Meeting Protective Relay Performance Requirements with IEC61869-13

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SUMMARY

IEC61869-13 standardizes merging unit analog acquisition requirements and recommendations for metering and protection applications, including measurement range, overall accuracy, transient response and thermal withstand during most onerous conditions. In addition to the enlarged dynamic range, such requirements as signal measurement clipping, transient response, thermal withstand and frequency response; impose serious challenges for the analog acquisition technologies currently in use, prominently dominated by magnetic core and shunt resistors. Such requirements are analyzed in the context of the most common protection functions considering the impact on the protection dependability and security by meeting or exceeding standard requirements. For example, performance requirements for the signal acquisition during open-close-open fault cycle with a fully DC offset CT signal are examined. Simulations and tests results are presented, considering merging units with different performances and protection functions main parameters. The intention of this paper is to evaluate the impact of the new requirements defined by the IEC61869 for the protection functions for Digital Substations and educate about challenges faced by the current and future technologies for analog interface for both protection and metering applications.

KEYWORDS

Stand Alone Merging Units, IEC61869-13, Measurement, Transient Response, Accuracy, Digital Substation, Requirements

1. INTRODUCTION

One of the key enabler concepts of the full digital substations is the capability to digitize instrument transformers, allowing the exchange voltage and current data in between IEDs in real time over network through Sampled Values protocol, in such condition that information comes from the through fiber optics cumulating advantages related to cable reduction, civil infrastructure, cost, simpler and safer installation and interoperable data share in between multiple IEDs [1].

Aiming to standardized the communication in between substation IEDs it was created the IEC61850 series, that among others define the concept of Merging Units (MU) [2] as a physical unit that perform a time coherent combination of voltage and/or current data coming from secondary converters, that can be from different types of transducer, and publishing them in Sampled Values format, described by the IEC61850-9-2 [4].

To catch-up with the new concepts of full digital substations the IEC61869 series, that cover requirements for instrument transformers, was released covering the instrument transformer capability of having digital interfaces standardized by the IEC61869-9 [3] including the concepts of Low Power Instrument Transformers (LPIT) and especially the Stand-Alone Merging Units (SAMU), as per the IEC61869-13 [4], being these the IEDs responsible to support analog acquisition from instrument transformers defined in other parts of the IEC61869 series and share data over network through the digital interface, as represented in the diagram of Figure 1.

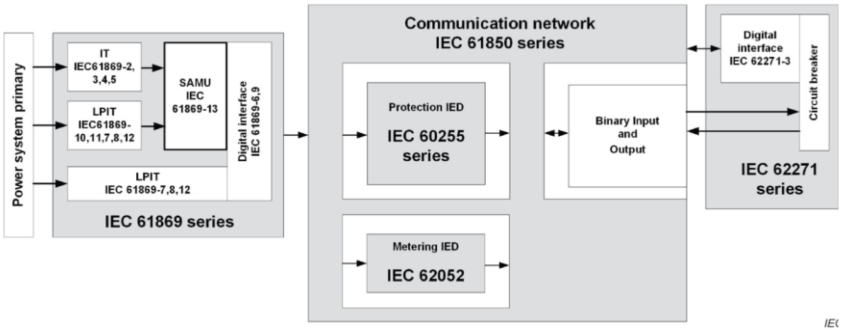

Figure 1. Diagram from IEC61869-13 clarifying the interaction in between various standards.

The IEC61869-9 and IEC61850-9-2 Ed 2.1 introduces new requirements and features mostly related to communication, sampling rate and extra optional fields, which can impact backward compatibility, processing power and acquisition frequency.

The IEC61869-13 covers a set of specification for a SAMU as an IED, introducing new accuracy classes, transient response requirements and, definition of accuracy over temperature, accuracy in different frequencies and EMC tests and acceptance criteria.

Meanwhile the IEC61869-9 might have limited impact in the architectural design for most of the solutions, the IEC61869-13 has a set of requirements that to comply products will need strong re-design, especially in the acquisition system. None of the two main technologies, magnetics CT or shunts, for current acquisition have advantages to cover required by -13. Magnetics are good to support current withstand and accuracy over temperature but have deficiencies on transient response. Shunts have good transient response, but poor accuracy over temperature and difficult design for high thermal current withstand.

This paper will cover the discussion about the complete set of standards and recommendations while analyzing the technological challenges to comply to the full set of requirements and possible positive and negative impacts of these standards for Protection and Control Systems.

2. THE IEC61869 STANDARD AND ITS RELATION TO THE IEC61850

In 2003 the IEC technical committee 57 (TC-57) published the first edition of IEC-61850 standard series titled communication networks and systems for power utility automation. The specific goal with this standard series was to provide interoperability between IEDs (Intelligent Electronic Devices) by defining communication services and information models, that is: how to communicate and what to transmit to execute automation and protection functions in a networked system composed by devices manufactured by different vendors. Beside defining communication mechanisms and providing data modelling, IEC-61850 stablished a substation architecture, dividing it in three automation levels (Process, Bay and Station) with two communication networks or buses (Process and Station). The vison of IEC-61850's Process bus was enabled by the existence of a special IED named Merging Unit (MU), which converted in its digital form voltages and currents acquired form the secondary winding of Instruments Transformers (IT) installed in the substation yard.

Following IEC-61850-9-2, the digitally converted signal could be transmitted on the process bus by using the so-called Sampled Value (SV) protocol so other IEDs could use the information for protection and automation purposes. Unfortunately, for its first release, the standard lacked consistency and important points were open, delaying its market adoption. In 2004, a document published by UCA International User Group, addressed several of those open points, becoming the "de-facto" standard since then. Acquisition and publication frequencies, Dataset content, synchronism, naming and mappings where fixed by this document, which now is known as the IEC-61850-9-2LE released with the name "Implementation Guideline for Digital Interface to Instrument Transformers Using IEC 61850-9-2", this was an advanced name to the time (2004) considering that the concept of MU was still under development. It was not until 2016, with the publication of the first edition IEC-61869-9, that a more elaborated and standardized concept of MU and Digital Interface to Instrument Transformers appeared. Keeping backward compatibility with IEC-61850-9-2LE, the newer standard specified: requirements for networking physical connection types, minimum components for HMI, maximum processing delays, standardized digital output sample rates and publication profiles, semantic improvement with data

modelling standardized names, flexible dataset content and consolidated PTP synchronization concept for analogical acquisition process.
IEC-61869-9 document was published under the name “Digital interface for instrument transformers” and within it defined a fundamental distinction between the concepts MU and Stand-Alone Merging Units (SAMU). In the standard’s own words: “…Unlike the merging unit in an instrument transformer, a SAMU is a separate product covered in IEC 61869-13. It accepts as inputs the outputs of instrument transformers, said outputs conforming to the specifications of one of the product standards in the IEC 61869 series… Output produced by a SAMU and output produced by an electronic LPIT with built in merging unit should in principle be indistinguishable from each other…”. Once again, for SAMU applications, by the year of its publication IEC-61869-9 was ahead of its times since analogical interfaces and type testing were not standardized yet. The only available source of information about this topic was encountered in IEC-61869-6 but with the big conceptual difference that the later was created to be applied on low-power instrument transformers instead of SAMU. With this, a conceptual void was created, yielding to confusion among customers and vendors alike.
It was only until 2020, with IEC-61869-13 first edition, that a specific standard for SAMU application was published. This newer standard adapts, from IEC-61869-2, IEC-61869-3 and IEC-61869-6 to SAMUs, the definition of analogical input ratings, insulation ratings, accuracy classes, signal clipping, signal saturation, transient response and type testing to be applied. This is a great step to achieve a fully interoperable digital substation as envisioned by IEC61850, both hardware and software wise, however technological and conceptual challenges still open, some of them are addressed in the upcoming sections of this paper.

4. DETAILING THE IEC61869-13 AND ITS TECHNOLOGICAL CHALLENGES

IEC 61869-13 defines these requirements for SAMU as a product, it relies on specification from other series of the IEC 61869 standard with some of them extended on the -13 while also redefining limits for accuracy and specifying type tests and its acceptance criteria.
In the subsection 5.6 of IEC 61869-13 Rated accuracy class, accuracy specification is defined for metering and protection applications, with different ratings and specific naming. Current channels specified for protection should have a designated metering accuracy class and they are defined separated by a slash with metering class specified first then the protection.
The standard accuracy classes for SAMU protection rated current channels are: 2TPM, 6TPM, 10TPM. The letters "TPM" mean protection rated SAMU current channels for transient performance with a specified secondary time constant Tsec, for which the saturation behavior in case of a transient short-circuit current is specified by the instantaneous error component defined below. All current channels with protection accuracy designation shall meet the asymmetrical fault current dynamic response requirements defined in the Table 1304.
In comparison with the conventional transformer standards such as IEC 61869-2 and -3, this new standard removes the higher metering accuracy classes, 3 and 5, while also adding a stricter 0.05 accuracy class with definitions for rated frequency as well as harmonics performance. Accuracy definition is extracted from three parameter the manufacturer shall declare:

- Accuracy class (0.05, 0.1, 0.2, 0.5 1) which defines the magnitude error from KImin to KImax (known as Dynamic Range) as well as a given phase error allowed
- KImin, dynamic range lower limit factor with preferred values as 2, 5 or 10% of rated input and with KImin/4 allowing for double the magnitude and phase error of KImin
- KImax dynamic range higher limit, point to where the accuracy is maintained with preferred values as 120, 200 or 400% of rated input

Metering accuracy class designation is defined as “class DR KImin-KImax", as an example the following 0.2DR1-200 mean a 0.2% accuracy is maintained from 1 to 200% of the rated input.
In comparison with the conventional instrument transformer standards the requirements become much tighter on the lower ranges, with the IEC 61869-13 requesting for minimum error at 10% of rated input while -2 and -3 would use a value of 80%. These tighter requirements require conventional solutions to be reevaluated and potentially shift to different measurement techniques with its tradeoffs ranging from reducing overall dynamic range, current withstand, weight and/or cost.

Two of the most common sensors used for measurement are conventional magnetic transformers and shunts or resistor dividers (current or voltage), each of them excels in specific areas, table below summarizes some of the most common differences between them.

Table 1 – Comparison in between magnetic and shunt or resistor divider technologies

Parameter/Solution	Magnetic	Shunt or Resistor Divider
Isolation	Intrinsic	Necessary
Cost	$	$$
Current withstands (shunt)	High	Low
Transient Performance (current)	insufficient	excellent
Size/Weight	High	Low
Magnitude error	Medium	Medium
Phase error	High	Low
Temperature introduced error	Low	High

As can be seen from the table above resistive based solutions have better transient and phase performance while needing isolation circuitry implementation to comply with the requirements, as the isolation is much easier to implement in the digital side it usually requires at least one ADC per channel potentially driving solution cost higher and more important its complexity.
Furthermore IEC 61869-13 goes on to define accuracy specification must be achieved throughout the temperature range stated on the device rating plate, with an allowance for different temperature range specification for protection rated channels, in which case temperature range specification can be provided for metering and protection, even when both are the same channel. Although IEC 61869-13 does not go into details on the test procedure for accuracy over temperature it is considered IEC 61869-6 as a product family standard which contains IEC 61869-13, then its subclauses apply to it otherwise specified by each product standard. Test procedure is defined in IEC 61869-6 as a set of measurement steps at minimum, maximum, and ambient temperature, with a temperature change ramp no lower than 5°C/h. The figure below illustrates the temperature profile the SAMU is submitted to during the test and its mandatory measurement instants.

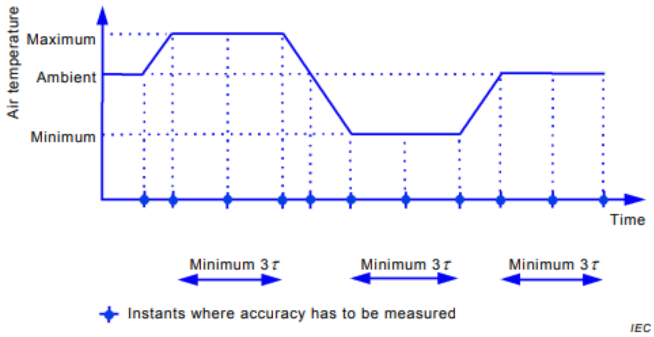

Figure 2. Requirements for temperature tests according to IEC61869-13. Source IEC61869-13

Although accuracy might be one of the biggest challenges brought up by IEC 61869-13, it also brings clarity to the expectation for a SAMU during type testing and the necessary tests and levels. The scope is aligned to what is commonly used today from IEC 60255-1, -26 and -27, with the later to be followed fully until the relevant IEC 61869 series safety standard is developed.
For immunity testing the standard defines three different acceptance criteria, A, B and C with each of them having requirements in terms of allowed error or loss of functions. Table below summarizes the three criteria and its condition for acceptance.

Table 2 – Acceptance criteria and condition for acceptance for SAMU EMC tests

Acceptance Criteria	Condition for acceptance
A	Normal performance within the accuracy specification limits including the state of quality and sync bits. Additionally, no individual sampled value error shall exceed 10 % of the input quantity RMS level.
B	Normal performance within the accuracy specification limits for protection rated channels including the state of quality and sync bits. Additionally, no individual

	sampled value error shall exceed 200 % of the input quantity RMS level. Temporary degradation of measuring accuracy, with self-recovery at the end of the test is acceptable. A reset or restart is not allowed.
C	Temporary loss of function provided the function is self-recoverable. A reset or restart is allowed. Streaming may be interrupted, but when the stream is present, quality bits within the stream shall represent the SAMU operating state and meet requirements of IEC 61869-9:2016, 6.903.9. Current state of the SAMU synchronization shall be correctly represented.

All the criteria presented above regarding accuracy are related to the metering specification while for protection rated channels have slightly different definitions, these are presented on section 6.11.3.601 of IEC61869-13 as every protection rated channel is evaluated during EMC testing with a per cycle RMS calculation using instantaneous over/under voltage/current protection elements. Protection elements threshold shall be set at two times the stated TPM accuracy class for currents and at two times the ±6% tolerance specified in 5.6.1302 for voltage channels.
As an example, protection rated channels on a given SAMU with a 6TPM accuracy class for current will have the elements for both current and voltage set as ±12%. Under current/voltage elements will be set at 0.88pu while over current/voltage elements will be set at 1.12pu.

5. THE IMPACTS OF IEC61869-13 REQUIREMENTS ON PROTECTION AND CONTROL SYSTEMS

IEC 61869-13 defines requirements for the accuracy and transient performance for the protection class SAMU in a new way. It allows manufacturer of the SAMU to declare the performance class and it's up to the user to decide if given SAMU meets required specific protection application requirements or not. Most challenging are requirements for the protection grade current channels transient performance and there are 4 major ratings that manufacturer must declare:

- Transient performance protection class "TPM" (specified 2TPM, 6TPM or 10TPM values)
- Clipping limit "**NamClipRtg**", which is >= 2*Kssc*√2 to cover initial 100% DC offset of the fault current transient (40 or 100 for example)
- Rated symmetrical short-circuit current factors for the transient performance "Kssc" (specified 20, 30, 50 and 100)
- System time constant for the transient performance "Ti" (specified 50, 120, 180, 250 ms and DC values)

The most onerous condition that SAMU must comply by the standard to qualify for a declared class is so called C-O-C-O fault current cycle with initial full DC offset fault at 50Hz for a duration of ti=150ms to 160ms, followed by the autoreclosure dead time of tfr=300ms, and finally reclosing onto permanent fault for a duration of t''=290 to 310ms. During this C-O-C-O cycle SAMU error should not exceed declared accuracy class error.
Figure 3 below demonstrates such cycle for two different sample SAMU units for the Kssc=30 (meaning SAMU will not exceed declared maximum error for up to 30 times rated symmetrical current) and Ti=120ms designation (which corresponds to the primary system X/R=45 ratio). It can be seen that SAMU1 transient performance (blue trace) has better transient performance than SAMU2 (green trace) and it'll be demonstrated the difference and highlight importance for protection systems.

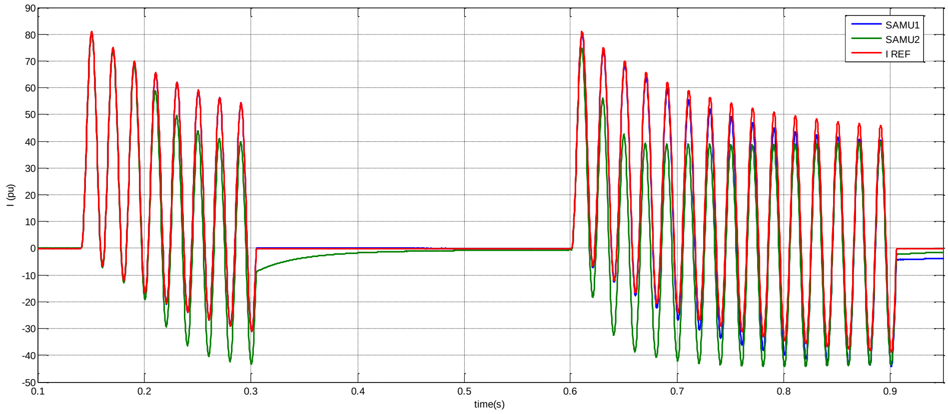

Figure 3. C-O-C-O cycle for two different SAMUs, 30pu RMS worst-case inception angle

Both IEC 61869-13 and IEC 61869-2 standards are defining how to estimate transient performance and measure the error and finally SAMU accuracy class. Instantaneous error is obtained by measuring difference between SAMU data acquisition and reference channel. Figure 4 below demonstrates instantaneous error for the same two SAMUs under investigation, evidencing that SAMU1 has better transient performance if compared to SAMU2.

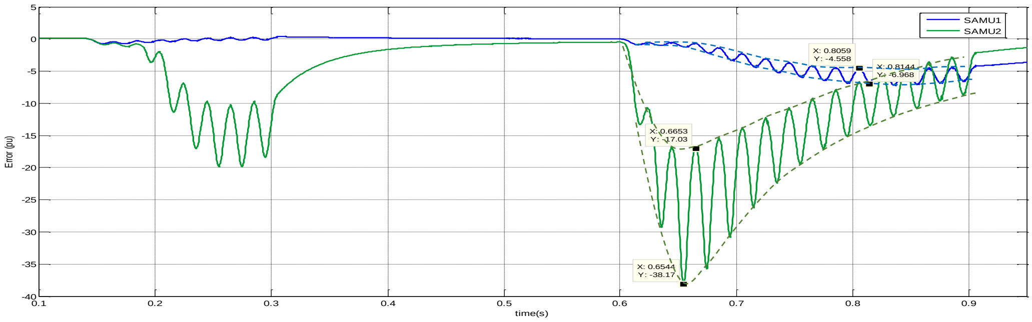

Figure 4. Instantaneous error for SAMU1 (blue) and SAMU2 (green)

According IEC61869 series, transient error is estimated by measuring value b, which is maximum difference between two neighboring positive and negative peak values of the envelope of the instantaneous error shown above. From the values in Figure 2, it is estimated the instantaneous transient error for the SAMU1 and SAMU2.

$b_{SAMU1}= |-4.56-(-6.97)|=2.41$ (pu)

$b_{SAMU2}=|-17.03-(-38.17)|=21.14$ (pu)

According to IEC 61869-13 standard, to meet 6TPM class criteria, error "b" has to be below 12% of the RMS value of the symmetrical short-circuit test current, multiplied by a square root of two, which gives a value of the $bmax=30*\sqrt{2}*0.12=5.09$pu. Consequently, SAMU1 is meeting 6TPM class criteria (bSAMU1 < bmax), but SAMU2 does not (bSAMU2 > bmax).

When SAMU is not meeting transient performance criteria, it may jeopardize protection. The impact of the excessive error is demonstrated below in the Figure 5, where fundamental frequency phasor magnitude is presented for the injected 30pu with a full DC offset current. SAMU2 is experiencing phasor magnitude error as high as 10.7%, where SAMU1 error is not exceeding 2.7%. Although the C-O-C-O cycle requirements may appear to have too many contingencies, such as long fault duration, reclose onto the permanent fault causing remanence effect of the SAMU inputs, worst-case fault inception angle, high X/R ratio, high fault current, but realistically high SAMU2 error can cause incorrect operation of some protection functions, for example distance or differential protection.

However, for applications with a lower system X/R ration, lower fault currents and protections functions not so sensitive to the error, even SAMU2 can possibly be applied. For example, in the distribution circuits, where predominantly overcurrent protection is used, transient error of the SAMU2 likely will not cause any problem. Or even for differential applications modern digital relays, which are employing today advanced algorithms, stabilizing protection such as CT saturation detection, external fault detection and directional supervision, such transient error may not cause any problem.

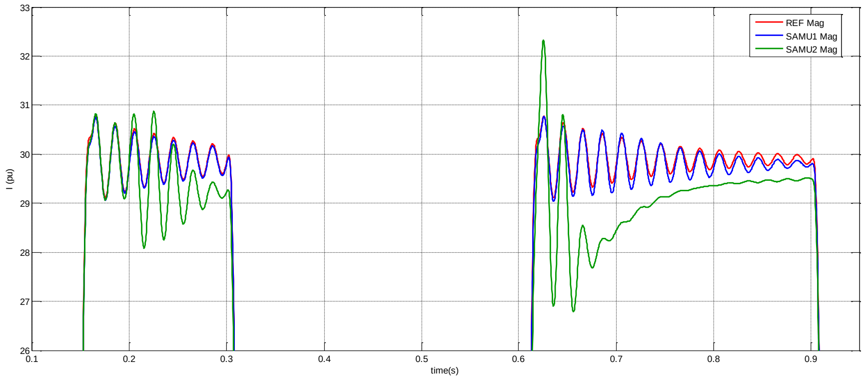

Figure 5. Magnitude estimation for SAMU1 (blue), SAMU2 (green) and reference signal (red)

6. CONCLUSIONS

The IEC61869-13 for the first time specifies a SAMU as an IED with type tests requirements, a complete set of functional tests, acceptance criteria and acquisition characteristics from the IED perspective rather than the instrument transformer, standardizing accuracy classes for dynamic range and transient response, but also adding requirements for frequency response, thermal current withstand, and accuracy over temperature. The combination of requirements brought by the IEC61869-13 standard imposes a technological challenge for the two most common acquisition technologies in this segment due to the sensor's constructive characteristics. For transformers with magnetic core the challenge is to have good response during transient performance during C-O-C-O tests and accurate frequency response. For shunts/Resistor Divisor, there are challenges in thermal Current Withstand and sustain accuracy over temperature.

The impact of the IEC61869-13 in P&C systems is connected to a clear and standard way to specify IEDs in terms of analog acquisition from its perspective and not re-using classes and requirements originally designed for physical instrument transformers, establishing, for the first time, parameters and recommendations of classes that shall be followed by a SAMU during transient response, which is particularly important in a distributed acquisition architecture where you are no longer obligated to test your P&C performance and algorithms with their own acquisition, but rather with digitized data from Merging Units.

The comparison in between SAMUs with different transient response classes evidence that the errors during transient response can be high if not limited to the performance recommended by the IEC61869-13 and this can jeopardize certain types of protections sensitive to acquisition error, like distance or differential, for faults where you have the worst-case fault inception angle, high X/R ratio or high fault current. The applicability of tight transient response requirement is debatable for cases of non-error sensitive protection, like overcurrent in distribution systems, or faults in systems with low X/R ratio and lower fault currents. Considering modern digital relays transient response errors can be suppressed even for error-sensitive protection functions by applying advanced algorithms such as CT saturation detection, external fault detection and directional supervision.

The new set of standards composed by the IEC61869 series, especially -13 brings to the industry clearer definitions and specification regarding various topics for evolving the maturity level of the full digital substations solutions. Along with the advance, challenges are also presented indicating that there are still developments and innovation to fulfil the full set of requirements and recommendations in the standards.

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