact closed is closed. But this is not really true, as protection engineers know that a binary input should not be inverted inside the protection IED, because "zero" could mean "contact open" but also "contact closed and DC Voltage missing". Thus, protection engineers deal with Normally Open and Normally Closed contacts together for critical operations, and handle the clear "01" and "10" conditions for these double contacts, together with the erroneous "00" or "11", in order to make sure that "open is really open" and

Table 2 Interpretation of detailed quality for sampled values subscribed by protection functions

[IEC 61850-7-2:2010 + AMD1		IEC 61869-9:2016 [applicable to SV published by MU]	Application for Protection Functions		
Detail Qual	**Definition**		**Invalid**	**Question-able**	**Meaning of DetailQual for received data**
Overflow	Value beyond the capability of being represented properly	Not Used. Always set to FALSE	X	Prohibited by IEC 61850-7-2: 2010 + AMD1 (Annex D)	Not used in IEC 61869-9:2016 May be applicable to other analog information, e.g. phasors (PhV, A) The protection shall process the input as invalid
Out of range	Value beyond a predefined range of values	True in case of Clipping Publication with validity attribute "Questionable"		X	Publication with validity attribute as "Questionable" preferred The relevant functional standard shall specify how to process the input Applicable to SV and other analog information, eg. phasors (PhV, A)
Inaccurate	The value does not meet the stated accuracy of the source	True if signal does not respect the specified accuracy	Prohibited IEC 61850-7-2: 2010 + AMD1 (Annex D)	X	Applicable to any type of received input data The relevant functional standard shall specify how to process the input Applicable to SV and other analog information, e.g. phasors (PhV, A)
Badreference	Value may not be a correct value due to a reference being out of calibration	Not Used. Always set to FALSE		X	Publication with as "Questionable" preferred. The relevant functional standard shall specify how to process the input. Not used in IEC 61869-9:2016 May be applicable to other analog information, e.g. phasors (PhV, A)
Oscillatory	Signal changes in a defined time twice in the same direction	Not Used. Always set to FALSE		X	Not Applicable to analog input data (SV, phasors, etc..), only to binary input data The protection shall process the input as invalid
Failure	Indicates that a supervision function has detected an internal or external failure	Used for detected errors	X	Prohibited by IEC 61850-7-2: 2010 + AMD1 (Annex D	Applicable to any type of received input data The protection shall process the input as invalid
Olddata	If an update is not made during a specific time interval	Not Used. Always set to FALSE	Prohibited by IEC 61850-7-2: 2010 + AMD1 (Annex D	X	Not used in IEC 61869-9:2016 May be applicable to information, e.g. phasors (PhV, A) The relevant functional standard shall specify how to process the input
Inconsistent	Indicates that an evaluation function has detected an inconsistency	Not Used. Always set to FALSE	Prohibited by IEC 61850-7-2: 2010 + AMD1 (Annex D	X	Not used in IEC 61869-9:2016 May be applicable to other information, e.g. phasors (PhV, A) The relevant functional standard shall specify how to process the input

"closed is really closed". All of this, to be more abstracted and formalized, is the meaning of handling the "quality associated to the communicated value".

A generic "simple suspension (blocking) of operation" of the protection function for these cases is not acceptable, since this would potentially lead to very low overall availability of protection functions in PACS. In addition, most GOOSE inputs are not critical for the core protection function and can be ignored by using a safe default value to be defined. This has to be done for every input DO used by the protection function.

The Technical Report under preparation by WG2 proposes a formal approach for the specification on this behaviour as seen in Table 3, based on the Basic Application Profiles which are being defined under IEC 61850 (IEC TR 61850-7-6).

6 Requirements regarding published GOOSE

DO published by a protection function may also have associated non-nominal quality values. As for any other PACS function which is not directly interfaced with the process, most of the Detailed Quality attributes are not applicable. Normally, a protection function is expected to publish its DO as "Valid", even if some of the subscribed data from the function itself is non-nominal. The TR introduces the term of dynamically blocking of a protection function, and in this case, the DOs are published as valid by the protection function, with output value set to default.

As for the received GOOSE and SV, the expected behaviour of the protection function needs to be specified and tested.

7 Requirements regarding implementation of IEC 61850 communication interface

IEC 61850 communication interface is implemented on the IED level which hosts the protection function. Multifunctional IED are very common now. In order to have a meaningful separation of the functions implemented in one IED, it is possible to associate each implemented protection or automation function of the IED using more than one LN to one individual Logical Device. This facilitates management and testing of each function, allowing, e.g., to switch off one single function or to put one single function into test mode.

Most of the requirements for IEC 61850 are driven by the architecture and characteristics of PACS rather than individual functions. Requirements of IEC 61850 interface related to protection functions may include:

- Number of subscribed SV and GOOSE streams,
- Capacity of the communication interface (e.g., 100 Mbit/s, 1Gbit/s),
- Capacity to switch between several SV or GOOSE streams, e.g., a nominal stream and a test stream or redundant stream,
- Implementation of test mode and/or simulation model [9].

8 Testing

Functional testing of the protection function should not be confused with the functional testing of the complete functional chain (see Figs. 1 and 2). For digitally interfaced protection functions, the latter is performed during PACS integration tests. The functional standard of a digitally interface protection function should only cover the functional test of the function itself, i.e., based on the inputs represented by the DO and SV subscribed by the function, and on the outputs represented by the DO published by the function.

In addition to the "conventional" tests of the performance of the protection function, all the new features described in the previous sections for protection functions interfaced with digital secondary systems need to be tested [9]. This may require new features in test systems and the development of new tests in IEC 60255-1xx series. Users have to be aware that adequate testing of the other elements is also required, and in particular, SAMU and/or LPIT associated to their MU and the Binary Input/Output IED (BIOI).

9 Timeline and disclaims

The Technical Report prepared by the WG is also intended to enable organisations that do not have the full competence to handle IEC 61850 projects alone [17–19], to technically specify their IEC 61850 protection systems with reference to the Technical Report. Thus, this paper gives the estimated schedule for the document to be available, i.e., it is intended to circulate the updated draft considering the comments (≈1000) received in the first circulation, by end of 2021. Depending on the comments received, the final version can be envisaged for mid-2022.

On the other side, it has to be emphasised that this paper refers to the content of the Technical Report at the moment of writing (October 2021). As the process in IEC is long, and there is the general commitment to reach a wide consensus within the community, it is possible that some contents in this paper will be different from the final release of the Technical Report.

10 Conclusion

IEC TC95 AhWG3 has published recommendations [6] for the next steps in order to elaborate requirements for protection functions covered by TC 95 (IEC 60255

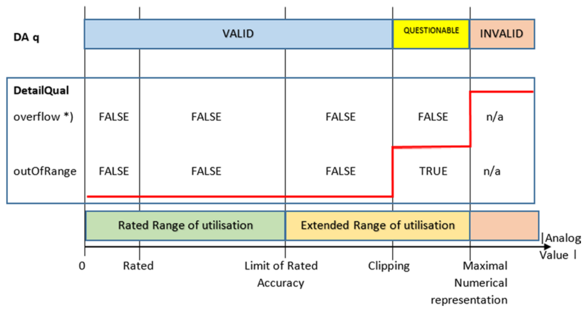

Fig. 6 Relation between quality attributes and range of analog energising values according to [4]. *) DA overflow is not used in IEC 61869-9

series) interfaced with digital secondary system. These recommendations include:

- Maintain the WG in order to finalise the Technical Brochure describing the findings and recommendations in detail. TC 95 has decided in its Plenary TC meeting in 2018 to convert former AhWG3 into a permanent TC 95 WG (WG 2), with the intention to propose participation to other relevant IEC TC, and in particular, TC 38 and TC 57. A draft of the TR under preparation has been circulated in 2020.
- Define mandatory requirements and tests for a number of general features, possibly in a new part of IEC 60255 (IEC 60255-1xx series) giving general requirements for protection IED with digital interfaces.
- For each functional part of IEC 60255, add the relevant requirements and tests for protection functions. This can be done at the same time as an existing standard is revised or a new standard is developed.
- Create a new part of IEC 60255 for IED interfacing binary I/O (BIED).
- Investigate if a part of IEC 60255 describing additional requirements for multifunctional IED interfaced with digital secondary system is necessary. This should cover minimal requirements for making functions independent from each other in order to be testable, e.g., using one separate LD per function.

WG 2 is now formally installed and its work program has been defined on the base of the above recommendations.

With respect to requirements and tests applicable to all digitally interfaced protection functions, it has become clear that many of them are generic, i.e., not specific for a given protection function. For this reason, WG 2 has recommended to create a new part in IEC 60255 series covering general requirements of digitally interfaced protection functions. This part should contain mandatory requirements and tests for the following features:

- Accuracy definitions for input energising quantities including effective range, operative range, rated quantities, etc.
- Requirements for the digital interface of protection functions (IEC 61850 profile and IEC 61869-9 profile)
- Definition of a frame for generic test procedures.
- Requirements for implementation of IEC 61850 based test features and associated tests, including Sim, Mod, Source, InRef.
- Generic definition and methodology for criteria for publishing output data with non-nominal quality attributes.
- Expected behaviour in case of SV with non-nominal time synchronisation and associated tests.
- Requirements for protection functions receiving more than one SV streams and associated tests.
- Method for defining the expected behaviour in case of missing or non-nominal digital inputs.

WG 2 has also recommended to complete functional standards of IEC 60255 series as follows:

- Add a specific clause for digitally interfaced protection functions in the clause "Influencing functions / conditions". This clause should define the requirements applicable to the protection function covered by the functional standard if the subscribed data is non-nominal or missing, including the definition of the Basic Application Profile (BAP) for the function (seen Table 3).
- Add a subclause "Settings" to the clause "Functional Logic" (often clause 4.4 in IEC 60255 series). Settings are independent of the interface of a given protection function. If a protection function is digitally interfaced using IEC 61850, it should be encouraged to use the settings defined there. The subclause "settings" should provide a clear list and mapping between the different settings of the protection function covered in the functional standard and the settings provided in associated Logical Nodes defined in IEC 61850. All IEC 61850 based settings are based on primary values.
- Split clause "Effective and Operating Ranges" (often clause 5.2 in IEC 60255 series) in two subclauses, one for protection functions with analogue inputs corresponding to the existing clause 5.2, and the other new subclause for protection functions using digital inputs.

Table 3 Table form to specify the expected behaviour of a protection function depending on the quality of subscribed data

Input	QUALITY												Meaning of "Ignore Input"	Interpretation of input DA	Comments
	INVALID			QUESTIONNABLE											
	Detailed Quality										SOURCE				
	Overflow *)	Faillure	Other (not associated to detailed quality)	Oscillatory **)	BadReference *)	OutOfRange *)	OldData	Inconsistent	Inaccurate *)	Other (not associated to detailed quality)	PROCESS	SUSTITUTED			
SV or PhV															
other DO															

- Split clause "Accuracy related to the characteristic quantity" (often clause 5.3 in IEC 60255 series) in two subclauses, one for protection functions with analogue inputs corresponding to the existing clause 5.3, and the other new subclause for protection functions using digital inputs.
- Create a new clause covering non-nominal performance of subscribed SV (loss, jitter, etc.) under the main clause "Performance Specification" (often clause 5 in IEC 60255 series). The new clause should, where possible, directly refer to the requirements of future part on general requirements for protection functions with digital I/O.
- Adapt the description of the functional tests.
- Add a section or an annex describing MU (associated to LPIT or implemented in a SAMU) requirements to the functional standards in analogy to which is in place for the requirements for current transformers.

Abbreviations

FD-PACS: Fully digital protection, automation and control systems; SV: Sampled values; GOOSE: Generic object oriented substation event; IT: Instrument transformers; PACS: Protection automation and control systems; SAMU: Stand alone merging units; MU: Merging units; LPIT: Low power instrument transformers; CT: Current transformers; DA: Data attribute; BAP: Basic application profile.

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Author's information

VolkerLeitloff (1965), studied El ectrical Engine ering at the universityof Stuttgart/Germany from where he earned the Dipl I ng. degree i n 1991.From 1991 to 1994 he has been preparing his PhD t hesis at theLabo ratoire d'Electrote chnique de Grenoble and re ceived the Dr. IN PGdegree from th e Institut Nati onal Polytechnique de Grenoble (INPG) in1994. From 1994 to 2002, he was wit h the R&D Di vision of Electricitéde Fra nce were he worked successive ly on network pro tection and ontran sformers and network techn ology. Since 20 03 , he is with the FrenchTransmis sion Network Operator Rte, where he works on protection oftransmission netw orks and sub station control. He is chair of IEC TC 38and CENELEC TC 38 (Instrument Tr ansformers), conven or of IECTC95 WG2 (Digita l I/O of protec ti on IED), past con venor of CIGREWG B5.06 on DSAS Maintenance and actual or past member of IECTC38WG37, TC38 WG47, TC95MT 4 and CIGRE WG 34.10, B5.10,B5.13, B5.43, B5.53, B5.64, B5.69 and the SAG of SC B5.

Hao Chen (1980), studied Electr ical E ngineerin g at Southeastuniv ersity/China fr om where he earned the Bachelor of Engineeringdegree in 2002 and Master of Engineering degree in 2005. From 2005 to2011, he was with the Nanjin g power supply co mpany where he work edon power grid protectio n and control. Fr om 2011 to 2015, he has beenpre paring his PhD thesis at Southeast University and received the PhDdegree in engineer in 2015. Since 2011, he is wit h State Grid JiangsuElectric Power Co., Ltd. where he works on p rotection of transmissionnetwor k and sub st ation control. He is active memb er of IEC TC95AhWG3 (now WG2) Digital I/O of protection IED.

Dehui Chen (1977), receiv ed his bachelor and master d egree in 1998and 2007, and m ajored in power system analysis and informationtelecommunication respectivel y. Now Dehui is a re search enginee r inState Grid Electric Power Instit ute in Nanj ing. From 1998 to 2003, asr elay protect ion engineer, dealing with t esting, FAT, SAT andcommissi on. From 2004 to 2007, Dehui enrolle d as candidate for masterdegree, engagin g in study with how to implement p rotocol stack usinggraphic lan guage. After grad uation from unive rsity 2007, he worked a s a power system engineer, and was dealing with R&D relat ed to domain ofrelay protection, su bstation automation system. Meanwhile, as projectleader, his responsibilit y for system integration of Yan 'an 75 0kV smarts ubstation which i nclude ECT/ EVT, Merging Unit, IEC 61850 processbus , relay protection with digit al I/O, etc. which also was the high estvoltage pilot smart substation projec t in China. Addition al, he is memb erof TC57WG10, TC57WG17, TC57W G19, T C95WG2, CIG RE B5.59and he i s also lead ing the task force IEC TR 61850 90 22. A dditionally,Dehui is secreta ry of China IEC TC57 as well.

Andrea Bonetti graduated as electrotechnical e ngineer at SapienzaUniversity of Rome, Italy, in 1993, after having studied the first two yearsof engineerin g at Univers itá di Trento, Italy . After fiv e years in ABB It alyas pr otection engineer, Andrea worked 10 years as HV relay protectionspecialist a t HV relay protection manufacturer ABB Grid AutomationProducts in Västerås, Sweden, for re lay post fault anal ysis, relay settings,comm ission ing supp ort and training for distance protection linedifferential protec tion, with IEC 61850 and conventional app lications.From 2008 to 2013 Andre a worked at Megger in Stockholm, as productmanager and t echnical specialist for relay t est equipment, deali ng withthe development of I EC 61850 test set and tools, test algorithms fordistance protection and transformer d ifferential protection relays. Fro m2013 to 2018 Andrea worked as consultant in Relay Prote ction and IEC61850 Application s: procurement speci fication fo r TSOs, IEC 61850specific ation and attendance for FAT/SAT, IE C 61850 troubleshooting inoperative subs tations, trainings, IEC 61850 top down specification andengineering process, development o f IEC 61850 test eq uipment and tools.From Ap ril 20 18, Andr ea works at Megger i n Stockho lm, as senior specialist in relay pr otection and IEC 61850 applications. Andr ea holdsa patent in the area of I EC 61850 testing tools and algorithms. Activemember of t he IEC TC 95/MT 4 s ince 2006, A ndrea has been sub g rouplea der for the developm ent of th e IEC 60255 121 standard and hasrec eived the IEC 1906 Award in 2013. Since 2 008 Andrea is a guestlecturer at KTH (Royal Institute of Technology, Stockholm) for IEC61 850 for Substation Automation a pplications.

Lei Xu(1976) received his Master's degree in electric power system automation from State Grid Elec tric Power Research I nstitute in 2001.Then he joine d NR Electr ic as an R&D engi neer. He major in research and development of digital substation related technologies. From 2001 2003 he developed protection related products an d from 2003 2007 he develope d intelligent primary equipme nt such as LPIT, MU CSD and BIED. Fr om 2007 he worked as the project manager and now the principal en gineer in digital substation related research and depar tment. Being the team leader, he leads the development and imple mentatio n of the first generation dig ital substations in China. He is mem ber of IEC TC17MT2, TC38WG37, TC95MT2/MT 3 /WG2, member of CIGRE A3.35, B3.39 , B5/D2.67 , B5.7 0 and conve ner of B5.59.

Ahmed Mohamedis graduated as an Electrical Power Engineer fromH e lwan Uni versity Egypt in 2005. He i s working as Pr otection an dControl Enginee r since 2006. He started in Egypti a n ElectricityTransmission Compan y (EETC) then moved on 2008 to DubaiElectricity and Water Authority (DEWA) and from 2013 untill date iswor k ing in S cottish and Southern Energy Network (SSEN), Glasgow,U K. He is w orking in the Transm ission sector as a P& C

Engineer for thelarge Capital P rojects and is involved in a different innovation projectwhich is handling/ utilising the digital Input for t he prote ction relays andProcess bus implemen tation . He is a m ember of t he IEC TC 95/WG2"Pr otection functions wi t h Digital input/output".

Carl Byman (1963), studied Engineering Physics at the university ofUppsala/ Sweden from where he earned the Master degree i n 1989. Afteruniversity he started w orking with devel opment of substat ion control a ndprotection. From 1 9 89 to 1998 he was working for ABB Relays inVästerås, Sweden, followed by 2 years at ABB in Baden, Switzerlan d.From 2000 Carl is working for H itachi Ene rgy in Västerås S weden . H eis a member of IEC TC95 WG2 (Prote ction Functions with Digital Inputsand O u tputs) since 2019.

Author contributions

Andrea Bonetti brings up the idea to gives an overview over these features and the proposed way to take them into account in IEC 60255 standard series. All authors participated in enriching the manuscript and carried out the revising the manuscript (editing grammatical and lexical mistakes). All authors read and approved the final manuscript.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This article does not contain any studies with human or animal subjects performed by author.

Competing interests

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details

[1]French Transmission Network Operator Rte, Paris, France. [2]State Grid Jiangsu Electric Power Co., Ltd., Nanjing, China. [3]State Grid Electric Power Institute, Nanjing, China. [4]Royal Institute of Technology, Stockholm, Sweden. [5]NR Electric Co., Ltd., Nanjing, China. [6]Scottish and Southern Energy Network (SSEN), Glasgow, UK. [7]Hitachi Energy, Västerås, Sweden.

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