TOTAL ACCURACY OF THE WHOLE MEASURING CHAIN – SENSOR & IED

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ABSTRACT

This paper discusses the performance and functionality of the combination of Low-power stand-alone sensors and IEDs. For the first time in MV applications, we report testing performed on the combination of sensors and IEDs with digital output according to the IEC 61850-9-2LE format. Accuracy measurements performed on prototypes show high promise both for metering and protection applications. The influence of cable lengths up to 100 m on the accuracy of existing sensor products in combination with new IEDs is discussed and good performance for protection functions like differential protection is proven.

INTRODUCTION

The conventional way to assess the accuracy of current and voltage measurement in MV networks is based on existing IEC standards related either to conventional or to electronic instrument transformers. However, the situation is less defined for the equipment connected to instrument transformers, such as various meters and especially protection relays. There is no standard defining precisely how the accuracy of IEDs should be measured and no accuracy classes are specified for IEDs as in the case of instrument transformers. The accuracy of IEDs is typically specified by manufacturers according to internal test procedures and it is not easily usable for predicting the accuracy of the whole measuring chain.

Modern IEDs comprise powerful electronics, which enable advanced processing of the signal produced by instrument transformers in order to improve its accuracy and to make it more suitable for the needs of certain protection functions. This creates opportunities for optimum use of sensors to provide superior performance over traditional instrument transformers such as enhanced accuracy, linearity, rated measurement range, and functionality of the whole measuring chain.

Commonly used sensors in MV applications rely on Rogowski coil for current measurement and the voltage divider, resistive or capacitive, for voltage measurement. Such sensing technologies have already been described in several papers where the advantages of low-power sensors are also explained [1], [2]. Even though some of the advantages offered by sensors are already well known, like the lack of saturation, it has been difficult to prove till now the superior accuracy when the whole measuring chain, including the IED, is considered. With the ability of the IED to publish synchronized sampled values according to the standard format IEC 61850-9-2, it becomes now possible to better investigate the total accuracy of sensors and IEDs. The accuracy of the whole measuring chain is not important only for revenue metering, as commonly believed, but also for certain protection functions where it improves overall performance and enables better control and reliability of the power network. Differential protection is a typical example of application that would benefit from improved accuracy of the whole measuring chain, and eventually from IEC 61850-9-2 communication.

It is the scope of this paper to present accuracy tests performed on prototype sensors connected to IEDs with IEC 61850-9-2LE output capability and comment on the excellent accuracy of the whole measuring chain. The measurements were performed using a test setup featuring unique accuracy and flexibility, developed in-house for R&D applications. The R&D test setup is also described here.

The paper further includes a study on the accuracy dependence of stand-alone sensors versus large cable lengths up to 100 m and shows that protection functions like differential protection are possible even with IEDs where high-end features like IEC 61850-9-2LE output are not available. EMC conformance test are also described and they indicate that stable results are ensured even with large cable lengths.

TOTAL ACCURACY OF THE WHOLE MEASURING CHAIN

Test setup

Two test setups have been developed for testing current sensors and voltage sensors respectively. The setups have been designed to offer high level of flexibility and accuracy being particularly suitable for R&D applications in low voltage, medium voltage, and high voltage. They feature compact and modular construction based on PXI systems while the test routines are developed in LabVIEW and are fully automatic. Various test routines have been implemented according to standards like IEC 60044-7/-8 and IEC 61850-9-2 as well as customized protocols (e.g. linearity test, frequency response, impulse response, etc.). The test setups can measure sensors with analog output or the combination of sensors and IEDs (or MUs) with digital output such as IEC 61850-9-2LE.

The R&D current sensor test setup is schematically shown in Fig. 1 in a configuration suitable for high AC currents and current sensors with analog voltage output. The instruments and the controller are all embedded in a PXI system. The digitizer features 4 input channels making it possible to connect a reference sensor and test 3 sensors simultaneously. The signal is generated by an arbitrary waveform generator (AWG) connected to a high power amplifier, making it possible to cover a high frequency range from DC to 20 kHz up to peak currents of 400 A. Higher currents are reachable by using more conductor loops or a current boost transformer.

Because the primary current is generated by an AWG and then amplified it is not influenced by network instabilities and allows full control over the waveform generated.

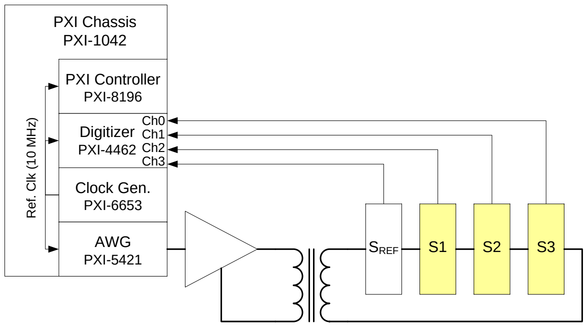

Fig. 1 Sketch of R&D current sensor test setup used to measure Low-power stand-alone current sensors.

The same test setup can measure the accuracy of measuring chains consisting of sensors and IEDs with digital output according to the IEC 61850-9-2LE guidelines, as shown in Fig. 2.

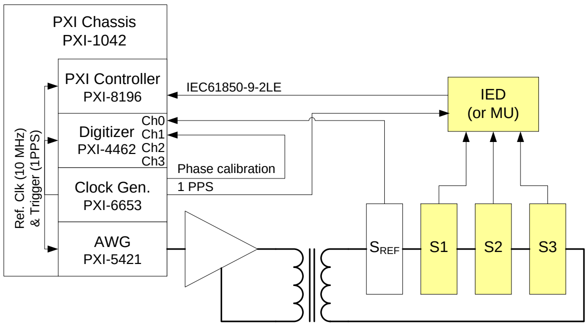

Fig. 2 R&D current sensor test setup configured to measure the whole measuring chain, i.e. current sensors connected to IED.

The output of the reference sensor S_{REF} is connected to the digitizer while the output of the test sensors S1, S2, and S3 are connected to the IED. The IED communicates the sampled values to the controller in IEC 61850-9-2LE format and receives the 1 PPS synchronization signal from a very high accuracy clock generator (50 ppb). The clock generator can generate various signals synchronized to its time base and distribute them on the PXI backplane and on the front panel connectors. This allows implementing sophisticated synchronization and triggering schemes in order to optimize the accuracy of the test setup. For example, the digitizer and the AWG are both phase-locked to the 10 MHz clock time base distributed by the clock generator on the PXI backplane. All instruments are thus sharing the same highly accurate time base and no relative phase drift between them is possible. The digitizer and the IED are both synchronized to the 1 PPS signal which is sent to the IED via a front panel connection and to the digitizer via the PXI backplane. Additionally, a phase calibration signal is sent by the clock generator to one of the analog inputs of the digitizer in order to correct for additional phase delays present in the analog signal path of the digitizer. The measurement configuration described here leads to a phase error of less than 10 ns when measuring the whole measuring chain, sensors plus IED, with IEC 61850-9-2LE output format.

The R&D voltage sensor test setup is based on the same concepts as the current sensor test setup described above.

Results

Prototype current sensors with excellent accuracy were developed based on the Rogowski coil principle using high stability coil core and winding process. A prototype IED with exceptional accuracy and IEC 61850-9-2LE output was also developed. The accuracy of the whole measuring chain was rigorously tested using a test setup configuration like in Fig. 2. The amplitude error and the phase error measured versus the primary current at 3 different temperatures are given in Fig. 3 and Fig. 4 respectively. The results correspond to 3 current sensors connected to one IED and placed at the same temperature in one climatic chamber.

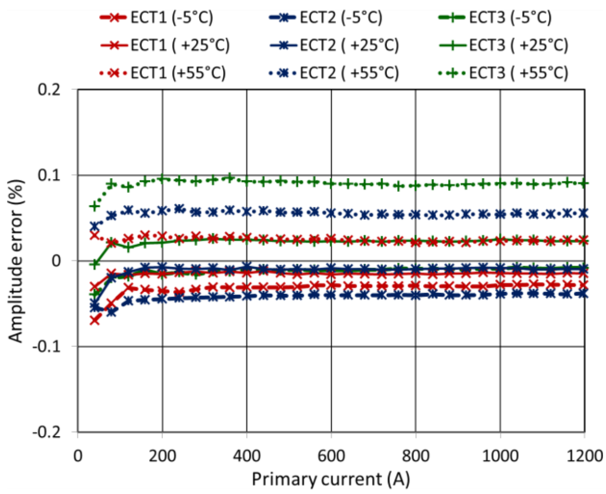

Fig. 3 Amplitude error of the whole measuring chain versus primary current measured at 3 different temperatures.

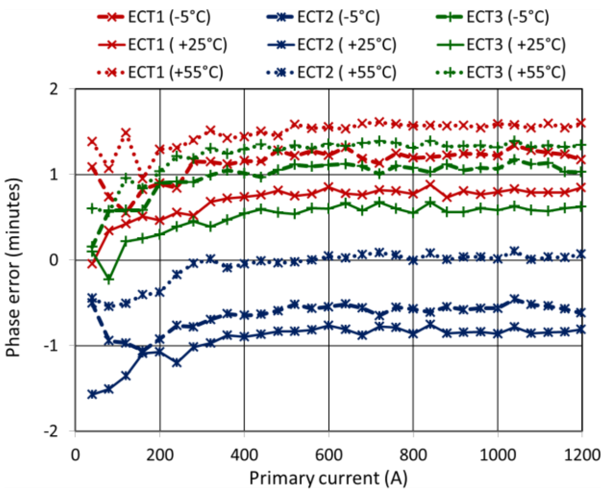

Fig. 4 Phase error of the whole measuring chain versus primary current measured at 3 different temperatures.

It is noticed that very good accuracy is achieved by the whole measuring chain over a wide current range and at practical temperatures. No accuracy degradation was observed at higher currents, which is expected for Rogowski coil type sensors as they are not prone to saturation effects. The maximum measureable primary current depends on the input range of the IED and transformation ratio of the current sensor and is around 50 kA for the prototypes described here.

The test results from Fig. 3 and Fig. 4 fulfil the requirements for accuracy class 0.1, however, effects like aging drifts are not included. When all possible product variations and drifts over its lifetime are taken into account it is found that accuracy class 0.5 can be comfortably ensured for full package of sensor + IED. Even better accuracy class may eventually be possible.

The combination of modern current sensors and IEDs are thus able to fulfil metering accuracy class. Moreover, metering like accuracy is ensured over the full current range required for protection, leading to new possibilities to optimize the protection functions. The communication of sampled values according to IEC 61850-9-2LE format would also allow simpler implementation of functions such as differential protection.

Similar measurements and results were achieved on the combination of voltage sensors and IED. The voltage sensor prototypes were based on a new resistive divider design optimized for high accuracy. Accuracy class 0.5 was also ensured for the whole combination of sensor + IED, accounting for all possible product variations and drifts over its lifetime.

DIFFERENTIAL PROTECTION AND LONG SENSOR CABLES

The application of sensors for differential protection requires long sensor cables. Sensors have not been previously used in this application as it was believed that they cannot reliably work with long cables. However, the high accuracy and dynamic measurement range of sensors could bring many benefits to differential protection application. The challenging situation for traditional differential protection based on measurement from conventional CTs is mainly CT saturation. This could happen during faults outside or inside the protected zone when high fault current occurs in primary system. To avoid false operation during faults outside the protected zone, the traditional differential protection uses stabilized characteristic with slopes. Unfortunately the slopes can make differential protection less sensitive and consequently differential protection could detect the faults in the protection zone in later stage when the fault current could reach high values. On the other hand sensors with their linear characteristic without saturation could change dramatically differential protection characteristic and the slopes which should stabilized the differential protection on CT saturation could be removed. Since the only obstacle of sensor utilization in differential protection application was the presumption that sensor with extended cable length cannot be used, the tests have been carried out to refute this fallacy.

Type test setup

The current sensors were measured using a type test setup based on the same commercial system from ZERA Gmbh but with different generator and with a TETTEX current transformer (CT) reference. The current sensors were based on existing products using Rogowski coil technology. The test circuit for accuracy measurements in steady state corresponds to the one described in IEC 60044-8, 2002.

The voltage sensors were also measured using a type test setup based on a commercial system from ZERA Gmbh and a voltage transformer (VT) reference. The voltage sensors investigated are based on existing products and use a resistive divider principle.

Burden of sensors was in all cases set to 10MΩ.

Results

Influence of four different cable lengths on accuracy of both current and voltage sensor has been investigated. Cable lengths used were: 6.5m, 20m, 50m and 100m. Three sensor samples have been used with each cable length. Measured results of amplitude and phase error are nearly identical for all sensors and are summarized in Fig. 5.

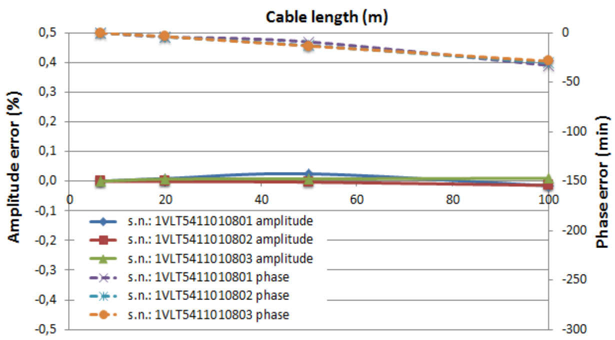

Fig. 5 Amplitude and phase error variation of current sensor with different cable lengths.

It has to be mentioned, that the sensor used was originally designed for operation with 6.5m cable length. It is evident that for different cable lengths the current sensor does not need any correction of amplitude accuracy to be introduced to a given IED, in order to reach high accuracy, nevertheless if very high accuracy is of concern, corrections mentioned in Tab. 1 could be used.

Cable length	Correction factor adjustment			
	V-sensor		I-sensor	
	amplitude	phase	amplitude	phase
6,5m	1,0000	0	1,0000	0
20m	1,0007	34	1,0000	4
50m	1,0025	113	0,9999	12
100m	1,0066	242	1,0001	31

Correction factors - available limit range in IEDs			
0,9000-1,1000	± 300	0,9000-1,1000	± 300

Tab. 1 Correction factor adjustments required for use with different sensor cable lengths

In case the accuracy of the full measuring chain is of our interest [2], influence of different cable lengths could be easily corrected within an IED. Therefore, the IED error would be significantly less than shown in Fig. 5.
In the case of voltage sensors, the effect of different cable lengths is a bit bigger. Measured results of amplitude error are summarized in Fig. 6.

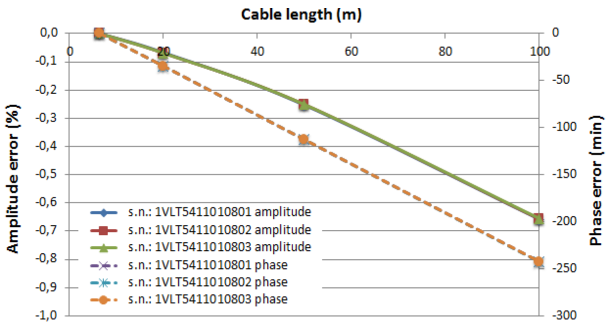

Fig. 6 Amplitude and phase error variations of voltage sensors with different cable lengths.

It has to be again mentioned, that the sensor used has been originally designed for operation with 6.5m cable length. Longer cables have been also connected and used during our investigation. Even though one can see a very small variation of accuracy with different cable lengths, the value of this variation is well known, stable in all cases and could be, for known cable length, further easily corrected by changing the correction factor within the IED. Required correction factor adjustments are again summarized in Tab. 1.

EMC tests

In order to verify performance of sensors with different cable lengths in harsh environments, also EMC tests have been performed, for all voltage and current sensors and all cable lengths investigated, in order to prove suitability for application at power systems. EMC tests have been performed on a sensor connected to the IED, which fully corresponds to the real application in service. Example of electromagnetic field immunity test setup is shown in Fig. 7.

Fig. 7 Electromagnetic field immunity test

It has been proved that connection of such sensors together with IEDs does not cause any EMC issues, which confirms suitability for differential protection applications, showing significant benefits in setting up of the IED and the use of standardized sensors. In case one combines this verification with accuracy tested for the whole measuring chain described before, it is possible to create very reliable information about network situation and improve accuracy of protection functions, such as e.g. differential protection.

CONCLUSION

It is concluded that excellent performance and functionality is offered by the combination of Low-power stand-alone sensors and modern IEDs. The IEC 61850-9-2 output format provides easy interoperability as well as an excellent means to test the accuracy of the whole measuring chain. Excellent linearity is reached by the whole measurement chain and both protection and metering accuracy classes are ensured over a wide range of rated currents and voltages. The overall metering accuracy class 0.5 is fulfilled with high margins by the combination of the latest designs of MV current and voltage sensors and IEDs. The excellent accuracy and IEC 61850-9-2 output format is believed to enable optimized implementations of functions like differential protection.
However, present sensor and IED products are also good candidates for application in differential protection, as shown by the accuracy and EMC tests performed even with long sensor cables up to 100 m. In fact, Low-power stand-alone sensors show installation and operation benefits in comparison to current transformers as the protection function itself can be optimized without having to care about saturation effects.
In the short term, Low-power stand-alone sensors and IEDs are still offering improvements in protection applications. In the longer term, improved accuracy of the whole measuring chain and IEC 61850-9-2 communication will open a full range of possibilities for protection, metering, and power quality.

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