A Calibration System for Instrument Transformers with Digital Output

JON IVAR JUVIK

Department of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

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Abstract

Accurate measurement of power and energy is important in the electrical power system. The measurement of voltages above 1 kV and currents above 100 A is made through instrument transformers. Lately new types of instrument transformers with digital outputs have reached the market. Although the actual sensing element may still be a classical transformer an A/D conversion takes place at some stage, and the secondary signal becomes available only as a digital signal.

The A/D-conversion and data processing introduce a time delay. This delay and the digital output necessitate a new and different calibration method to prove that the desired accuracy has been achieved. This is particularly important for the measurement of the phase displacement or phase error.

The main part of this work describes the development of a system for the calibration of instrument transformers with digital output. The system is based on already established high-voltage standards combined with a separately verifiable A/D-converter and specialised software. The system is optimised for calibration with 50 Hz sinusoidal current or voltage and the measurement uncertainty is found to be less than 0.01 % uncertainty for ratio and less than 0.4 min for phase with a 95 % confidence level. These uncertainties are a factor five times less than those obtained for industrial calibration systems and hence sufficient for the calibration of the references used in these systems.

International standardisation of non-conventional instrument transformers is on its way, but at the moment manufacturers use different digital protocols. The new calibration system is primarily designed for operation with the digital protocol proposed in the draft for the new standard IEC 60044-8, but may also handle other protocols with a few alterations to the software.

An evaluation of the measurement uncertainty in an industrial calibration system has also been performed. This system is intended for the calibration of transformers of at least accuracy class 0.2, and the estimated uncertainty is found to be adequate for this purpose.

An on-site, long-term comparison between a conventional measurement system and a system based on non-conventional transformers has been started. The result from the first period is investigated and differences between these systems are found to be within the theoretical estimated interval and well within the accuracy requirements valid for a measurement system in the grid.
Keywords: calibration, phase measurement, phase displacement, phase error, measurement uncertainty, instrument transformers, current transformers, potential transformers, digital signal processing
Acknowledgements

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ABB Switchgear and ABB Power Systems through Morgan Adolfsson and Martin Nilsson have shown the author a remarkable openness and given the opportunity to get in contact with the real world of non-conventional instrument transformers. This possibility has also been given through Statnett and ABB’s project “Optical measurements” in Hadeland substation. Here the author again likes to express his thanks to the project leader Elizabeth Romansky, not only for the work on the Hadeland project, but also for her great support and enthusiasm at every level of the research.

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</table>
0 Definitions, terms and abbreviations

0.1 Metrological definitions
Taken from [1] (definition number)

**traceability** (6.10)
property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

**measurement uncertainty** (3.9)
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

**calibration** (6.11)
set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.

**error (of measurement)** (3.10)
result of a measurement minus a true value of the measurand

**(measurement) standard** (6.1)
material measure, measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference.

**national (measurement) standard** (6.3)
standard recognized by a national decision to serve, in a country, as the basis for assigning values to other standards of the quantity concerned.

**reference standard** (6.6)
standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived.

**measuring system** (4.5)
complete set of measuring instruments and other equipment assembled to carry out specified measurements

**measuring transducer** (4.3)
device that provides an output quantity having a determined relationship to the input quantity

### 0.2 Definitions for electrical instrument transducers

Taken from [2]. (definition number)

**merging unit (MU) (3.1.9):**
Physical unit used to do the time coherent combination of the current and/or voltage data coming from the secondary converters. The merging unit can be part of one of the transducers in the field or may be a separate unit e.g. in the control room.

**phase displacement ($\varphi$) (3.1.26):**
For analogue output, the difference in phase between the primary current phasor and secondary output phasor, the direction of the phasors being so chosen that the angle is equal to its rated value at the rated frequency for a perfect transducer. The phase displacement is said to be positive when the secondary output phasor leads the primary current phasor. It is usually expressed in minutes or centiradians. [IEV 321-01-23 modified]

\[ \varphi = \varphi_s - \varphi_p \]

Where:
- $\varphi_p$ is the primary phase displacement;
- $\varphi_s$ is the secondary phase displacement.

For digital output, the time between the instant a certain current is present at the primary terminals and the instant the transmission of the belonging digital data set starts (expressed in angular units relative to the rated frequency).

**Notes**

1. This definition is strictly correct for sinusoidal current only;
2. For both analogue and digital output, the phase displacement $\varphi$ can be considered to be made up of two components: the rated phase offset $\varphi_{0r}$ and the rated delay time $t_{dr}$;
**phase error** \((\varphi_e)(3.1.29)\)
The phase error is the phase displacement minus the displacement caused by the rated phase offset and the rated delay time. The phase error is relative to the rated frequency.

\[
\varphi_e = \varphi - \varphi_{0r} + 2\pi f t_{dr}
\]
For digital output intended to be synchronised with clock pulses:
The phase error is the time between a clock pulse and the sampling of the primary current belonging to the corresponding digitally transmitted value (expressed in angular units relative to the rated frequency).
The phase error is usually expressed in minutes or centiradians.

**current error** (ratio error) \((\varepsilon\% )\)
The error which an electrical current transducer introduces into the measurement of a current and which arises from the fact that the actual transformation ratio is not equal to the rated transformation ratio. [IEV 321-01-21 modified].
For analogue output, the current error expressed in per cent is given by the formula:

\[
\varepsilon\% = \frac{K_{ra} U_s - I_p}{I_p} \times 100
\]

Where:
- \(K_{ra}\) is the rated transformation ratio;
- \(I_p\) is the r.m.s. value of the actual primary current when \(I_{pres}(t) = 0\);
- \(U_s\) is the r.m.s. value of secondary converter when \(U_{sdc} + u_{sres}(t) = 0\).

NOTE - This definition is only related to components at rated burden and rated frequency of both primary current and secondary voltage. This definition is compatible with IEC 60044-1.

For digital output, the current error expressed in per cent is given by the formula:

\[
\varepsilon\% = \frac{K_{rd} I_s - I_p}{I_p} \times 100
\]

Where:
- \(K_{rd}\) is the rated transformation ratio;
- \(I_p\) is the r.m.s. value of the actual primary current when \(I_{pres}(t) = 0\);
- \(I_s\) is the r.m.s. value of the digital output when \(I_{sdc}(n) + I_{sres}(t_n) = 0\).

Note - The current error is the result of a digital calculation.
rated delay time \(t_{dr}\) (3.1.27)
The rated value of time needed for digital data processing and transmission.

rated phase offset \(\varphi_{or}\) (3.1.28)
A rated phase displacement of the ECT due to the technology employed and which is not affected by the frequency.

electrical instrument transducer (3.1.1):
An arrangement consisting of one or more current or voltage sensor(s) which may be connected to transmitting systems and secondary converters, all intended to transmit a measuring quantity in a proportional quantity to supply measuring instruments, meters and protective or control devices. In case of a digital interface this is done by using a merging unit for a set of electrical instrument transducers.

electrical current transducer (ECT): (3.1.2)
An electrical instrument transducer in which the output of the secondary converter in normal conditions of use is substantially proportional to the primary current and differs in phase from it by a known angle for an appropriate direction of the connections.

primary terminals: (3.1.3)
The terminals through which the current to be measured flows.

primary current sensor: (3.1.4)
An electric, electrical, optical or other device intended to transmit a signal corresponding to the current flowing through the primary terminals to the secondary circuit, either directly or by means of a primary converter.

primary converter: (3.1.5)
An arrangement that converts the signal coming from one or more primary current sensors into a signal suitable for the transmitting system.
**secondary converter (SC):** (3.1.8)
An arrangement that converts the signal transmitted through the transmitting system into a quantity proportional to the current between the primary terminals, to supply measuring instruments, meters and protective or control devices. For ECTs with analogue output the secondary converter directly supplies measuring instruments, meters and protective or control devices. For electrical instrument transducers with digital output the secondary converter is generally connected to a merging unit before supplying the secondary equipment.

---

### 0.3 Other terms

**IEEE488-bus**
A common bus interface system for instruments, also known as GPIB or HPIB

**Sampling**
A discretisation or digitising process, where a continuous signal is turned into a sequence of numbers. When measuring, an analogue-to-digital converter does this.

---

### 0.4 Abbreviations

**CT:** Current Transformer

**VT:** Voltage Transformer

**MSB:** Most Significant Bit

**SP:** SP Swedish National Testing and Research Institute

**A/D converter:** Analogue-to-digital converter

**RMS:** Root-Mean-Square

---

### 0.5 References

1. BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML. *International vocabulary of basic and general terms in metrology.* 1993, ISO.
1. Introduction

Electrical energy is transmitted from the production sites to the consumers by power lines at different voltage levels. Current and voltage are measured both for revenue and protection purposes. The measurement of voltages above 1 kV and currents above 100 A is done through instrument transformers.

The instrument transformers basically have had the same design for generations. However, the last decades a large amount of research has led to new designs based on different measurement principles.

Conventional transformers are bulky and have some restrictions to their measurement properties. The new non-conventional instrument transformers are generally smaller in size and avoid some of the restrictions in measurement properties seen in the conventional.

1.1 Conventional Instrument Transformers

Conventional voltage transformers (VTs) for AC-systems are voltage dividers of either the capacitive or the magnetic type. Their secondary output is in the range of 100 volts.

Conventional current transformers (CTs) are normally of the ring-core type. This means that the current is detected through a winding wound on the outside of an iron core encircling the primary conductor. The secondary output is a current with a nominal value of 1, 2 or 5 ampere.

Both voltage and current transformers are voluminous objects since full system voltage insulation must be ensured between the primary and secondary side. With the oil-insulated hairpin types of CT’s, the possibility of an explosion due to short-circuit is also considered to be a risk by some utilities.

Due to the iron in the conventional transformers ferro-resonance might occur when the primary voltage or current contain frequencies different from the fundamental frequency of 50 or 60 Hz. This phenomenon is particularly disturbing in VT’s, where the frequency response of the transformers shows a strong variation already at 300 Hz [1],[2]. This causes problems both for the ratio and phase measurements since the frequency response is dependent not only on the type of transformer, but also on the burden connected at the secondary side.
An additional consideration is that the output from these transformers is unnecessarily high (in the order of 300 W). Modern relay and meter technology needs only a fraction of the power mentioned.

The present state of the art makes it now possible to develop a new generation of instrument transformers that omits many of the problems mentioned above that follows from the conventional technology.

### 1.2 Non-conventional Instrument Transformers

The technology used in non-conventional instrument transformers varies between manufacturers and models. One of the advantages that is shared by many model is that they generally are a significantly smaller than their conventional counterparts, both in weight and dimension. This reduction in size is most often made possible since fibre optic transmission is used, and the high-voltage insulation can be simplified.

The optical measurement principle considered to be most feasible for non-conventional current transformers is the Faraday-effect. This principle is based on the change in phase in linearly polarized light when exposed to a magnetic field. The Pockels-effect, which is used for voltage measurements, is similar since it is based on a phase shift between two orthogonal oriented linearly polarised lights exposed to an electric field. Other technologies used in non-conventional instrument transformers partly apply traditional transformer techniques but the secondary output might be analogue with lower values than conventional transformers, or it is digitised at some point inside the transformer unit itself. In many designs optical fibre is used for the signal transmission from high potential to the control room. This simplifies the isolation since the optical fibre itself is non-conducting as opposed to electrical cables.

Today non-conventional instrument transformers are available as commercial products on the market. The main restriction is the problem of interfacing the new transformers with existing equipment in the substations. Because of this the market for non-conventional Instrument Transformers is limited to sites were a completely new substation is built. Another restriction is the lack of standardisation of the secondary output. This makes it difficult for utilities to combine a transformer from one manufacturer with meters and relays from another. The standardisation work is well underway and a new IEC standard describing both analogue and digital output is in its final stage of preparation and may be released soon [3].
1.3 **Calibration of Instrument Transformers**

The conventional instrument transformer is calibrated using an analogue bridge and a reference test transformer. With some modifications this method can also be used for non-conventional instrument transformers with analogue output. The accuracy of this kind of calibration is suitable to calibrate transformers of accuracy class 0.2 and 0.2S, which are the highest classes for commercial voltage and current transformers respectively.

However, when the secondary output is a digital signal other methods must be used. Theoretically the signal could be D/A-converted and calibrated with the analogue bridge method, but the time delay introduced by the repeated conversions will cause a phase displacement that is outside the handling range of the standard analogue bridges. Instead, one of the solutions is to make an analogue bridge. This is a measuring system that digitises the output from a reference standard and mathematically compares this signal with the output from the non-conventional transformer. The manufacturers have developed such systems to calibrate their own products [4-6]. In appendix 2 it is shown that such a system is able to calibrate a non-conventional current transformer with a ratio uncertainty of ± 0.04 %.

The calibration system described in this thesis is designed to be used at an even higher accuracy level. It is also designed to be able to calibrate non-conventional transformers with digital output using different protocols.

To achieve as low uncertainty as possible the reference standards used are of highest achievable accuracy, and calculations are performed with methods ensuring that all known measurement errors may be corrected for.

1.4 **Literature**


Chapter 1


2. **Non-conventional Instrument Transformers**

Some of the measurement principles employed in non-conventional instrument transformers are described in appendix 1. A more thorough analysis by other authors of non-conventional current transformers can be found in [1] and of methods for both voltage and current measurements in [2]. This chapter focuses on the particulars of instrument transformers with digital output that have to be taken into account during calibration. Since the concept of conventional transformation not necessarily is employed in the non-conventional types, the expression transducer often replaces transformer. When the notation (secondary) signal is used without any other specification it indicates either an optical or electrical signal that can be either analogue or digital.

### 2.1 What is a non-conventional instrument transformer?

Today a number of different sensors and technologies are used which are gathered under the general umbrella of non-conventional instrument transformers. They range from traditional cores and dividers having an output at lower levels than present day standards, via air core coils to optical units employing electro- or magneto optical effects. Each technology has its advantages and disadvantages. The future will probably show that each different technology will be used in the areas where their specific advantages are useful.

Since the technology on which the sensing element is based diverse in the different non-conventional instrument transformers, the signal treatment between primary sensor and merging unit varies widely. The most straightforward signal path is found in transducers with a low-level analogue output, where for instance a voltage representing a transformation of the primary current or voltage can be measured directly over a fixed burden. The most complicated signal path may also be found in transformers with analogue output, if the signal passes through both A/D and D/A converters in addition to filtering and/or other signal treatment as for instance down-sampling or transformation to and from the frequency domain. A transducer with digital output is normally somewhere in-between. Since the primary signal is analogue digital sampling has to take place. How much additional filtering, analogue or digital, or transformations performed on the signals depends on the chosen technology and also on how the values are to be used.
2.2 Merging Unit (MU)

The merging unit is something new compared to conventional instrument transformers. As shown in figure 1 (taken from [3]) the merging unit receives the signals from all transducers in a bay. In the figure 3 Electrical Current Transducers (ECT) for measurement, 3 ECTs for protection and 3 Electrical Voltage Transducers (EVT) are shown. In addition one ECT for the neutral line and two EVTs for neutral and busbar respectively are included. One of the merging units main tasks is to convert the received transducer signals into the standardised outputs.

Another task, just as important, is to synchronise the signal samples to be used within one protocol in time. This is either done by interpolation method or synchronised sampling. An interpolation method means that the current and voltage values are calculated to a specific common instance using interpolation between the samples and taking into account the known delay times in the individual transducers. Synchronised sampling, e.g. the ECTs and EVTs are sampled at the same instance, is achieved either with an internal clock or with external synchronising signals as for instance time pulses from a GPS controlling all transducers in the bay.

The merging unit is normally situated in the control-room of the substation or in a similar protected environment. From the merging unit output signals are sent to all the equipment utilising measured values. This means that calibration of non-conventional instrument transformers also have to be performed at this output.

In the standard [3] the actual sensing element and the signal treatment before the merging unit are considered to be manufacturer specific. This choice is made to ensure that the standard will not be a restriction on future development of the transducer technology.

Note: SC of EVT\textsubscript{a} is the secondary converter of the electrical voltage transducer of phase a (see IEC 60044-7). SC of ECT\textsubscript{a} is the secondary converter of the electrical current transducer of phase a.
2.3 Standardised digital output

In the proposed standard [3] the digital output is described in detail. This includes of course also the rated values. Often the only difference between measurement values and protection values is the dynamic range chosen in the digitising of the signal. The standard takes this into consideration by setting two different rated values. Rated current or voltage equals the hexadecimal number 2D41 H (=decimal 11585) for measuring and the hex number 01CF H (=decimal 463) for protection.

The digital output proposed in the draft [3] is a protocol for a point-to-point link. This means that the data are continuously submitted with the given data rate directly from the merging unit to the relay, meter or other equipment. The data rates are given as multiples of the rated frequency \( f_r \) with proposed values 80\( f_r \), 48\( f_r \) and 20\( f_r \). The physical layer of the signal is in Manchester coding with standard transmission speed 2.5 Mbits/s with the most significant bit (MSB) transmitted first. With Manchester coding transition from low level to high level is read as binary 1 and transition from high level to low level is read as binary 0. Figure 2 illustrates this.

The proposed protocol’s link layer has been adapted from the format FT3, described in IEC 60870-5-1. The content of the frame is shown in figure 3 below.
### 2.4 Contents of the Frame

<table>
<thead>
<tr>
<th>Byte 1</th>
<th>Header</th>
<th>msb Number of blocks ( = 1)</th>
<th>lsb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byte 2</td>
<td>Block 1</td>
<td>msb Length of block ( = 43dec)</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Byte 4</td>
<td></td>
<td>msb Data group ( =02)</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Byte 6</td>
<td>General data</td>
<td>msb DataSetIdentifier (=01)</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 7</td>
<td></td>
<td>msb Source</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 8</td>
<td></td>
<td>Identifier</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 9</td>
<td></td>
<td>msb Rated Phase Current</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 10</td>
<td></td>
<td>(I_r)</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 11</td>
<td></td>
<td>msb Rated Neutral Current</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 12</td>
<td></td>
<td>(I_{nr})</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 13</td>
<td></td>
<td>msb Rated Phase Voltage</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 14</td>
<td></td>
<td>(U_r)</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 15</td>
<td></td>
<td>msb Rated Delay Time</td>
<td>lsb</td>
</tr>
<tr>
<td>Byte 16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Byte 1 | Dataset | msb Current Phase A, prot. | lsb |
| Byte 2 | | (A.PhsA) | lsb |
| Byte 3 | | msb Current Phase B, prot. | lsb |
| Byte 4 | | (A.PhsB) | lsb |
| Byte 5 | | msb Current Phase C, prot. | lsb |
| Byte 6 | | (A.PhsC) | lsb |
| Byte 7 | | msb Neutral Current, | lsb |
| Byte 8 | | (A.Neut) | lsb |
| Byte 9 | | msb Current Phase A, mes. | lsb |
| Byte 10 | | (A.PhsA) | lsb |
| Byte 11 | | msb Current Phase B, mes. | lsb |
| Byte 12 | | (A.PhsB) | lsb |
| Byte 13 | | msb Current Phase C, mes. | lsb |
| Byte 14 | | (A.PhsC) | lsb |
| Byte 15 | | msb Voltage Phase A | lsb |
| Byte 16 | | (V.PhsA) | lsb |
### Figure 3 - Universal Frame (From [3])

As seen in the figure the proposed protocol contains information about the transducer in addition to the measured values. The transmission of the rated values for current and voltage (byte 9 to 14 above) is optional. Two status words give information about malfunctioning and parity checks are possible to ensure that the received information is correct.

#### 2.5 Priorities

Since the data rate out from the merging unit is one of the rated values for a transformer with digital output, interrupts due to other data processing than the transmission are not supposed to happen. This means that both the processor in the merging unit and in the equipment receiving the data have to be able to operate at a higher internal speed to make sure that other necessary tasks can be performed between the data transmissions. For calibration purposes it might be feasible for the calibration system to postpone other operations until the determined number of values have been received. If the information is time tagged with reference to a common clock these considerations are not necessary for a calibration system working with a limited number of samples, since the data then can be sorted at a later stage in the process.
2.6 Restrictions

Even though the technology is still under development some restrictions are considered to be necessary on the manufacturer specific side of the transducers to make sure that the performance is satisfactory under all conditions. One of the proposals is that the anti-aliasing filter used before sampling should be standardised to a Bessel filter where the coefficients are given in the standard. This filter is supposed to have a good damping in the stopband and a close to linear phase response in the passband. Some consider this requirement unnecessary since these characteristics may also be achieved with other filters or signal treatment procedures. Their view therefore is that the manufacturers should be free to choose whichever solution they prefer. This view can be considered relevant since there is a requirement in the proposed standard that the manufacturer has to publish the frequency response for the transducer as a whole.

2.7 Literature

Chapter 3

3 Theoretical analysis

3.1 Background
In addition to the possibility of conventional phase displacement and ratio error, the A/D conversion and data processing in transformers with digital output incurs a time delay. This chapter will describe the influence this time delay has on the measurements of ratio and phase error. The phase error has a new definition in the proposed IEC standard [1] that replaces the conventional phase displacement as the erroneous component of the transformer with respect to phase.

3.2 Time delay, phase displacement and phase error
The change of phase angle when a voltage or current is transformed in instrument transformers is caused by inductive or capacitive components inherent in the transformer itself, either in the primary voltage or current transformation or from inductive or capacitive secondary components used to obtain the desired output values. The analogue phase shift does normally not have a constant value over the specified operating range or burden interval since the impedances change with the magnetisation of the transformers.

In transformers with digital output the secondary phase displacement is a combination of the analogue deviation and the deviation caused by the time delay in the digital part. The time delay in the digital part is to a large extent a constant that is independent of the measured primary value. In [1] the constant time delay is defined as one of the rated values and should be included on the marking plate and data-sheet for the transformer. Even though this is the standard for current transducers, IEC TC 38 has decided that the part regarding the digital output also shall apply for voltage transformers with digital output.

Phase displacement is used in this chapter for the total angle between the primary and secondary signal as seen by measurement. Phase error is sum of the phase displacement and the effect of the rated delay time.

The understanding of the rated time delay indicates that this value is independent of the frequencies in the measured signal. Whether or not this will be the case in all transducers depends on the technology used and especially if the chosen filters have a linear dependent phase shift for all frequencies of interest (e.g. all frequencies within the passband).
3.3 Phase displacement in conventional transformers

$K_r I_s$

$I_p$

Figure 1: Phase displacement in conventional transformer

In figure 1 $I_p$ is the primary current, $I_s$ is secondary current and $K_r$ is the transformation ratio.

The general definition for phase displacement based on polar co-ordinates for a conventional transformer is:

$\phi = \varphi_s - \varphi_p$

where

$\phi$ is the phase displacement (in the transformer)
$\varphi_p$ is the primary phase displacement
$\varphi_s$ is the secondary phase displacement

$\phi$ is according to the definition said to be positive if the secondary output phasor leads the primary current phasor.
Most analogue instruments used for calibration of instrument transformers use the Cartesian representation of the results. This means that the relative error vector is decomposed into its in-phase and quadrature component [2].

The phase displacement is shown in Figure 1 and Figure 2 as the angle between the two phasors. As $\sin \phi \approx \phi$ for small phase displacements (with the angle given in radians) the polar and Cartesian representation yield approximately the same result. In the analogue measurement case this phase displacement is the error contribution from the transformer with respect to the phase measurements.

### 3.4 Phase error in transformers with a rated time delay ($t_{dr}$)

In the case when the transformer has a digital output the phase displacement consists of two parts as shown in Figure 3. Since $t_{dr}$ is introduced by the IEC as one of the rated values for a transformer, and this time delay causes an additional change in phase angle, it is necessary to introduce a definition of phase error that differs from the phase displacement.
In figure 3 $I_p$ is the primary current, $I_s$ is secondary current and $K_{rd}$ is the rated transformation ratio.

The total phase displacement is still defined as in the analogue case

$$\varphi = \varphi_e - \varphi_{\rho}$$

The phase error definition in IEC [1] is

$$\varphi_e = \varphi + 2\pi f t_{dr} - \varphi_{\rho}$$

where:

$\varphi_e$ is the phase error,
$\varphi$ is the phase displacement,
$t_{dr}$ is the rated delay time,
$f$ is the frequency and
$\varphi_{\rho}$ is the rated phase offset

According to [1] $\varphi_{\rho}$ shall only be used for apparatus having air-core coils without integrators. Taking $\varphi_{\rho}$ equal to zero may be done in this work since for all other transformers the rated phase offset is defined to be 0°. For the air-core coil without integrator the rated phase offset is defined to be 90°. The implication of this is that any other phase offset has to be included in the rated time delay.

Figure 4 where the rated time delay is included, also illustrates the fact that the same arguments using $\sin \varphi = \varphi$ as used in [2] also may be applied on transformers with digital output as long the rated time delay is small. In [2] a total phase displacement of 9 mrad is shown to give an error in the estimate of ±0.054 mrad when using quadrature components.
However, when the rated time delay is large it will introduce a significant error in the measurements. Since most analogue bridges in one way or the other are based on the principles described above they are going to measure with an error. In addition there is normally a restriction on the range of the bridge or transformer test set. For a typical bridge the largest phase displacement allowed is around 700 min (200 mrad). When operating near this range the reading resolution of the bridges will decrease significantly.

The problem with a large phase displacement due to $t_{dr}$ is important to take into consideration if one designs a calibration system where the measurement is based on an analogue signal that is reconstructed from a digital output. For transformers with large $t_{dr}$, the delay then has to be compensated before performing the measurements with the bridge. In practice the analogue reference signal has to be delayed with some method. The possibility of introducing new errors seems to be very large with such a solution for a calibration system.

In most practical cases the secondary output phasor of a transformer with digital output will be lagging the primary current phasor (e.g. $\phi$ has a negative value). This will, as shown in the figure 5 below, cause the phase error to be less then the measured phase displacement since the correction for the rated time delay will work in the opposite direction of the phase displacement.
3.5 Ratio error

The ratio error for the conventional case is according to [1]:

\[ \varepsilon = \frac{K_r I_s - I_p}{I_p} \]

where
- \( K_r \) is the rated transformation ratio
- \( I_p \) is the RMS value of the actual primary current
- \( I_s \) is the RMS value of the secondary current

As shown in [2] the formula above is approximately equivalent to using the in-phase component of the Cartesian representation if the phase displacement is small. Similarly it is possible to show that for small phase displacements the Cartesian and polar form gives approximately the same result [2].

The ratio error definition for transformers with digital output is almost identical to the analogue definition

\[ \varepsilon = \frac{K_{rd} I_s - I_p}{I_p} \]

where
- \( K_{rd} \) is the rated transformation ratio
- \( I_p \) is the RMS value of the actual primary current
- \( I_s \) is the RMS value of the secondary digital output
To measure the RMS value from a reference system using sampling techniques and comparing the result with a digital output from a transformer requires only minor changes to already established calibration methods for high voltage systems. The analysis of the error definitions therefore indicates that the main difference in calibration systems is the measurement of the phase deviation (phase displacement and phase error).

\[
\varphi = 2\pi f t_{\text{dr}} + \varphi_e
\]

**Figure 6: Transformer under test (solid) and reference system (dashed)**

Figure 6 shows an example where the phasors from a digitised reference system are inserted in the same diagram as in Figure 5 with the secondary phasor lagging the primary phasor. The phasors shown with dashed lines represent the phasors for the reference system. Important to observe is that the phase displacement in the reference system consists of a component that has a constant time delay in addition to the change in phase angle caused by the analogue components in the system. What is actually measured in the system is the difference between the two phasors representing the total phase displacement of each system. In the figure these are shown as the two lower ones. Since both the time delay and analogue phase displacement in the reference system are known with good accuracy their contribution can be corrected for. The resulting phase error of the transformer under test is then found by adding the correction for the rated time delay to the measured phase displacement.

In the calibration system described in this work the analogue part is calibrated with bridge methods using the already established reference standards at SP.
Chapter 3

The determination of the time delay caused by sampling, reaction time and data processing in the reference system is described in chapter 5 (Determination of the time delay in the calibration system).

3.6  Calculations used in this work

To avoid the problems with a large rated time delay as describe above, the calculations for phase and ratio error in the system described in this work are done separately on stored samples representing the signals from the two systems. The phase difference between the two signals is measured as a time difference (in seconds), and all corrections for time delays and known phase displacements are done as time units, bearing in mind that the frequency is known.

The ratio error is calculated from the RMS-values of the two sampled signals and directly the formulas described above.

The details about these methods are found in chapter 4 (Design and construction of a calibration system for instrument transformers with digital output).

3.7  Literature


4 Design and construction of a calibration system for instrument transformers with digital output

In the design of a calibration system the most important issue from a metrological point of view is the choice of components that ensure that traceability can be achieved and that the measurement uncertainty can be kept as low as possible. In this context traceability means to link the calibration of the instrument transformers with digital output to the already established analogue high voltage standards. This is done by using a multimeter that is separately (and traceably) calibrated as A/D-converter in the calibration system.

4.1 Reference standard

SP has already established measurement standards for high voltage and high currents, which are traceable to the realisations of the primary units. The process for achieving this traceability can simply be described as a step-up chain starting from basic voltage and current levels. The whole process is performed by using analogue measuring techniques. In addition the reference systems are verified through intercomparison between national metrology institutes throughout the world.

In the system described these standards already established by SP are used as the primary sensing elements transforming the high voltage or current to levels suitable for A/D conversion. The uncertainty in the variables on the secondary or low-level terminals (side) of these standards will then be the same as when using them with analogue methods. Uncertainties introduced by the digitalisation process and computerisation should not be larger than those introduced in traditional analogue measurement techniques.

The most accurate AC-current standard at SP is the transformer test set Guildline 9900 with a compensated current comparator. This system is without any active electronic amplifiers and shows a very good stability over time and for all ranges.
For measurements of higher currents SP has a reference system based on a Guildline Current Transformer Test Set Model 9908 and a reference shunt. The reference shunt has a nominal resistance 10 mΩ. This gives a secondary output of 100 mV with 10 A primary. The voltage over this shunt is used as input to the reference AD-converter (see below).

The reference system for voltage is based on SP’s MWB Messwandler-Bau NUEO 400 Standard-Voltage-Transformer (figure 1). The calibration of this transformer shows a good long-term stability, the changes in error are less than \( \approx 0.001\% \) for ratio and \( \approx 0.1\) min for phase displacement. The measurement uncertainty in the calibration done in the year 2000 is \( 0.007\% \) for ratio and 0.4 min for phase. A major part of these uncertainties is due to uncertainty components introduced by the analogue secondary equipment used in the specific measurement. These can be omitted when calculating the uncertainty for the calibration system described in this work.

For a complete uncertainty budget see chapter 6 (Uncertainty Analysis).

### 4.2 Reference AD-converter

To ensure that the traceability is kept also in the digitising process a sampling multimeter is chosen as the Analogue-to-Digital converter. The multimeter (see Figure 2) is the same type as was used by S. Svensson in his Sampling wattmeter [1].

The advantage of using a separate instrument as an A/D converter is that it can easily be calibrated and separately verified. This is not the case with for instance PC-card based A/D converters. Since the multimeter is also an instrument that is used to a great extent in different measurement scenarios and environments, its long and short time stability and its behaviour is well documented.
A further examination of the multimeter’s behaviour regarding reaction and delay time is described in chapter 5.

4.3 Computing equipment

A standard PC is used to control the calibration system. Except for the availability of an IEEE 488 communication board no special requirements are necessary. The PC used today is an industrial computer of type ”Rabbit” with a Pentium Pro 200 MHz processor.

Control and calculation software is programmed in LabVIEW, which is based on the graphical program language G. The program triggers and reads the A/D converter in the reference system and synchronises the reading with the retrieving of data from the instrument transformer under test.

The program also performs the calculations necessary to determine the ratio and phase error of the transformer. The calculations follow the definitions given in [2], and are optimised for calculations for a 50 Hz near-sinusoidal signal. Minor deviations in the wave shape should be accepted without affecting the measurement result more than the stated measurement uncertainty.

4.4 Calculation methods
The calculations are divided in two separate sections, one for the ratio and one for the phase error. This is done to optimise the accuracy of the calculations. Both calculations use the same data set gathered during a pre-set sampling period.

4.4.1 Ratio error
The ratio error calculations are done by comparing the RMS value measured with the reference system and transformer. The algorithm for RMS calculation given below requires an integer number of periods to give a precise answer. In the system a phase-lock has not been used. This choice is made as it will not be possible for the calibration system to actively control the digital output from the transformer under test. Instead the calibration system uses a set of data that is time coherent with the data-set gathered from the reference transformer. An error will then be introduced if there is an imperfection in the synchronisation between the sampling rate and the fundamental frequency of voltage or current. To reduce this error introduced due to the lack of an integer number of periods a Hanning-transform\(^1\) is performed on the signal. The Hanning-transform is a cosine-window, which reduces the weight of the first and last samples in a data set as seen in Figure 3.

\(^1\) The original development and verification of the RMS-measurement module with Hanning-window was performed by Dr. Hong Tang at SP in 1999
**Figure 3 Example of 5 periods with and without the Hanning-window applied**

The Hanning window can be described by:

\[ y_i = 0.5x_i[1 - \cos(w)] \quad \text{for } i = 0,1,2,\ldots,n-1 \]

\[ w = \frac{2\pi i}{n} \]

y is the output sequence and x is the input sequence consisting of n elements.

The RMS value of a sampled sequence is defined as:

\[ v_{RMS} = \sqrt{\frac{1}{n} \sum_{i=0}^{n-1} x_i^2} \]

If the input sequence is

\[ x = A \cos(\omega T) \quad \text{with} \quad T = k \cdot \frac{2\pi}{\omega}, k = 0,1,2,\ldots,n-1 \]

the RMS value is then

\[ v_{RMS} = \frac{A}{\sqrt{2}} \approx 0.707A \]

When the same input sequence is first subjected to the Hanning window and then the RMS value is calculated the result is:

\[ v_{RMS,\text{Hanning}} = A \frac{\sqrt{3}}{4} \approx 0.433A \]

When the Hanning window is used the true RMS value is obtained by multiplying the result with a scaling factor:

\[ s_{RMS} = \frac{v_{RMS,\text{Hanning}}}{v_{RMS}} = \frac{\frac{\sqrt{3}}{4}}{\frac{1}{\sqrt{2}}} = \frac{\sqrt{6}}{4} \approx 0.612 \]

Testing with different calculable wave shapes has shown that the use of the Hanning transform reduces the errors to within acceptable limits for the used sampling rates and sequence lengths.
4.4.2 Phase error calculations

In the phase error calculations the Hanning window is not used. The reason is that the phase information should not be destroyed in the transformation process. Basically the phase error of the transducer under calibration is measured as the time difference between the signal from the transformer and the sampled reference signal. The method presently chosen is to determine the zero-crossings of both signals for all periods that are gathered. The mean value of the time differences is taken as the result for the phase deviation.

To determine the zero-crossings the sampled signals are differentiated. The peak values of $dx/dt$ are then detected as a non-integer sequence index giving a high phase resolution. Under the assumption that the signals are sinusoidal, the peak values of the derivative will give the zero-crossings.

Even if the input is not perfectly sinusoidal the method will work. One condition is that none of the higher harmonics present in the signal has a large amplitude compared to the fundamental frequency. This restriction is necessary to avoid errors in the measurement due to differences in the frequency response of the reference system and transformer under test. Figure 4 shows a signal consisting of a sine wave with fundamental frequency and amplitude one and a 5$^{th}$ harmonic sine wave with amplitude 0,1. Also a time delayed copy (phase shifted $\pi/6$) is shown. The dashed lines are the results from differentiating these signals. As seen in the figure the differentiation increases the influence of the 5$^{th}$ harmonic, e.g. the wave shape is less sinusoidal. The maximum value of the derivative is still dominated by the fundamental frequency. The method used will then measure the actual phase displacement between the fundamental parts of the two signals. If the harmonic component is higher relative to the fundamental component, the system will measure the phase displacement of the harmonic component. Since measurement of harmonics is not the task of this measurement system a limitation on the harmonics content have to be put on the primary signal used for the calibration. Through calculations and knowledge about the wave shapes found in the laboratory it has been decided that no harmonic component should have a higher amplitude than 5 % of the amplitude of the fundamental component.
Chapter 4

Figure 4 Example of differentiation of two sine waves with a 5th harmonic added

The measured value of the phase displacement has to be corrected for the known delays and phase displacements in the two systems, as described in the theoretical and uncertainty chapters. The most obvious delay is the rated time delay of the transformer under calibration. This value given on the rating plate shall not be considered as a part of the phase error even though it contributes to the phase displacement (see chapter 0 and 3).

For the reference system two important contributions to the phase displacement correction are the analogue phase displacement in the reference transformer and the time delay in the sampling instrument. The calibration certificate for the relevant reference transformer gives the phase displacement, while the time delay in the sampling instrument is described in the chapter Influence of time delay in calibration systems for Instrument Transformers with digital output.

All calculations are made with time units rather than phase angles until the last conversion, where the values are converted to angular units for the presentation of the result.
Chapter 4

4.5 Literature


5. Determination of the time delay in the calibration system

5.1 Abstract

Calibration of instrument transformers with digital output requires the determination of the time delay in the digital system. The time delay of reference systems must therefore be accurately known. Measurements on 3 multimeters in SP’s measurement system have shown a time delay of 250 ns, 190 ns and 100 ns, for the three instruments, respectively. These results are adequate for the system but show that each sampling instrument must be treated and calibrated independently.

5.2 Key words

Calibration, instrument transformer, phase displacement, time delay, uncertainty.

5.3 Introduction

A number of instrument transformers with digital output have recently reached the market or will do so in the near future [1]. The sensors employed in these transformers may be based on conventional measuring techniques or on new techniques, for example optical. Most often the digital output from a merging unit is the only standardised and hence measurable signal available for calibration.

5.4 Phase error in digital output

All A/D-conversion, digital filtering and data processing introduces a time delay to the measured signal. This time delay does not have any significant influence on ratio measurements, but since the time delay is not immediately distinguishable from a phase displacement or phase error, it requires special attention in the phase calibration process.

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1 Summary paper accepted and content presented under the title “Influence of time delay in calibration systems for instrument transformers with digital output” (WE2C-3) at CPEM 2000 Conference on Precision Electromagnetic Measurement, 14-19 May 2000, Sydney, Australia.
Chapter 5

In both the analogue and digital case phase displacement is defined as the phase difference between the secondary output and the primary signal. The phase displacement is said to be positive if the secondary output phasor leads the primary phasor. A part of the phase deviation observed in the secondary signal from a transducer with digital output is constant and is defined as the rated delay time. Since this situation is not covered in existing standards a new definition of phase error in addition to the conventional phase displacement is necessary [2]. See equation 1 from [2]:

\[ \phi_e = \phi + 2\pi f t_{dr} \]  

(1)

where \( \phi_e \) is the phase error, \( \phi \) is the measured phase displacement and \( t_{dr} \) is the rated time delay.

5.5 Sources of phase error in reference system

Most conceivable methods for calibration of phase displacement rely on sampling of the output of an analogue reference, i.e. a current or a voltage transformer [3] [4]. It will be imperative in such systems to have a precise knowledge of the time delay between the trigger signal sent to the reference sampling system, and the actual acquisition of the first sample. This time delay will henceforth be called the reaction time. The total phase displacement of the reference system thus consists of this reaction time and of the traditional phase displacement (\( \phi \)) of the analogue instrument transformer.

5.6 Calibration system

The reference calibration system established at SP Swedish National Testing and Research Institute is based on a sampling multimeter and a PC with custom designed software. The sampling technique introduces a time delay in the calibration, the delay in the sampling multimeter and data processing. The value for the multimeter is found in the specifications, and depends on the chosen digitising mode of the meter. The given data is a reaction time. To verify these values for reaction time in real situations, measurements have been performed at SP. Two different methods to determine the reaction time were investigated.

5.7 Determination of the reaction time with a square wave

The principle of the method was the application of a square wave which was both used as an external trigger for the multimeter and as a measuring signal. Equal cable lengths were used both to the trigger gate and the measuring input of the meter. The
principle is that since the frequency of the square wave is known, it is possible to measure the time of the first captured pulse and then calculate how much is missing. The missing part is the reaction time according to Figure 1 and equation 2.

\[ t_{\text{react}} = \Delta t = \frac{1}{f} - t_{\text{meas}} \quad (2) \]

The frequency generator used was calibrated with the national frequency standards at SP. To avoid any time-scale bias in the computer or software the ratio 1/frequency was also measured using the measurement system in each test run. The rise time of the square wave will influence the accuracy of the measurements. In the test set-up with three 50 Ω resistors delta connected for splitting the output from the signal generator, the rise time (10/90) of the wave was measured to 100 ns. This value is included in the uncertainty budget.

Measurements were performed on two multimeters (labeled ”multimeter 1” and ”multimeter 3”) in the 10 ns sub-sampling mode on a square wave with a base frequency of 10 kHz. Without inserting any delay to the multimeters the reaction times were found to be 500 ns and 540 ns, respectively.

The specification of the multimeter [5] states that if measurements are to be performed in sub-sampling mode on a signal with frequency content above 1 MHz it is recommended to introduce a delay of 500 ns to the multimeter to ensure the accuracy of the first sample. To verify this, measurements with various delay times were performed. The calculated reaction time then consists of the constant factor (inserted delay time, \( t_{\text{ins}} \)) and the reaction time of the multimeter.

\[ t_{\text{react}} = \Delta t - t_{\text{ins}} = \frac{1}{f} - t_{\text{meas}} - t_{\text{ins}} \quad (3) \]

Measurement with inserted delay times of 500 ns and 700 ns on a 10 kHz signal were performed on the same two multimeters and the reaction times were found to be 190 ns for no. 1 and 240 ns for no. 3. The results show good consistency independent of the inserted delay time.
Chapter 5

The disadvantage of this method is that the frequency content of the square wave is more complex than a realistic calibration signal and hence does not represent the signal used in calibration and real measurement.

5.8 Determination of the reaction time with a sine wave

In order to get a better representation of the real measurement case a sine wave was chosen. The multimeter was triggered by a TTL-pulse synchronised with the sine wave so that the falling (triggering) edge came on the zero crossing of the sine wave. Investigations show that this synchronisation was within 10 ns, and is included in the uncertainty. The rise-time of the edge of the TTL-pulse was 10 ns. Figure 2 is an example of the analysis oscillogram used to measure the frequency and reaction time. This picture shows a sampled sine wave, with a fundamental frequency of 10 kHz. The calculations were performed as described above.

Figure 2 Example of analysis oscillogram

Three multimeters were tested with this method. The reaction time for ”multimeter 1” without inserting any delay time was measured to be 540 ns, while the additional reaction time with inserted delay time ≥500 ns was 250 ns.
For "multimeter 2" the measured reaction time was 510 ns without inserted delay and 190 ns with an inserted delay ≥500 ns. The measured values for "multimeter 3" were 420 ns and 110 ns.

These reaction times differ from the reaction time of 125 ns specified in the manual for the instrument [5]. The difference is obviously due to individual variations in the multimeters since "multimeter 3" behaves better than the specification, while the two other have a slower reaction than specified. As seen the reaction times with the sine wave is smaller than with the square wave. This is as expected since the high frequency content of the square wave causes additional delay when the multimeter is in subsampling mode [5].

The advantage of the sine-wave measurement is that it reflects the real measurement situation well. The disadvantage is that the time reading on the sine wave is more difficult than on the square wave.

### 5.9 Uncertainty budget

The uncertainty components influencing the result are mainly related to the time measurements and the resolution due to sampling time since the uncertainty in the supplied frequency is very low (<2 ns). For all the measurements 10 ns subsampling were used. This gives the uncertainty due to resolution

\[ u_{res} = \frac{10}{\sqrt{3}} \text{ ns}. \]  \hspace{1cm} \text{(4)}

The uncertainty due to the edge of the square wave is \( u_{edge} = \frac{100}{\sqrt{3}} \text{ ns.} \) The standard deviation of the mean of the measurements is calculated to be 5 ns. The total uncertainty for measurements with a square wave is:

\[ U_{tot-sq} = 2 \times u_{tot-sq} = 60 \text{ ns} \]  \hspace{1cm} \text{(5)}

For the sine wave measurements the contribution from the rise-time is \( \frac{10}{\sqrt{3}} \text{ ns} \) and the synchronisation \( \frac{10}{\sqrt{3}} \text{ ns.} \) The standard deviation of the mean is 10 ns and the uncertainty due to determination of the exact zero crossing is \( \frac{40}{\sqrt{3}} \text{ ns.} \) The total uncertainty for measurements with a sine wave is:

\[ U_{tot-sine} = 2 \times u_{tot-sine} = 50 \text{ ns} \]  \hspace{1cm} \text{(6)}

The method used for the uncertainty budget is according to ISO Guide to the Expression of Uncertainty in Measurement [6].
Chapter 5

5.10 Conclusions

The investigations show that it is important to determine the reaction time of the sampling unit in a calibration system for instrument transformers with digital output or any other system in which exact phase information is required. The value should be incorporated in the calibration set-up to avoid measurement errors due to reaction time in the sampling reference system, and hence reduce the uncertainty in the phase measurement significantly.

5.11 References

6 Uncertainty analysis

6.1 Background

When calibrating an instrument transformer the uncertainty associated with the measurement is as important as the actual measurement result. If the uncertainty is not specified the result does not provide the traceability of the values measured with the transformer. The uncertainty aimed for at a national laboratory like SP is normally 5 to 10 times lower than what is used in actual industrial calibrations. An uncertainty analysis for a system used for industrial calibrations is described in Appendix 2. This calibration system differs slightly from the one described here. The use of the systems differs also since repetitive measurement of each point is not found to be feasible in industrial applications. When using SPs calibration system and method the standard number of repetitions for each point is 10. This is done to ensure a sufficient degree of freedom without having to rely on a pool of variances as is used in the paper referred previously, and to decrease the uncertainty due to the short time variations.

The uncertainty analysis in this chapter follows the directions given in "Guide to the Expression of Uncertainty in Measurements" (GUM) [1].

6.2 Corrections

A basic assumption in [1] is that all known measurement errors are used for correction of the measured value. This is done in the reference calibration system described in this work; both for ratio- and phase error measurements. The largest correction values are found in the analogue reference transformers used and are given by the calibration certificates for each standard. Since a standard is never calibrated for each and every possible value within the range, some of the correction values have to be estimated using linear fitting.

The sampling multimeter used as an A/D converter may also have some known errors with respect to the ratio measurements. Also in this case the calibration certificate specifies the correction values.

With respect to the phase error measurements the most important correction is the time delay or reaction time in the reference measurement system as reported in chapter 5. The measurement method described in the paper has the advantage that delays from both the A/D converter and the controlling computer
equipment (soft- and hardware) are included. The delay depends upon the individual multimeter tested and is assumed to be stable over time. This must however be verified with further measurements.

A parameter that is not an error, but should be corrected for, is the rated time delay of the transformer under test.

When all known measurement errors are corrected for, the remainder is the measurement uncertainty.

### 6.3 Distribution and sensitivity of the uncertainty components

The calculations performed in the calibration system are ratio and phase calculations. As shown in chapter 3 (Theoretical analysis) the possible ”error leakage” between the phase and the ratio will be so small that it can be ignored as long as the initial errors are reasonably small.

When calculating the measurement uncertainty it is important to know the distribution of the components and the probability of their uncertainty. The components listed in this chapter are (unless otherwise stated) assumed to be of normal (Gaussian) distribution and are given with a level of confidence of 95%. For a normal distribution this is equivalent to a coverage factor (k) equal to 2.

Another assumption used throughout this chapter is that all the uncertainty components described have a sensitivity coefficient of 1 and are uncorrelated unless otherwise stated.

### 6.4 Main components

The analogue standards used as references in the calibration are the most important part in the traceability chain. These standards are calibrated as mentioned in the chapter 4 (Design and construction of a calibration system for instrument transformers with digital output) against other standards and through comparison.

The different standards have different uncertainties as shown in Table 1 below.

<table>
<thead>
<tr>
<th>Standard</th>
<th>NUEO 400</th>
<th>9908 (current)</th>
<th>9900 (current)</th>
</tr>
</thead>
</table>
The values for the current transformers are valid down to 5 % of the rated value of the range used.

The long-term stability of the references has been investigated over a number of years through repeated calibrations. Over one year the change is less than 0,001 % in ratio and 0,1 min in phase in case of the voltage transformer NUEO 400. The changes between the two current transformers in the range of 20% to 200% of the rated value are found to be less than 0,002 % and 0,2 min for ratio and phase respectively. Below 20% the drift increases. This does however not pose any problem since in a calibration situation it is easy to avoid the range below 20 % by changing the setting of the transformer test set.

The stability values are considered to be of normal distribution since they represent a natural drift over one year and the numbers given above are the 95 % values, meaning there is a 5 % probability that the values are going to drift more than stated.

The fitting of correction values between calibrated points introduces an uncertainty. The uncertainty in this estimate is included among the uncertainty components and is estimated to be 0,001 % and 0,05 min for the transformers.

### 6.5 A/D Converter

The multimeter used as A/D converter is calibrated at SP. In the system it is used in the DCV mode. It will affect the uncertainty of both phase and ratio measurements, but in slightly different ways as described below.

#### 6.5.1 Ratio measurements

The uncertainty given by the calibration certificate is 4 ppm (0,0004 %) in the relevant ranges. This value is the uncertainty in the certificate for 10 % of the range and is chosen since DCV sampling of a sine-wave will pass through the entire range, including values lower than the 10 % point.

The drift of the multimeter over one year is according to the specification 4 ppm (0,0004 %). The calibration history of the multimeter shows that this value can be taken as a 95 % gauss-distributed value.
When a signal is sampled the result is discrete values, both in time and quantity. Since the ratio measurements are based on integration over a number of discrete points it is impossible to make a distinction between the quantisation error and time jitter [2]. For the measurements in this system the quantisation error and the time jitter contributes with an uncertainty that is much less than 1/10 of the largest component and hence can be ignored in the uncertainty summation.

For near sinusoidal wave shapes, errors that are introduced when the synchronisation of the sampling rate and the fundamental frequency are not perfect can be ignored in this system. This is due to the use of the Hanning window as shown in chapter 4 and the fact that the sampling time is chosen such that the number of periods sampled is sufficient and the timing error is small.

6.5.2 Phase measurement

As shown in chapter 5 the multimeter and calibration system have a reaction time which is equivalent to the time difference between the moment the trigger command is given and the first sample is taken. The determination of this delay has an uncertainty of 50 ns, which is included in the phase uncertainty. Using 50 Hz as the frequency the uncertainty is:

\[ u_{\text{delay}} = 50 \cdot 10^{-9} \cdot 2\pi \cdot 50 \text{ rad} \approx 16 \text{ rad} = 0.06 \text{ min} \]

The uncertainty caused by sampling time jitter and quantisation errors influence the accuracy of the determination of the zero-crossings in the phase analysis. The time resolution of the sampling process depends on the chosen sampling rate and the sampling interval (i.e. number of points). In the measurements 16000 points with 10 \( \mu \)s between the samples will be gathered. This gives 8 periods of a 50 Hz signal, and the mean value of the time difference between the zero-crossings is taken to be the phase deviation. The detection circuit is using a quadratic fit to determine the peaks of the derivative, and the uncertainty is estimated to be less than 0.05 min with a rectangular distribution (worst case). Due to the quadratic fit this value is less than the time resolution in the sampling, and the quantisation error and error due to sampling time jitter is included in this estimate.

6.6 Temperature

The calibrations are normally performed in a temperature-controlled laboratory. An investigation of the standards and the multimeter used gives an uncertainty contribution less than 10% of the largest components and can therefore be
ignored when calibrating in the laboratory. When outdoor measurements are performed a component that includes the uncertainty due to the actual measured temperature must be added.

### 6.7 Frequency variations

The frequency of the generated high-voltage or high current is used in the calculations for both ratio and phase error. The value of the frequency used is the nominal 50 Hz. Since the frequency may vary slightly due to load conditions in the grid or in the laboratory, the use of a fixed nominal frequency in the calculations will cause an uncertainty in the result. The size of this component has to be evaluated for each calibration situation.

### 6.8 Short-term stability

The short-term stability of the transformer under test will have an influence on the total uncertainty in the measurements. To find this each measurement point is repeated at least ten times. As reported through the pool of variances in appendix 2 the variations are quite small for this type of transformer with a digital output. This may however vary depending on the chosen technology for the various transformers on the market.

The short-term stability is calculated as the experimental standard deviation of the mean of the measured values, according to the formula given in [1]:

\[
u_{\text{short}} = \sqrt{\frac{s^2(q_k)}{n}}\]

where

- \(s^2(q_k)\) is the experimental standard deviation
- \(n\) is number of measurements.

### 6.9 Expanded uncertainty and conclusion

The uncertainty budget show that it is possible to calibrate the transformers with an uncertainty of less than 0.01% uncertainty for ratio and less than 0.4 min for phase with a 95% confidence level. This is sufficient to fulfil the requirements for accuracy for all transformers available today and is better than the results normally given for analogue transformers.
6.10  Literature

7 Conclusion

It is shown through the work described here that a system for calibrating instrument transformers with digital output can be build based on traceable components. A measurement uncertainty that is sufficiently low for calibration at the highest accuracy level is calculated and theoretically described.

The principle of the calibration system described is to digitise the secondary output from analogue reference standards with a sampling multimeter. The necessary corrections are then implemented in software and it is possible to compare the reference signal with the signal from the transformer under test. Through calculations it is possible to obtain both the ratio and phase error of the object under test from a set of data consisting of approximately eight periods of the fundamental frequency of the primary signal.

Due to the flexibility of the system it is possible to use all relevant reference standards available at SP, both for current and voltage. This includes also the possibility to do the calibration on site using SP’s transportable standard transformer as a reference.

The measurement uncertainty is analysed and is found to be comparable with the uncertainty achieved with precision bridge methods used in analogue calibration systems. The estimated uncertainty is less than 0,01 % for ratio and less than 0,4 min for phase with a 95 % confidence level.
8  Further work

The designed calibration system has to be verified by comparison with other international reference systems. There are already laboratories around the world which are interested in participating in a comparison of this kind at the highest accuracy level.

Non-conventional instrument transformers are generally assumed to have a better frequency response than conventional types. For potential users this may be one of the reasons for applying this new technology, since the transformers will be suitable for power quality measurements. The calibration system described in this work, and other systems built, is designed for calibration with 50 or 60 Hz sinusoidal primary signals. To achieve a wide application of the new instrument transducers a calibration system for other wave shapes is necessary. Of special interest is a sinusoidal signal at fundamental frequency with higher harmonics added.

The low voltage side of the system described here can, with some modifications to the calculation algorithms chosen, be modified to treat other wave shapes. The challenge is to make a system for generating and verifying the interesting primary voltage and current. This verification also has to be traceable back to the primary units either through comparison or documented physical properties. The generation and verification of these kind of high voltages or high currents is, as far as the author knows, never performed or reported in any literature.

The stability and performance of instrument transformers for measuring purposes over time is of large interest for the utilities and other users of the measurement results. The investigation of a measuring system with digital output connected in parallel with a traditional measurement system will continue. Further results from this experiment will be investigated, including investigations of temperature effects.
Chapter 8
A1 Non-conventional Instrument Transformers. Measurement principles and possible calibration methods

Jon Ivar Juvik
SP Swedish National Testing and Research Institute
Physics and Electrotechnics, Electrical Metrology
Box 857, S-501 15 Borås,
Sweden
E-mail: jonivar.juvik@sp.se

Jaap Daalder
Chalmers University of Technology
Dept. of Electric Power Engineering
S-412 96 Göteborg
Sweden
E-mail: jaap.daalder@elkraft.chalmers.se

A1.1 Abstract

A non-conventional instrument transformer is essentially a current or voltage transformer having a secondary output of a significantly lower magnitude than conventional transformers or are transformers with their secondary output as a digital signal. Another typical feature of modern non-conventional transformers is that the measured signal in many products is transmitted through an optical fibre from the high potential level to the instrumentation potential in the substation. This significantly reduces the insulation problem associated with traditional transformers.

The paper will describe measurement principles used in new transducers. Both optical transducer technologies and analogue transducers with digital output will be treated. Some advantages and disadvantages will be discussed.

At the time being there is a lack of standards for instrument transformers with non-conventional output. This obviously is a challenge for calibration laboratories whose task is to calibrate these transformers, especially when the output is a digital bit-stream. Standard methods for instrument transformer calibration rely on applications of bridge technology. This approach is not readily applicable to digital bit streams since the digitising process will introduce a time delay that corresponds to a large phase displacement, causing overload of the bridge circuit. SP Swedish National Testing and Research Institute has started a project together with Chalmers University of Technology, Elforsk, ABB Switchgear and Statnett to develop calibration methods suitable for these transformers. The paper will describe possible solutions to the calibration problem.

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A1.2 Introduction

In recent years much research has been performed to find new methods for measuring current and voltage in high-power networks. The motivation for this is both practical and metrological. Today’s instrument transformers are large and their size and cost are increasing sharply with increased system voltage mainly because of increased insulation requirements. This results in the need for large areas and the use of heavy equipment for the installation of instrument transformers. The traditional current transformer (CT) is also subject to a certain risk for damage which may cause serious explosions and thereby injury to personnel.

The metrological properties of traditional transformers are also questioned today. There is an increasing interest in power quality issues and one of the main topics discussed is the presence of higher harmonics and who is going to pay for them. Before a system of payment can be worked out, it is necessary to measure the harmonics and determine their source. Since traditional instrument transformers, for both current and voltage mostly have unacceptable frequency response outside the nominal 50 or 60 Hz area, the need for new technologies is mandatory. It is then of course important to include the calibration at higher frequencies for these new transducers.

A1.3 State of the art

The technologies used for voltage and current measurement differ. Hence it is necessary to treat these separately.

a) Current transducers
During the last decades a number of methods for measuring current has been investigated. The traditional method of using shunts or transformers has been thoroughly tested and is well characterised. One of the new types of current transformers available today uses traditional analogue transformer technology, but converts the measured signal to a digital signal at high potential [1]. This signal is then transmitted through an optical fibre to the instrumentation placed in the control-room. An advantage of this system, apart from having solved the isolation problem, is that the dimension of the measurement core can be more freely chosen giving less risk for saturation. The technology even opens up for the use of for instance a Rogowsky-coil; in that case the frequency response is basically limited by the sampling frequency of the A/D-converter.
A new detection method used in transducers for current measurements is based on an optical effect called the Faraday effect [2, 3]. The Faraday effect is the rotation of the plane of linearly polarised light when exposed to a magnetic field. The rotation is proportional to the magnetic field, the Verdet constant and the permeability of the chosen optical material.

\[ \theta = \mu V \int Hdl \]

were

\[ \theta = \text{Faraday rotation in degrees} \]
\[ \mu = \text{permeability of the material (H/m)} \]
\[ V = \text{Verdet constant of the material (°/Tm)} \]
\[ H = \text{magnetic field intensity (A/m)} \]
\[ l = \text{path length of the light} \]

Some researchers and manufacturers have been working on concepts were the field inside a magnetic core is measured with an optical sensor in an air gap. Another method is an optical sensor situated near the conductor without a magnetic core. However the trend seems to be towards a sensor that encircles the conductor. As of today the two most frequently used optical pathways is either a bulk glass type or a fibre optical cable encircling the current-carrying conductor.

When the optical path encircles the current-carrying conductor it can be shown that:

\[ \oint Hdl = NI \]  \hspace{1cm} (Ampère’s law modified)

and hence

\[ \theta = \mu VNI \]

were N is the number of turns (or times) the optical path encircles the conductor. If the loop are completely closed and one has an exact number of turns the formulas above is accurate.

One of the advantages of the optical path encircling the conductor is that according to Ampère’s law it reduces the influence from other conductors and magnetic fields in the vicinity. It will also obviate the need to position the sensor accurately with respect to the conductor [4]. Gradually the remaining
problems, which include sensitivity of the method, bend introduced birefringence and temperature effects are being solved.

b) Voltage transducers

The same producer who delivers the traditional CT with digital output mentioned above also has a capacitive voltage divider that uses the same electronics to transmit a digital signal representing the voltage [1]. The D/A-converter is in this case built into a traditional VT housing, with voltage division down to a level the electronics can handle. The digital signal is again sent through an optical fibre to the instrumentation placed in the control-room.

During the last decade researchers have proposed different solutions for converting the electrical field into an optical effect. The optical conversion method that is most frequently tested is the Pockels effect. This electro-optical effect can be observed as a phase shift between two orthogonal oriented linearly polarised light beams. A number of attempts have failed due to construction difficulties when going from the development stage to the production stage. This is partly due to the fact that the crystals that demonstrate the Pockels effect are not able to withstand the full voltage in power systems. Some sort of voltage division or a sensor detecting a predetermined part of the electric field in air has to be used. Another difficulty observed is that the Pockels effect is temperature dependent. This makes it necessary to have either a well-controlled temperature on the Pockels crystal, which is difficult outdoors, or to measure the temperature and use some mathematical compensation for the temperature dependency. These problems are some of the reasons why it is difficult to obtain an optical voltage transducer with stable characteristics, and probably also why the market status is far behind that of optical current transducers.

A1.4 Market status

The market status of new types of current and voltage transformers is somewhat different. Analogue current transformers with digital output have been used for surveillance and relaying purposes in a number of installations, for instance in large rectifier installations and in series capacitor installations, and are now being installed for metering. Optical current transducers have been used for fault-location in switchyards and are now introduced in installations both for metering and relaying.

Analogue voltage transformers with digital output are also being installed for relaying and metering today, together with the CT’s mentioned above. This is quite natural since the metering unit used is specially designed for this specific
optical digital input. So far, apart from certain field tests, no installations have been reported where voltage transformers with digital output or optical VT’s have replaced the traditional types.

There seems to be an increasing acceptance regarding the non-conventional current transformer. Especially when there is a need for close surveillance of currents in a switchyard or similar. A real breakthrough in full optical and/or digital measurement, including both voltage and current, is not likely to happen until the integration with relays and other equipment is more complete. This will probably require outputs from the transformers that can readily be transmitted through a databus directly to the relay control. To achieve this with an open choice of technologies it is obvious that there is a need for the standardisation of the output from the transformers. Probably both a digital and a low-level analogue standard are required. There is already work going on within IEC to specify a standard for the low energy analogue output.

### A1.5 Calibration particulars

What is the problem with calibrating these new transformers? Here it is important to remember that calibration of analogue instrument transformers is done by balancing an analogue bridge with the help of a null-detector. The readout from the bridge is the ratio- and phase-error of the transformer. This is an analogue method all the way and the errors can not be too large, otherwise the bridge can not be balanced.

A transformer with digital output has an A/D-conversion somewhere on the secondary side. The electronics will cause a time delay of the signal. Using a bridge after a D/A-conversion, this time delay will be seen as a phase error in the transformer. If the time delay is small the error may be mathematically compensated, but this is not necessarily the case. Most probably the delay is so large (milliseconds) that the bridge can not be balanced.

Another disadvantage when converting the digital signal into an analogue signal for calibration purposes is that this procedure adds to the uncertainty and that this probably is not the way the signal is treated in real measuring situations. As mentioned earlier a direct data transfer by a bus from the transformer to relays and other equipment is most likely in the future.

### A1.6 Possible solutions
The goal of the project is to specify calibration methods applicable both in factory laboratories and at the national laboratory level. The intention to build up the national calibration system at SP in Borås.

The Swedish company that manufactures transformers with a digital output has already established a calibration system for the use in their factory. In this system the output from the calculation unit of the transformer is compared with a reference voltage or current that is sampled with a multimeter. The data are transmitted through separate databases to a PC where calculations are done which determine the ratio- and phase-error. The sampling is made at the secondary side of traditional voltage or current reference transformers. The transformers and the multimeter are calibrated at SP. The method seems to have enough accuracy for this purpose and has the advantage that the same equipment can be used for calibrating the energy meter unit that is an integral part of the calculation unit.

The planned system at SP will be based on the same type of multimeter, HP 3458A, used in a sampling mode. The computation unit is a portable PC with a Pentium Pro processor and Windows NT. At present the timing control of the multimeter and the computer is analysed. It is obvious that the accuracy requirement for the calibration method at a national level is higher than in a routine calibration laboratory. It is therefore necessary to investigate closely how the data are treated in every step during sampling and transmission. Some of this work is already done during the realisation of SP’s Digital Sampling Wattmeter [5], but with a slightly different configuration of the measurement system some investigations have to be done for this specific system. The choice of references is not decided at this stage. It is possible to use the proposed measurement system with different references and signal types. The critical part of the calibration is the comparison between the sampled curve from the multimeter and the output from the instrument transformer under test. Since the calibration is intended to cover transformers from all kinds of manufacturing, it will be necessary that the output is standardised.

A1.7 Conclusions

Instrument transformers with digital output or transformers applying electro-optical conversion to measure voltage and current have not yet taken any major market share. The full breakthrough is not likely to happen until direct data communication from transformer to protection and control instrumentation is readily available. To achieve this a standardisation of the output is necessary.
Today’s methods for instrument transformer calibration rely on applications of bridge technology. This approach is not readily applicable to transformers with digital output since the electronics performing the digitising process will introduce a time delay that corresponds to a large phase displacement. This will inevitably cause overload of the bridge circuit. Converting the digital signal back into an analogue electrical signal for calibration purposes introduces additional uncertainty components, and it is probably not the way the signal is treated in real measuring situations. Furthermore, it is very likely that a direct data transfer by a bus from the transformer to relays and other equipment will be used in the future. It will therefore be of great interest to be able to perform the calibration directly on the digital output.

The goal of our project is to establish a calibration method to be implemented at a national laboratory level and to contribute to the development of calibration methods that can be used in routine calibration laboratories.

### A1.8 Literature


A2 CALIBRATION SYSTEM AND UNCERTAINTY BUDGET FOR INSTRUMENT TRANSFORMERS WITH DIGITAL OUTPUT

Jon Ivar Juvik, SP Swedish National Testing and Research Institute, Sweden
Martin Nilsson, ABB Switchgear AB, Sweden

A2.1 Abstract

This paper describes the reference system employed during calibration of instrument transformers with digital output. The reference system can be used for calibration of both current and voltage transformers by changing the references. The uncertainties associated with the calibrations of current transformers are evaluated and typical values are presented, including the established pool of variances for this calibration. This leads to a total uncertainty for transducer calibration of the same order of magnitude as that of analogue bridge calibrations in industrial environment for traditional instrument transformers.

A2.2 Introduction

Today the buyers of instrument transformers have greater focus on the traceability and uncertainty of the calibration performed by the manufacturer before installation. The accuracy of the calibration should be significantly better than the accuracy class of the transformer, and the measurement uncertainty of this calibration has to be stated.

Instrument transformers employing optical transmission of the measured quantity have been under development for a long time. They are now coming of age and are today available on the market. Relinquishing the traditional 5A and 110 V interface in favour of an optical interface between high voltage and control house equipment poses new requirements on the calibration methods and calibration standards; requirements that have to be met in an industrial environment with full traceability of the calibration.

When the transformers have a digital signal as the only secondary output the traditional calibration methods have to be reconsidered. The method described in this paper uses simultaneous sampling and

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calculation of values from the reference as well as the transformer under test. This system is used in the routine calibrations performed at ABB Switchgear AB in Ludvika on their Digital Optical Instrument Transformers, DOIT; a product based on digital signal transmission.

To avoid time consuming calibrations, the method uses only one measurement at each voltage or current level. To achieve an accuracy of the measurement that fulfils customer and regulatory requirements it is then necessary to establish a pool of variances, which according to ISO ”Guide to the Expression of Uncertainty in Measurement”[1] (the Guide) can be used as an uncertainty component in the evaluation of the results. This component replaces the calculated standard deviation of the mean, which traditionally is used. The computations on the pool of variances have been performed at SP Swedish National Testing and Research Institute by the author based on real calibration data from ABB Switchgear. However, the method described is applicable for all calibration facilities for similar products.

A2.3 Description of calibration system

Current:
A mobile calibration set has been built. It consists of a current source with 3 busbars for different currents. Each busbar is equipped with a reference current transformer (CT). The current from the transformers is passed through a reference shunt and the shunt voltage is sampled with a HP 3458 multimeter. A common trigger is used to ensure simultaneous reading of current on the reference transformer and the digital optical current transducer (DOCT) under calibration.

One reading on each of 6 current levels is taken during the calibration sequence. The test software calculates the differences between readings of the reference CT and DOCT under calibration at each point and displays the ratio error and phase displacement and the actual current at each level.
Voltage:
The voltage calibration is performed in one of the existing test rooms in the factory. The voltage signal from the reference transformer is sampled with a HP 3458 multimeter. A common trigger is used to ensure simultaneous reading of voltage on the reference transformer and the digital optical voltage transducer (DOVT) under calibration. One reading on each of 6 voltage levels is taken during the calibration sequence. The test software calculates the differences between readings of the reference VT and DOVT under calibration at each point and displays the ratio error and phase displacement and the actual voltage at each level.

A2.5 Uncertainty budget for CT ratio error

The calibration is a direct comparison between the reading of the reference system and the object under test. The mathematical expression for the measurement is then simple.

\[ Y = X_{\text{obj}} - X_{\text{ref}} \]

All values for uncertainty components are here given as the equivalent of one standard deviation. This means that all components that are considered to be of rectangular distribution are divided by the factor \( \sqrt{3} \) to obtain the corresponding standard uncertainty, while other components are divided by their coverage factor.

Uncertainty components:
1. Uncertainty in calibration of reference standards \( [u_{\text{cal}}] \). Found in Calibration Certificate with normal distribution.
2. Uncertainty caused by drift in the reference standards \( [u_{\text{drift}}] \). This value is estimated by the calibration history based on results from previous calibrations of the standards and of rectangular distribution.
3. Uncertainty in corrections for the value of the reference standards \( [u_{\text{corr}}] \). Since the references are calibrated only at a limited number is calculated in percent with the reference value as base. This value is displayed together with the actual current readings.
of points, the possible interpolation error is estimated and considered to be of rectangular distribution.

4. If there are differences in temperature dependence of reference standards and the object under calibration this has to be corrected for or treated like an uncertainty component \( u_{\text{temp}} \). This component is probably of small size and can be considered to be zero in the calculations. The same applies to temperature dependency of the multimeter.

5. Uncertainty given in the specification for the multimeter (HP 3458) \( u_{\text{spec}} \). The specification limit is assumed to be of rectangular distribution.

6. Uncertainty in calibration of multimeter (HP3458) \( u_{\text{calHP}} \). Found in Calibration Certificate with the distribution stated as normal.

7. Uncertainty caused by drift in the multimeter \( u_{\text{driftHP}} \). This value is found as long term stability on the data sheet for the instrument.

8. Stochastic variations in the measurements (as 1 standard deviation) estimated from the pool of data described below.

Size of the individual components in %:

\[
\begin{align*}
    u_{\text{cal}} &= \frac{0.007}{2} \\
    u_{\text{corr}} &= \frac{0.004}{\sqrt{3}} \\
    u_{\text{temp}} &= 0 \\
    u_{\text{spec}} &= \frac{0.01}{\sqrt{3}} \\
    u_{\text{calHP}} &= \frac{0.005}{2} \\
    u_{\text{driftHP}} &= \frac{0.014 + 0.002}{\sqrt{3}}
\end{align*}
\]

A2.6 Pool of variances

The pool of variances is calculated according to classical statistics and the Guide [1] based on 38 independent series of measurement. These series of measurements were performed on three different current transformers from the same production series. All transformers have the same rated current \( I_r \) and identical design. The measurements were performed on the current levels 100, 200, 400, 1600, 2000 and 2400 A, and have each between 4 and 11 degrees of freedom. The calculated variance for the individual series varies from \( 8.33 \times 10^{-6} \) to \( 3.17 \times 10^{-3} \). There is no indication that the variances \( s_i^2 \) depends on the current level and therefore the variances can be gathered in one common pool of variances.

The formula used in the calculations of the pool of variances is taken from note H.3.6 in the Guide [1]:

\[
    s_p^2 = \frac{\sum_{i=1}^{N} \nu_i s_i^2}{\sum_{i=1}^{N} \nu_i}
\]

where

\[
\begin{align*}
    N &= \text{number of independent measurement series} \\
    s_i^2 &= \text{experimental variance of the } i\text{th series of } n_i \text{ repeated measurements} \\
    \nu_i &= (n_i - 1) \text{degrees of freedom of the } i\text{th series of measurement}
\end{align*}
\]
The denominator in the formula gives the degrees of freedom for the pooled variance. The experimental variance of measurements characterised by the pooled estimate of variance is: 

\[ u_{pool}^2 = \frac{s_p^2}{m} \]

where \( m \) is the number of repeated measurements performed each time. This variance (and from this calculated standard deviation) has the same degrees of freedom as the pooled variance itself.

The measurements gave a pool with degrees of freedom \( \nu = 270 \). The value of the uncertainty component from the pool of variances is:

\[ u_{pool} = \sqrt{u_{pool}^2} = \sqrt{\frac{s_p^2}{m}} = \sqrt{\frac{2.272 \cdot 10^{-4}}{1}} = 0.015 \]

Here \( m = 1 \) since no repeated measurements are performed during the routine calibration, this component also has 270 degrees of freedom.

**A2.7 Expanded uncertainty**

The combined standard uncertainty of the measurement \( u_c \) is the positive square root of the combined variance. All uncertainty components listed above are found to have a sensitivity coefficient of 1. This gives:

\[ u_c = \sqrt{u_{cal}^2 + u_{dip}^2 + u_{corr}^2 + u_{spec}^2 + u_{calHP}^2 + u_{dipHP}^2 + u_{pool}^2} \]

and hence

\[ u_c = 0.019\% \]

Since the dominant component in the budget is from the pooled variance with 270 degrees of freedom and the total degrees of freedom is even higher, the combined standard uncertainty is assumed to have a normal (Gaussian) distribution. The coverage factor (k) is therefore chosen as \( k = 2 \) to achieve a level of confidence of approximately 95%. This gives an expanded uncertainty:

\[ u_{tot} = 2 \cdot u_c = 0.038\% \]

Preliminary results have been achieved which indicates that the uncertainty for DOVT calibration will be of the same magnitude as for the DOCT shown above.

**A2.8 Discussion**

According to the established practice for electrical routine calibration today a transformer is accepted as long as the measured value is below the stated class limit regardless of the uncertainty in the measurement. In the German national laboratory rules for legal metrology of 1977 [2] another practice is used. It is according to this document sufficient to have an accuracy of the bridge on 0.02% and an accuracy of the reference transformer of 0.02% to be able to calibrate transformers of class 0.1. This implies that the uncertainty calculated above is small enough to calibrate transformers of class 0.1.
Yet another practice is established in accredited laboratories within European Accreditation (EA) were the class limit is reduced with the measurement uncertainty. The consequence of this method is that the calculated uncertainty above can verify that a transformer is within Class 0.2 if the measured ratio error is <0.16% in the whole range.

A2.9 Further work

The established pool of variance for the CT measurements will be expanded to ensure that the values is representative also for transformers with other rated currents. It is also necessary to test the pooled values over time, by doing some repeated measurements. These new values can be included in the pool if they are consistent with the already established values; e.g. the variance is of similar magnitude, or they can initiate a recalculation of the pool. There is also a need to look closer at the stability and some of the other uncertainty components for the measurement of the phase error. A pool of variances will be established with the described method for VT calibrations and for the calibration of the energy meter.

For calibration of an entire energy metering system (e.g. the Optical Instrument Transformer Platform (OITP) in energy metering mode complete with Optical Voltage and Current transducers), a phantom power circuit has been developed. This circuit consists of separate current and voltage supplies with individual control of magnitude. The voltage and current signals from the reference instrument transformers are connected to a digital wattmeter with a Wh option that measures the active energy during a pre-set time interval and compares this with the value from the OITP. For the energy calibrations pools of variances for different measurement time can be used as a tool for deciding on the most suitable integration time to be used in practical calibrations. It will also be important to verify that the energy measurement with current rating from 0.05 I to 1.2 I have variances that are within the same range. If not, different pools of variances, and thereby a different expanded uncertainty, have to be established for the different momentary power levels.

A2.10 Conclusions

The calibration system established has shown to be stable for the DOCT measurements, and a pool of variances with 270 degrees of freedom is calculated. The value of the pooled uncertainty is calculated to a magnitude of 0.015% (as 1 standard deviation). The expanded uncertainty for the calibration of ratio error is calculated to be 0.038% with a level of confidence of 95 % (k = 2). This makes it possible to verify a Class 0.2 transformer. Preliminary measurements indicate that the same accuracy is achievable.
for the phase errors and for DOVT calibrations.

**A2.11 Literature**


A3 ON SITE, LONG TERM COMPARISON BETWEEN INSTRUMENT TRANSFORMERS WITH DIGITAL OUTPUT AND A CONVENTIONAL MEASURING SYSTEM

Jon Ivar Juvik, SP Swedish National Testing and Research Institute, Sweden
Martin Nilsson, ABB Power Systems AB, Sweden
Arve Maalø, Statnett SF, Norway

A3.1 Abstract
Measurements have been performed to verify the long-term stability of a high voltage energy-metering system based on transformers with digital output. The method chosen was to install the system in parallel with a conventional metering system, and to compare the results through the automatic reading system of the substation. The results show a difference between the two systems of 0,11% and this result is in line with the calculated theoretical difference between the two metering systems.

A3.2 Introduction
Instrument transformers employing optical transmission of the measured quantity have been under development for a long time [1]. They are now coming of age and are today available on the market [2]. One of the demanding tasks for instrument transformers is to give input values to revenue metering. For a system where the instrument transformers submit a digital output, the energy meter is merely a numerical calculator. The calculator multiplies time coherent current and voltage values to find the instantaneous power and sums these over time to find the transmitted energy. The summing of discrete values is in this case equivalent to integrating over time.

The accuracy of this system is possible to investigate in the laboratory, but since the technology is new it is also of great interest to examine the performance over time and in varying environmental conditions.

To investigate this, a measuring system with digital output was connected in parallel with a conventional system at one of the lines at Hadeland substation, Norway. The measured hourly energy values from both systems were fed into the same type of metering counter unit and then transmitted to the automatic reading system used by the owner of the grid, Statnett SF.

The system voltage of the line is 132 kV and the rated current is 1500 A.

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There is at the moment no specific requirement on the total system accuracy for metering in the Norwegian high-voltage grid, but the accuracy is generally expected to be better than 1%. This is due to the requirements posted on the individual components used.

**A3.3 Substation**

The substation has four overhead lines that both export and import energy at the 132 kV level. In addition there is one transformer to supply lower voltages.

The two systems to be tested are installed in parallel in each phase at one of the 132 kV lines. The physical distance between the transformer sets in each phase is as small as practical possible. With this it is possible to avoid any losses or voltage drops between the two measurement points.

**A3.4 Description of the conventional system**

The conventional measuring system consist of one three phase set of capacitor voltage transformers of accuracy class 0.2 in accordance with IEC 186 and one three phase set of SF₆-insulated current transformers with accuracy class 0.2S in accordance with IEC 185. Neither voltage nor current transformers are of the same manufacturer as the system with digital output described below. The transformers were tested by the respective manufacturers prior to the installation and the results were given in conventional test reports.

The secondary output of the voltage and current transformers for all three phases are connected to a three-phase energy meter with accuracy class 0.2S. The cabling from the transformers to the meter is an entirely separate circuit. This is done to avoid any negative influence or changes in the measurement circuit due to other activity in the substation.

The output from the energy meter is given as “energy pulses” (each pulse represents a pre-defined amount of energy). These pulses are transmitted to the stations metering counter unit,
which is a part of the substations automatic reading system.

**A3.5 Description of the system with digital output**

The system with digital output is manufactured by ABB under the description DOIT (Digital Optical Instrument Transformer) [3]. The Current transducer is of ring-core type with a fixed burden and an A/D-converter at high potential. The power to the A/D-converter, as well as the digitised output representing the measured current, is transported through an optical fibre between the high potential and the control unit in the control room.

The voltage transformer consists of a capacitor voltage divider that divides the voltage down to a level that is suitable for the same type of A/D-converter as used in the CT. Also in this case one optical fibre is used both for power and signal.

The control unit, called OITP (Optical Instrument Transformer Platform) is basically an industrial PC without keyboard and with enhanced environmental shielding. The OITP receives the optical signal and calculates the instantaneous current or voltage values.

In the OITP used in this project an additional algorithm is included that calculates the instantaneous power and the energy. Also in this case the output is given as "energy pulses" and is fed to the same type of metering counter unit as used with the conventional meter.

**A3.6 Retrieval of measurement data**

In the automatic reading system the data from both systems are stored and made available for remote reading. The format of the stored values is chosen to be watt-hour (Wh), and the value for each hour is stored. This is done for active energy in and out on the line as well as for reactive energy (VArh) in and out. To ensure the validity of each hourly value great care is taken to synchronise the timing between the two systems.

A PC is set up to gather data for the two systems from the automatic reading system. Due to the storage function of the counter unit it is not necessary to perform this reading at strict intervals. In this project it was decided to collect the data on a monthly basis.

When the data are collected it is possible to perform analysis to check the correlation between the two systems.
**A3.7 System comparison**

The collected data for December 2000, which are reported here, show that the average current during this month is 100 A per phase. Based on the calibration data given in the test reports from the manufacturers and the measurements performed on site a theoretical deviation between the two systems at this current was calculated.

**A3.7.1 System with digital output**

For the DOIT a phase-by-phase system calibration was performed by the manufacturer. The system calibration means that the whole measurement chain, including CT, VT and metering unit, was calibrated together in a synthetic circuit. The synthetic circuit feeds voltage to the VT and current to the CT separately, and thereby makes it possible to do the energy calibration without having to supply the full power [4]. The calibration was performed at a phase-to-ground voltage of 76.2 kV and the current varied from 50 A to 1200 A. The total error was calculated by summing the error for each phase and then dividing by 3 to get the mean value. Due to the relatively low line currents during the time of the results reported, the most relevant calibration data are for the 100 A and 200 A points.

The 100 A point gave the following expression:

\[ e_{DOIT-100A} = \frac{0.05 + (-0.10) + 0.12}{3} = 0.02\% \]

The 200 A point gave, with the same calculation method, an error of – 0.07%.

**A3.7.2 Conventional system**

The calculation of the error in the conventional system is more complicated than in the digital output case. It is not common to perform a system calibration for conventional metering systems. Instead the values from the manufacturers test reports for the transformers and the meter have to be combined to find the expected error of this system. Conventional transformers have a burden dependency, so it was also necessary to measure the burden to make sure that the design specifications were met.

For the voltage transformers, the cable from the secondary output to the meter does also contribute with a resistive loss, which is seen as an additional error. To calculate these errors special software developed at SP were used [5]. The result from these calculations was that the expected error at approximately 150 A was 0.09%.

**A3.7.3 Deviation**

When the expected error were found for both systems, the theoretical deviations were calculated with the conventional system as reference:
\[100A: e_{\text{100A}} - e_{\text{conventional}} = 0.02\% - 0.09\% = -0.07\%
\]
\[200A: -0.07\% - 0.09\% = -0.16\%
\]

From these calculations it is seen that the theoretical deviation in the measurements is between \(-0.07\%\) and \(-0.16\%\).

**A3.8 Results and discussion**

When all the gathered results over the month were calculated a total difference of -0.11\% was the result. This was well within the accuracy class of the two measurement systems, and it was also interesting to note that it was inside the expected theoretical region.

However, when the individual one-hour results were studied some phenomena were discovered. The most significant was the large relative difference at low current.

![Figure 3 Comparison of the measured difference between the two systems (points) and the uncertainty component due to resolution (solid line), for different hourly power levels](image)

Figure 3 clearly shows how the difference expressed in percent (referred to the conventional system) decreases when the power increases. One of the reasons for this is the limited resolution of the automatic remote system. The data stored there have only a resolution of 0.05 MWh. This causes a \(2\sigma\) uncertainty component according to the formula [6]:

\[ u = 2 \cdot \sqrt{2 \cdot \frac{0.05^2}{12}} \approx 0.041 \]

At the average power, 23 MWh per hour, this resolution gives a relative uncertainty of 0.18 \%, while at the lowest power shown (2.4 MWh) the relative uncertainty is 1.70 \% and at the highest registered power the relative uncertainty is 0.08 \%. The relative uncertainties are shown in figure 3.

The effect of the uncertainty due to the resolution was also shown when the correlation coefficient for the two series was calculated for data series with the energy summed diurnally and compared with the correlation coefficient for the hourly series. For the hourly series the coefficient was calculated to be 0.99998297, while the coefficient for the data over the 31 days was calculated to 0.99999562.

**A3.9 Further work**

Since the average current that has flown in the line is low compared to the rated current, the calibration data for the conventional system might be
uncertain. Even though the measurements performed show good consistency it will be necessary to perform a new calibration of the energy meter, where also the low load range is tested.

The experiment is set up to look at the long-term stability of the system with digital output. The collection and analysis of the results will therefore continue and cover a longer period of time.

Another interesting feature is to investigate the influence of temperature on the system. To get this information hourly temperature values (outdoor) are logged and stored in the substation. When more data are collected an analysis of this will be performed.

**A3.10 Conclusions**

Two energy-metering systems have been compared over a period of time. The difference between the systems is found to be 0.11%. This difference is less than the implicit requirement of 1%. The method seems to be useful, but for low energy values and shorter evaluated time periods a better resolution in the automatic reading system could be advantageous. The recorded difference between the two systems is also found to be in the same range as the theoretical value calculated from the manufacturers test reports.

**A3.11 Literature**


