HIGH ACCURACY MEASUREMENT CAPABILITIES INTEGRATED INTO RECLOSERS FOR MV POWER NETWORKS

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ABSTRACT

This paper presents the study of uncertainty on a recloser with high accuracy capabilities in the measurements of electric quantities. The fundamental elements of the recloser will be presented and the proposed uncertainty analysis will be described. It will be shown that the uncertainty evaluated using experimental results is correctly within and numerically consistent with the uncertainty interval evaluated using the procedures reported in the Guide to the expression of Uncertainty in Measurements (GUM). This procedure will be proposed for inclusion in the upcoming IEEE P1878 Standard "Measurements on Electric Power Systems: uncertainty evaluation and expression". The main conclusion of this paper is that the aforementioned procedure can be used successfully for forecasting the accuracy specifications in the design of new power systems.

INTRODUCTION

A smart grid must accomplish, among other things, the fundamental functions of providing intelligent energy management, real-time pricing, and intelligent diagnosis of network assets. It requires advanced intelligent monitoring and analysis that can anticipate contingencies and prevent local disturbances. All critical features of smart grids are made possible by the measurement of electrical quantities in many nodes of power networks combined in distributed measurement systems. The most critical aspect of smart grid operation is that measurement information be expressed in the correct terms and that it meet the standards that recommend a proper well-established uncertainty. Highly accurate voltage and current sensors are needed to allow for a proper and correct automatic control of electric grids and to gather necessary information for a deep monitoring and diagnosis of the network infrastructure.

Typical examples of quantities measured in power networks where high accurate measurement systems are required are voltage phasors, voltage and current fast transients (for TRV measurements, fault detection and locations [3]), and higher order harmonics (up to 30 kHz and beyond) for voltage and current pollution measurement in distributed generation, etc.

In order to accomplish a more intelligent, reliable and complete operation of the power network in the presence of distributed generation, G&W Electric and Altea B.V. present in this paper a new methodology for analyzing uncertainty of voltage measurements of the complete measuring system, as presented in Fig 1.

The recloser presented in this paper performs typical protection and control functions, but it can also perform a large variety of additional measurement functions, including the following:

- Energy measurements
- Power measurements
- Power quality measurements:
  - Harmonics and frequency components up to 30 kHz
    - Non-periodic events
    - Fast transients
- Fault detection and location
- Synchrophasors (for PMU integration)
- Partial discharges monitoring arising in the nearby accessories.

This paper will focus on the analysis of uncertainty affecting the measurement results according to the rules described in the Guide to the expression of Uncertainty in Measurements (GUM) [1, 5]. It will be demonstrated that uncertainty analysis performed by experiments has been correctly performed. The proof is given by the verification that the experimental uncertainty values obtained fall within and are numerically consistent with the uncertainty interval evaluated by using the procedure described in the GUM – Supplement 1 [5]. All the procedures described will be proposed to be included in the upcoming IEEE P1878 Standard "Measurements on Electric Power Systems: uncertainty evaluation and expression" [2].

The paper is organized as follows: a description of the whole recloser, along with some specific characteristics of each item; the measurement setup used for experimentally evaluating the measurement uncertainty of the whole measurement system; an illustration of experimental and simulation results and comments on them. The paper ends with conclusions that can be drawn.

RECLOSER WITH HIGH ACCURACY VOLTAGE MEASUREMENT CAPABILITIES

Fig.1 is a schematic block diagram of the recloser under consideration. It consists of 6 AccuSense voltage sensors (developed by Altea B.V and G&W Electric Co), Viper-ST recloser, junction box, and SEL-651R Relay, installed inside the control enclosure. A description of each component follows:

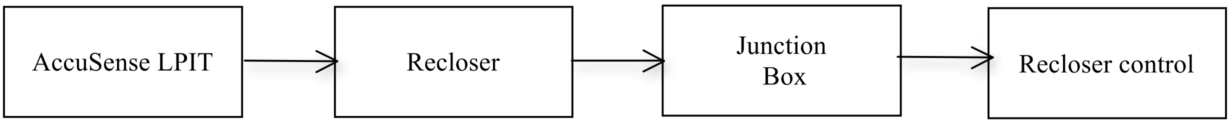

Fig. 1: Block Diagram of the recloser system capable of highly accurate voltage measurement.

AccuSense is an active electronic, low power instrument transformer (LPIT). It is a capacitive voltage divider with a transformation ratio of 1:5000. It weighs 1.8 kg. The electronic circuit installed inside the sensor conditions the signals and provides temperature compensation. The AccuSense sensor can be used for different voltage ratings (up to 38 kV) and features high accuracy (up to class 0.2) over a wide temperature range (-40 to +65C) or class 0.1 in a narrower temperature range (-10 to +55C); the bandwidth ranges from 30Hz to 30kHz (-1dB). Such sensors are used for measurements as well as protection applications. It can come with a supplementary output with bandwidth 50kHz – 30MHz for high frequency phenomena measurements, like partial discharges and fast voltage transients, and for fault analysis.

The **Viper-ST recloser** is a fault-interrupting device rated for 38kV, 630A or 800A, 12.5kA symmetrical interrupting. It combines the proven reliability of electronic control and vacuum fault interrupters with the benefits of a maintenance-free solid dielectric insulated device.

- It has 3 distinct mechanical operation modes: 1-phase trip / 1-phase lockout, 1-phase trip / 3-phase lockout or 3-phase trip / 3-phase lockout.
- It provides protection for systems through 38kV maximum, 630A or 800A continuous current and 12.5kA symmetrical interrupting.
- It has 6 built-in voltage sensors with 4% accuracy. AccuSense LPITs are used when higher accuracy voltage measurements are required.
- It is tested for compliance to the IEC 62271-111 / IEEE C37.60 standard.

The **junction box** serves the following functions:

- To supply power to the sensors;
- To convert the differential-mode signal provided by the sensors into single-ended-mode signals.
- To bypass the signals from the current transformers.

Here are some of the main features of the **SEL-651R-2 relay**:

- Reclosing Control: it applies four-shot reclosing with sequence coordination, synchronism check, and voltage check.
- Phase and Ground Directional Elements: it trips forward or reverse faults for overcurrent protection.
- Low-Energy Analog (LEA) voltage Inputs: it reads three or six LEA inputs (AccuSense included).
- It determines the real or reactive power flow direction and magnitude.
- Built-In IEEE C37.118 synchrophasors measurements: it measures synchrophasors in distribution applications.
- Fault Location: it provides distance-to-fault measurements using the impedance-based fault locator.
- Metering and Power Quality (PQ) Monitoring: it measures fundamental, power factor, RMS, energy, maximum, minimum and instantaneous peak demand metering data. It also measures harmonics up to the 16th component.

It features a 0.2% ratio error (up to 8V for LEA inputs) and 0.5° phase error on the instantaneous voltage measurement; 0.1% of reading (up to 2A) ±0.5 mA for the current measurements. It also features 1.2% on the rms value of the voltage (up to 8V for LEA inputs) and 0.2% of reading (up to 2A) ±0.5 mA for the current.

Figs. 2-4 illustrate the AccuSense LPIT, the Viper-ST recloser (as well as the Junction Box and AccuSense LPITs) and the SEL-651R-2 Relay.

Fig. 2: AccuSense LPIT

PROPOSED PROCEDURE FOR VOLTAGE UNCERTANTY MEASUREMENTS

As described in the Introduction, our purpose was to test a procedure for evaluating the propagation of uncertainty in measurements performed by complex systems operating in a power network including LPITs [4, 5]. A series of measurements were carried out at the G&W test facility to evaluate the accuracy performance of the realized recloser.

The present work presents only the evaluation of uncertainty in the rms voltage measurement at fundamental frequency. However, further investigation on uncertainty evaluation in current measurements as well as at harmonics continues.

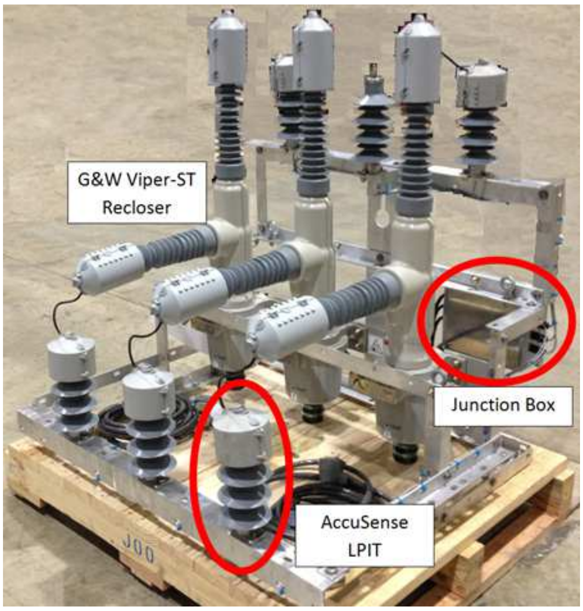

Fig. 3: Viper-ST recloser, including the junction box and the AccuSense LPITs

Fig.4: SEL-651R-2 Relay

To conduct an experimental analysis of uncertainty in measurements performed by the presented recloser, a proper measurement setup was assembled.
Fig. 5 is a schematic block diagram of the test bed. The reference voltages were provided by the Fluke 5700A Multiproduct Calibrator featuring a full-scale voltage of 1100V and an accuracy in the range of interest (330–1020V according to the product specifications) of 0.2% of output + 500μV.
The Calibrator provides a single-phase output, so it was simultaneously connected to three AccuSense sensors of the recloser and the uncertainty propagation was studied on the three channels.
As mentioned previously, the junction box supplies power to the sensors as well as converting the output signals from the sensors from differential mode into referenced single mode. This function was implemented by using the general purpose, unity-gain differential amplifier AD8276. The error introduced by such a component in the *rms* evaluation of the voltage has been verified to be negligible, so it will not be considered in the uncertainty propagation study through the measurement blocks.
Furthermore, due to the limited amplitude of the output voltage of the Calibrator and taking into account the transformation ratio of the sensors, the voltage amplitude at the input of the Relay was too low. This resulted in an undesired quantization error and then a large error in the *rms* value. It was then decided to use a very accurate three-phase voltage-current amplifier (shown in Fig. 6) designed by Altea with a voltage gain 1:50/sqrt(3). Only the voltage stage was used for the tests. The ratio error of such an amplifier has been verified as negligible (on the order of 1/10000) with respect to the uncertainty contributions, mainly due to the sensors and to the Relay.
A PC was connected to SEL-651R-2 and set up to collect and download all the measurement results automatically. Off-line data analysis followed.

Experimental results

As mentioned previously, this paper reports only the error analysis performed at fundamental frequency. For each voltage value applied to the sensors, 100 measurements have been acquired. In this way, mean value and standard deviation have been evaluated in order to apply the Type A method of the GUM, which requires performing statistical analysis of a given sample of repeated measurements in order to take into account the contributions to uncertainty due to random sources of error like temperature, electromagnetic interferences,

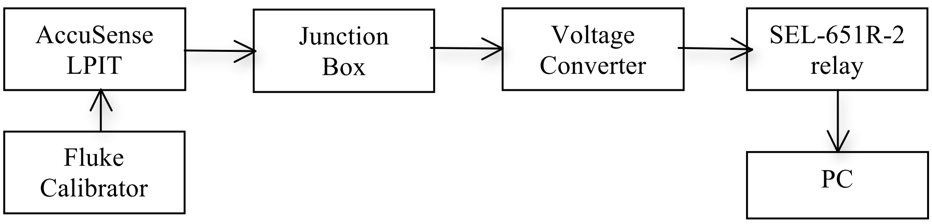

Fig.5 –Schematic block diagram for the analysis of the uncertainty of the voltage measurements

operator actions and so on. The standard deviation of the sample of measurements is known as *Standard Uncertainty* u_A and represents one of the two components of the so-called *Combined Standard Uncertainty* u_c. Usually this value is expressed "per unit" (p.u.) and is given by the ratio between the standard deviation and the expected value of the probability distribution of the random variable represented by the instrument reading. However, given that the mean value is a corrected and consistent estimator of the expected value of a random variable, then it is assumed to be an efficient estimator of

Fig. 6: 3-phase voltage/current amplifier

the expected value and represents the value attributed to the measurand. In this case then, the Standard Uncertainty u_A is relevant to the mean value. According to the Central Limit Theorem, the standard deviation on the mean value is given by the standard deviation of the sample divided by the square root of the number of elements in the sample.

The second contribution to u_c is obtained by using a different method, referred to as the Type B method. It allows taking into account the contribution of all the systematic effects arising within the measurement system, such as those due, for instance, to the non-ideal behaviour of components, to strain capacitances and inductances, and also due to the operator action. This second contribution to u_c is referred to as u_b, and, like u_a, it is also expressed in p.u. as the ratio of the difference between the instrument reading and the reference value divided by the reference value.

According to GUM, the uncertainty u_c is then given by the following expression:

$$u_c = \sqrt{u_a^2 + u_b^2} \tag{1}$$

The mean value of the measurements is then compared with the rms value set on the calibrator in order to evaluate u_b. This term is commonly known as *ratio error* η and is evaluated by means of the following equation:

$$\eta = \frac{U_R - U_m}{U_R} \tag{2}$$

where U_R is the rms value of the reference voltage and U_m is the mean value of the acquired measurements.

The operation of having evaluated the mean value of the acquired measurements for evaluating (2) has made it possible to evaluate the ratio error due only to the systematic contributions to uncertainty arising in the hardware and to filter away all the random contributions, which represent the term u_a of the combined uncertainty u_c.

The whole test setup is shown in Figs. 7a and b.

a)

b)

Fig. 7 – a) Three AccuSense LPIT along with the junction box (red circle); b) SEL-651R-2 Relay and the voltage-current amplifier (yellow circle)

The results:

- By applying 1000V to the three sensors at 60Hz, in the worst case (among the readings of the three channels of the relay), the mean value of 100 measurements has been 1000.35V. According to the aforementioned considerations, the standard uncertainty u_A is given by the standard deviation of 100 measurements divided by 10 and it is equal to 0.0038V, i.e., 4e-^{6} in p.u.. The ratio error has been equal to 3e^{-4} in p.u..
- By applying 1100V to the three sensors at 60Hz, in the worst case, the mean value of 100 measurements was 1099.14V. The Standard Uncertainty u_A on the mean value was 0.0045V, equal to 4e^{-6} in p.u.. The ratio error was equal to 6e^{-4} in p.u..
- By applying 800V to the three sensors at 60Hz, in the worst case, the mean value of 100 measurements was 800.25V. The Standard Uncertainty on the mean value u_A was 0.0029V, equal to 4e^{-6} in p.u.. The ratio error was equal to 3e^{-4} in p.u..

Based on these results, the combined standard uncertainty u_c in p.u on the rms voltage measurements at fundamental frequency is:

$$u_c = \sqrt{u_a^2 + u_b^2} = \sqrt{(4e^{-6})^2 + (6e^{-4})^2} \approx 6e^{-4} \tag{3}$$

Determination of the maximum standard uncertainty u_b for the recloser

Such results have been compared with simulation results. According to Supplement 1 of the GUM [5], a Monte Carlo simulation was carried out with 10000 trials for evaluating the standard uncertainty u_b. A set of random variables with uniform distribution (according to the principle of maximum entropy) were generated, one for every uncertainty term reported in the accuracy specification sheets provided by the device's manufacturers. Such random variables varying between -/+ the value reported in the sheets. For the AccuSense LPIT, the considered ratio error has been $2 \cdot 10^{-3}$, so a random variable with uniform distribution between $-2 \cdot 10^{-3}$ and $+2 \cdot 10^{-3}$ has been generated. For the SEL-651R-2, a ratio error of $2 \cdot 10^{-3}$ was used. Hence a random variable with uniform distribution between $-2 \cdot 10^{-3}$ and $+2 \cdot 10^{-3}$ has been generated. All the other error contributions have been considered negligible, resulted always in the order of 10^{-4}

Fig. 8 shows the simulation results for the reference voltage of 1000V. The mean value represents the estimate of the instrument (recloser) reading; the spread of the results is representative of the uncertainty term u_b, which, in turn, is representative of the ratio error of this system type. The frequency distribution is symmetrical.

By considering the 95% of confidence level for the measurement results, the associated confidence interval is found to be in the range [996.9 – 1003.1] V. The standard uncertainty u_b is then $6.2 \cdot e^{-3}$. The conclusion is that a system as presented in this paper features a ratio error on the voltage rms value ranging from -/+ $3.1 \cdot e^{-3}$ around the estimate of the measurand. The system used for experiments performed very well and its measurement uncertainty fell, as expected, into the above range.

A second simulation has been carried out for a rated voltage of 800V. Fig. 9 shows the simulation results for this test. Also in this case the standard uncertainty u_b with a confidence level of 95% is -/+ $3.1 \cdot e^{-3}$, being the associated confidence interval equal to [797.5 – 802.5]V. The actual measurement uncertainty again fell into the above range.

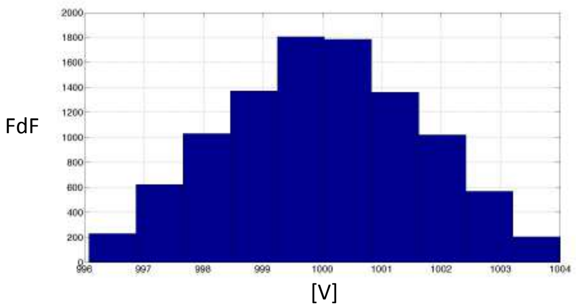

Fig. 8: Simulation results: frequency distribution function (FdF) of the instrument readings, rated voltage =1000V

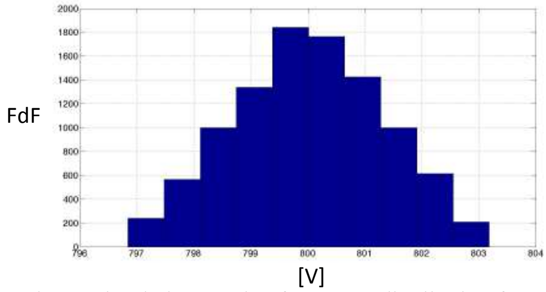

Fig. 9: Simulation results: frequency distribution function (FdF) of the instrument readings, rated voltage =800V

CONCLUSIONS

This paper presented an investigation on uncertainty analysis in measurements performed by a recloser with high accuracy capabilities and using LPITs. Particular care was given to the development of the voltage sensors, as well as to all electronic circuitry for conditioning their output signals. Uncertainty analysis has been studied according to the recommendations of the GUM. Furthermore, measurement uncertainty has been obtained by means of simulations according to Supplement 1 of the GUM. Experimental results have shown that measurement uncertainty of the presented recloser is very low and is correctly within and numerically consistent with the uncertainty interval of such devices: -/+ $3.1e^{-3}$.

The presented recloser features then very accurate rms voltage measurements. Moreover the procedure reported in the GUM can be successfully used in the design stage of power measurement systems that employ LPITs for forecasting measurement uncertainty.

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