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Calibration of High Resolution Digital Recorders for Impulse Measurements
Abstract

This report discusses calibration and evaluation of a digital recorder used in high voltage impulse measurements. A 390 AD digital recorder with sampling rate of 60 MSa/s and 10 bit vertical resolution is calibrated in accordance with IEC 1083-1. The critical parameters for a digital recorder, like static integral non-linearity, differential non-linearity under DC and dynamic conditions, internal noise level, rise time, ripple, non-linearity of time base and impulse scale factor of 390 AD are investigated. Detailed calibration procedures and the subsequent data processing are also described.

Key words

digital recorder, calibration, performance test, impulse measurement

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Preface

This report is a presentation of a research within SP and our results in calibration of a digital recorder used in high voltage impulse measurements. The calibration requirements given in IEC 1083-1 contain rigorous technical specifications. Different instrumentation, software and data process are involved in the calibration procedures. Here, we would like to thank following persons for their support and help on this work.

Prof. Stanislaw Gubanski, Division of High Voltage Engineering, Chalmers University of Technology, for his interest in calibration of digital recorder and providing relevant instrumentation.

Dr. Jari Hällström, High Voltage Institute, Helsinki University of Technology, for his providing a step generator which is essential for the determination of impulse scale factor in our calibration.

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Borås, February 1998
Summary

Over the past decade considerable work has been performed on the application of digital recorders to measurement in high voltage impulse tests and many laboratories are presently using digital recorders to record high voltage impulses. The IEC-Standard 1083-1 [1] "Digital recorders for measurements in high-voltage impulse tests" specifies digital recorders and calibration requirements to meet the measuring accuracy during high voltage impulse test in accordance with IEC-Standard 60-2 "High-voltage test techniques, measuring system"[2]. The overall uncertainty of a digital recorder must be smaller than the uncertainty for the complete measuring system consisting of the voltage divider and the digital recorder. High voltage impulse measurements are complex and further more digital recorders have non-linear behaviour such as sampling and quantisation that contribute to the measuring problems. Therefore IEC 1083-1 provides rigorous technical specifications on a digital recorder to ensure the measuring accuracy of impulse measurements.

This report will discuss calibration of a digital recorder in accordance with IEC 1083-1. As an example, the calibration of a 390 AD digital recorder with sampling rate of 60 MSa/s and 10 bit vertical is performed. The details of the calibration procedure and the data processing are presented. The critical parameters for a digital recorder, like static integral non-linearity, differential non-linearity under dynamic and DC conditions, internal noise level, rise time, ripple, non-linearity of time base and impulse scale factor of 390 AD are investigated. The described metrology and the calibration procedures are an attempt to provide guidance for application purposes.
1. Introduction

Power system apparatus, such as power transformers, switchgears and arresters, must withstand not only the rated voltage but also overvoltages caused by lightning strikes and power system operations. High voltage impulse tests are normally used for verifying apparatus in power industries. The standard methods of measurement of high voltage impulse and the basic techniques for application to all types of apparatus are laid down in the relevant international standard, IEC 60-1 [3]. In a measuring system, analogue impulse oscilloscopes and digital recorders are common tools for recording the impulse wave forms.

The advent of digital recorders since the past decades has already given a profound impact on high voltage impulse tests and measuring techniques. Due to many advantages associated to trigger facility, non volatile storage, possibility of automated test, digital recorders have already become widely used and have replaced analogue impulse oscilloscopes in many high voltage laboratories. Furthermore, signal processing and computer assisted analysis on the original recorded data can also enhance the effectiveness of quality control of tested objects. However, a digital recorder has a non-linear characteristic which is introduced by the acts of sampling and quantisation. Imperfections in the practical implementation of sampling and quantisation will lead to increased non-linearity. Also due to the complexity of high voltage impulse measurements, the possible error sources in a digital recorded impulse wave form can be numerous.

Sampling rate and vertical resolution are basic characteristics of a digital recorder, as they determine the size of the recording errors inherent in the analogue-to-digital conversion process. In other words, the sampling rate and resolution of a digital recorder could give magnitude of the presented error if the digital recorder is assumed to operate in an ideal mode. However, in the practical realisation of a digital recorder, further more errors are introduced. The nature, limits, and consequences of the errors encountered in a digital recorder vary depending on the instrument design. Therefore, determination of a digital recorder must consist of two stages. The initial stage consists of specifying the sampling rate and vertical resolution based on the assumption that the digital recorder behave ideally. Secondly, the dynamic performance of the digital recorder must be checked. The latter covers the assessment of the instrument’s dynamic errors which may be present in a high voltage impulse measurement.

In IEC 1083-1 [1], static non-linearity, differential non-linearity under DC and dynamic conditions, internal noise level, non-linearity of time base, rise time ripple and impulse scale factor, are used to characterise the digitising process of a
digital recorder. If a digital recorder fulfill the requirements of the mentioned specification, it can be assured to have a measuring uncertainty of 2% in the impulse peak voltage measurement and 4% in the measurement of the time parameter, as required for an impulse test.

It should be pointed out that high voltage impulse testing may perform on both self-restoring (such as outer-door insulation) and non-self-restoring insulation (such as some inner insulation of power transformer). Normally, a high voltage impulse test on non-self-restoring insulation calls for a comparison of the recorders of two impulse wave forms rather than a precise measurement of their magnitude. Hence, depending on the type of insulation under test, requirements on a digital recorder are also different.

In this report, the detailed calibration procedures of the performance test and their analysis, with respect to the standard IEC 1083-1, on a digital recorder with vertical resolution of 10 bit and sampling rate of 60 MSa/s will be described.
2. Definitions and symbols

For the purpose of this report, the following definitions are applied.

2.1 Lightning impulse

Impulse voltages with front duration varying from less than one up to a few tens of microseconds are considered as lightning impulses. In the IEC recommendations [3], widely accepted today through national committees, a standard full lightning impulse used in high voltage laboratory is defined in Fig. 1 (a). Two time parameters, front time $T_1$ and half-value time $T_2$ are used to define a full lightning impulse. The front time $T_1$ of a full lightning impulse is a parameter defined as 1,67 times the interval $T_x$ between the instants when the impulse is 30% and 90% of the peak value (see Fig. 1 (a) and Equation 1). The time to half-value $T_2$ is a parameter defined as the time interval between virtual origin $O_I$ and the instant when the voltage has decreased to half the peak value. The standard lightning impulse is a full lightning impulse having a front time of 1,2 μs and a time to half-value of 50 μs. The tolerance of the front time is ±30%, time to half-value ±20%. It is normally described as an $1,2\pm30% / 50\pm20\%$ impulse. A chopped lightning impulse is a full lightning impulse chopped by an external gap after 2 to 5 μs which is represented by $T_c$, see Fig. 1 (b).

$$T_1 = 1,67T_x$$  \hspace{1cm} (1)

(a) Full lightning impulse
2.2 Digital recorder

2.2.1 Digital recorder

An instrument which can make a temporary digital record of a scaled high voltage impulse and which can convert this temporary digital record to a permanent record. The permanent digital record shall be displayed in the form of an analogue graph.

2.2.2 Rated resolution

The nominal minimum increment which can be detected. It is expressed by the reciprocal of two to the power of the rated number of bits, \( N \), namely \( r = 2^{-N} \). For a digital recorder used in impulse measurements, a rated resolution of 0.4% (2\(^{-8}\),8 bit) or better is recommended for tests where only the impulse parameters are to be evaluated. For tests which require comparison of wave forms a rated resolution of 0.2% (2\(^{-9}\), 9 bit) or better is recommended.

2.2.3 Sampling rate

The number of samples taken per unit time, in the unit of Sa/s (samples/second). For a digital recorder used in impulse measurements, the sampling rate shall be greater than or equal to \( 30/T_s \), where \( T_s \) is the time interval to be measured.

2.2.4 Full-scale deflection
The smallest input voltage which produces a change in the output equal to \((2^n - 1)\).

2.2.5 Quantisation characteristics

The characteristic showing the relationship between the output of the digital recorder and the DC input voltage which produces this output, see Fig. 2.

2.2.6 Code bin width \(w(k)\) of code \(k\)

The range of input voltage allocated to code \(k\), see Fig. 2. The average code bin width \(w_0\) is defined as the product of the full scale deflection and the rated resolution.

![Diagram showing quantisation characteristic](image)

*Fig. 2 Quantisation characteristic of an ideal 3 bit digital recorder showing code transition threshold \(c(2)\) and \(c(3)\), a code bin width \(w(3)\).*

2.2.7 Integral non-linearity \(s(k)\)

The difference between corresponding points on the measured quantisation characteristic and on the ideal quantisation characteristic, see Fig. 3.

2.2.8 Differential non-linearity \(d(k)\)
The difference between a measured code bin width and the average code bin width \( w_0 \) of a digital recorder. The differential non-linearity is expressed in per unit of the average code bin width.

\[
d(k) = \frac{w(k) - w_0}{w_0}
\]  

(2)

Fig. 3 Integral non-linearity \( s(k) \), curve 1 and 2: quantisation characteristics of an ideal and a non-linear 6 bit digital recorder.

Fig. 4 Differential non-linearity under DC conditions. Quantisation characteristics of a 3 bit digital recorder with level 2,3,4 showing large \( d(k) \). \( w_0 \) is an average code bin width of a 3-bit digital recorder.
3. Tested object

The 390 AD, manufactured by Tektronix, is a high-performance, fully-programmable wave form digitizer with two input channels, 10 bit vertical resolution, maximum sampling rate of 60 MSa/s, and an analogue bandwidth of DC to 15 MHz [4]. The sensitivity of the input range is ±0,1 V to ±50 V full scale with 1-2-5 sequence, 9 steps. The full scale deflection is 0,2 V (10 bit resolution from -0,1 to 0,1 V). Hence, the performance test on input range of ±0,1 V will represent the digitising characteristics of the A/D converter.

This 390 AD, together with input voltage dividers controlled by HP 3488A switch control unit and HP computer system forms a digital impulse registration system [5] which was designed in Ludvika ASEA transformer in 1980s and is now owned by the Division of High Voltage Engineering, Chalmers University of Technology. The impulse registration system was designed for the purpose of power transformer testing and the software is also specialised for early HP computer systems. Since calibration procedures are quite different from routine transformer tests, a new program written in LabVIEW 4.1 (Graphical programming for instrumentation) was developed for controlling the 390AD and the HP 3488A switching control unit (see Appendix).

This report shows the calibration procedure and its analysis carried out on the 390 AD digital recorder. The calibration on the input voltage divider controlled by HP 3488A switching unit will be reported later.
4. Performance test

In accordance with IEC 1083-1, the performance test shall be performed on each new digital recorder and after any significant repair or when the performance of a digital recorder is in doubt. In general, the overall uncertainty of the digital recorder used in impulse measurements shall be within:

±2% in the measurement of the impulse peak amplitude;
±4% in the measurement of the impulse time parameters.

Digital recorders shall meet these limits without signal processing of the recorded raw data. In order to stay within the limitation, the individual limit of uncertainties given in the performance test of IEC 1083-1 should be met.

The 390 AD provides 10 bit vertical resolution. The calibration was carried out only on channel 1 of the 390 AD with the highest sampling rate of 60 MSa/s and input sensitivity of ±0,1 V. Special notice will be given if other setting of the 390 AD was applied.

4.1 Direct voltage calibration

This test specified in IEC 1083-1, sub clause 2.2.1, will evaluate the code bin width for different codes under DC conditions. The static integral non-linearity shall be within ±0,5% of the full scale deflection; and differential non-linearity shall be within ±0,8 per unit of the average code bin width \( w_0 \).

4.1.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, Multi-product calibrator Fluke 5500A.

4.1.2 Calibration process

Step A: Apply a DC voltage \( V_i = -0,0998 \) V to the digital recorder. Take a record and store the average value as \( A(i) \) with \( i = 1 \).

Step B: Raise the input voltage by an increment \( \Delta V \) which shall be within 0,1\( F \) and 0,25\( F \). \( F=0,1953 \) mV is the product of full scale deflection (0,2 V) and the
rated resolution \(2^{-10} = 1/1024\). In this calibration, the increment \(\Delta V\) is selected to be 0.04 mV. Four steps (\(\Delta V=0.2F\)) are used for evaluation of each code bin width. The use of ten steps (\(\Delta V=0.1F\)) per code bin width can not be justified since noise may contribute to the measurement uncertainty.

**Step C:** Repeat step B using the same increment voltage and increasing \(i\) by 1 from 1 to as high as is needed to cover the full scale deflection of the digital recorder. Totally 5000 steps are needed for completing the step B and C.

*Fig. 5 Flow-chart of the direct voltage calibration, step A,B,C.*
Fig. 5 shows an outline of the flow-chart for the direct voltage calibration (step A, B and C). The program for controlling the 390 AD, Fluke 5500A and data calculations was written in LabVIEW. The static non-linearity and differential non-linearity under DC conditions were determined by evaluation of values of applied voltages, and measured DC voltages (step D to step H). Calculation from step D to step H was programmed in Matlab.

**Step D:** Locate the code transition threshold $c(k)$ from code $k$ to code $k+1$ by

(a) find $A(n)$ for the largest value of $n$ such as $A(n)$ is less than or equal to $k + 1/2$
(b) find $A(m)$ for the smallest value of $m > n$ such that $A(m)$ is not less than $k + 1/2$
(c) the code transition threshold $c(k)$ from code $k$ to code $k+1$ is:

$$c(k) = V_1 + n\Delta V + \frac{(k + 1/2) \times fsd - A(n)}{A(m) - A(n)} (m - n)\Delta V \quad (3)$$

where fsd stands for the full scale deflection.

Fig. 6 shows a diagram how to locate $c(k)$ from measured DC voltages. Fig. 7 shows the calculated code transition threshold $c(k)$ based on the DC voltage calibration.

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**Fig. 6** The code transition threshold $c(k)$ is where the line joining $(V_1 + n\Delta V, A(n))$ and $(V_1 + m\Delta V, A(m))$ intersects the $(k + 1/2)$ level.
Step E: The voltage, $p(k)$, is taken as the average of the two code transition threshold which delineate level $k$:

$$p(k) = \frac{1}{2} \{ c(k) + c(k - 1) \} \quad (4)$$

The width, $w(k)$ of code bin $k$ is:

$$w(k) = c(k) - c(k - 1) \quad (5)$$

Fig. 7 Calculated code transition threshold $c(k)$.

Fig. 8 Experimental determination of the code bin width $w(k)$. The average code bin width is given by the product of the full scale deflection and the rated resolution $w_0 = 0.2 \times 2^{-10} = 1.953 \times 10^{-4} V$. 
Step F: Determine the static scale factor $F_s$ from:

$$F_s = \frac{p(x) - p(y)}{x - y}$$  \hspace{1cm} (6)

where $(x-y)$ is greater than or equal to 90% of the full scale deflection 0.2 V. The ideal static factor $F_s$ should be equal to the average code bin width $w_0$ which is the product of full scale voltage and the rated resolution.

Step G: Determine the static integral non-linearity $s(k)$ for every level from:

$$s(k) = p(k) - p(y) - (k - y)F_s$$  \hspace{1cm} (7)

Fig. 9 shows the diagram of the static integral non-linearity which is within ±0.5% of full scale deflection (0.2 V), which is required by the standard.

![Graph of static integral non-linearity](image)

*Fig. 9 Experimental determination of the static integral non-linearity.*

Step H: Determine the differential non-linearity $d(k)$ under DC condition:

$$d(k) = \frac{w(k) - F_s}{F_s}$$  \hspace{1cm} (8)

The differential non-linearity can be also considered as the relative error of the each code bin width to the average code bin width $w_0$. Fig. 10 shows the differential non-linearity $d(k)$ within the limitation of ±0.8 per unit of average code bin width, which is required by the standard.
Fig. 10 Experimental determination of the differential non-linearity $d(k)$ under DC condition.

4.1.3 Conclusions and uncertainties

The static integral non-linearity is within ±0,5% of full scale deflection (0,2 V) and the differential non-linearity is within the limitation of ±0,8 per unit of average code bin width, which fulfill the requirement of IEC 1083-1.

The combined uncertainties for the code transition threshold (formula 3) and the code bin width (formula 5) for a coverage factor of 2 are given as follows:

<table>
<thead>
<tr>
<th>Quantities</th>
<th>Formula</th>
<th>Expanded uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>code transition</td>
<td>$s_{c(k)} \approx 2 \times \sqrt{u^{2}<em>{\text{v+t+addV}} + u^{2}</em>{e}}$</td>
<td>21 μV</td>
</tr>
<tr>
<td>threshold $c(k)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>code bin width</td>
<td>$s_{w(k)} = 2 \times s_{c(k)}$</td>
<td>42 μV</td>
</tr>
<tr>
<td>$w(k)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where $u_{\text{v+t+addV}} = 5.8 \text{ μV}$ is the maximum standard uncertainty for an applied voltage; $u_{e} = 20 \text{ μV}$ is an estimated standard uncertainty for the variance of the applied voltage.

4.2 Differential non-linearity under dynamic conditions

This test specified in IEC 1083-1, sub clause 2.2.2, will evaluate the vertical resolution of a digital recorder for input signals with high frequencies. The
differential non-linearity under dynamic condition shall be within ±0,8 per unit of the average code bin width \( w_0 \).

4.2.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, Signal generator WaveTek Model 185; Frequency counter PM6665.

4.2.2 Calibration process

The differential non-linearity under DC condition can be calculated from the DC calibrations. However, the differential non-linearity may increase dramatically if input signals are of higher frequencies. The differential non-linearity under dynamic condition can be inferred from the statistical distribution of large number of triangular wave forms, which is recommended in IEC 1083-1.

Apply symmetrical triangular waves whose amplitude is within (95±5)% of the full scale deflection. The slope of the triangular wave shall be greater than or equal to \( \frac{f \cdot s \cdot d}{0,47 T_x} \), where \( T_x \) is time interval between the instants when the impulse is 30% and 90% of the peak value of a lightning impulse. For a full lighting impulse, the front time \( T_f \) can vary from 0,84 \( \mu \)s to 1,56 \( \mu \)s (tolerance of the front time 1,2 \( \mu \)s is ±30% ). Thereby the minimum value of \( T_x \) of a lightning impulse will be \( T_x = T_f / 1,67 = 0,5 \) \( \mu \)s. The full scale deflection of 390 AD is 0,2 V. Hence, the slope of the triangular wave shall be greater than or equal to \( 0,2 / (0,4 \times 0,5) = 1,0 \) V/\( \mu \)s. Fig. 11 shows the applied symmetrical triangular waves generated by the signal generator WaveTek Model 185. The frequency of the triangular wave is 2,765 MHz which gives the slope of the wave 1,063 V/\( \mu \)s.

Fig. 12 illustrates a diagram how a histogram for different digital levels for one period of triangular wave is developed, assuming a vertical resolution of 3 bit. The basic phenomenon behind histogram testing is that a statistically large quantity of data is taken and a tally is kept for how many times each code is converted. If an AD converter and input triangular wave forms are ideal, the input wave form will spend an equal amount of time in each code bin. It can be expected that the tally count for each code will be equal. Therefore, the differential non-linearity under dynamic condition can be defined as the deviation of each point from the average value divided by this average value. The conversion from the measured triangular waves to a cumulative histogram of different digital level and its further calculation for the differential non-linearity under dynamic condition were programmed in Matlab. In this calibration, totally 4700 symmetrical triangular
waves were recorded and analysed for determination of the differential non-linearity under dynamic conditions.

![Graph of voltage vs time](image)

**Fig. 11** Oscillogram of applied symmetrical triangular waves, with frequency of 2,765MHz and the slope is larger than 1.0 V/μs

![Histogram diagram](image)

**Fig. 12** Development of the histogram for the occurrence of different digital levels, assuming a vertical resolution of 3 bit.

It is known that the accuracy of the vertical resolution of high frequency digitising cannot be adequately defined by the parameter used in the low frequency digitising. Therefore, two types of cumulative histograms of digital level are plotted, by assuming the nominal resolution of 10 bit and by treating the 390AD having 9 bit vertical resolution. It is shown that there are many zero codes for assuming the recorder with 10 bit vertical resolution. Better results are obtained under the assumption of a reduced resolution 9 bit, see Fig. 14.
Referring to the definition of the differential non-linearity an ideal digital recorder will have a differential non-linearity of 0.0. The dynamic differential non-linearity shown in Fig. 14 is also within ±0.8 per unit of average code bin width. However, one may notice that the dynamic differential non-linearity is just on the margin of qualification in accordance with IEC 1083-1, even when the 390AD was assumed to have a 9 bit vertical resolution.

(a) The 390AD with an assumed vertical resolution of 10 bit under dynamic conditions

(b) The 390AD with an assumed vertical resolution of 9 bit under dynamic conditions

Fig. 13 Cumulative histogram of digital levels under dynamic conditions
4.2.3 Conclusions and uncertainties

The dynamic differential non-linearity is within ±0,8 per unit of average code bin width under an assumption of 9 bit vertical resolution, which fulfills the requirement of IEC1083-1.

The uncertainty in a frequency measurement at 2,765MHz is ±0,08Hz for coverage factor of 2.

4.3 Internal noise level

This test specified in IEC 1083-1, sub clause 2.2.3, will evaluate the internal noise level of a digital recorder. The internal noise level shall be less than 0,4% of the full scale deflection for a digital recorder used for the evaluation of impulse parameters; 0,1% of full scale deflection for a digital recorder used also in a test where the comparison measurement is required.

4.3.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, Multi-product calibrator Fluke 5500A.
4.3.2 Calibration process

A constant direct voltage was applied to the 390 AD. 2048 points were recorded. The average value of recorded points was calculated as a measured DC voltage and the standard deviation of these samples is an adequate approximation of the internal noise level. Fig. 15 shows a recorded wave form, the applied DC voltage is 76 mV. Fig. 16 shows the standard deviation over the full scale deflection at different voltage level. It shows that the internal noise level is less than 0.25% of the full scale deflection (0.2 V).

![Oscillogram of a recorded 76 mV DC voltage, 2048 points, average value 76.28 mV, standard deviation 0.43 mV.](image)

Besides the inherent internal noise level of a digital recorder, another two effects can also result in a high value of the standard deviation for a measured DC voltage. First, since the applied DC voltage is in the order of millivolts, high frequency disturbances may couple to input cables and give rise to spikes which are shown in Fig. 15; Secondly, this higher noise level may also be contributed by the calibrator itself. There are no specifications of the noise level of Fluke 5500A under the bandwidth up to 15 MHz. However, it is difficult to draw any conclusion quantitatively at this stage.
Fig. 16 The standard deviation of the recorded samples over the full scale deflection versus the applied DC voltages.

4.3.3 Conclusions and uncertainties

The internal noise level is less than 0.25% of the full scale deflection (0.2 V), which exceeds the limitation for the 390 AD used in a test where comparison measurements are required.

The uncertainty for applied DC voltage at 0.1 V is ±10 μV for coverage factor of 2.

4.4 Time calibration

This test specified in IEC 1083-1, sub clause 2.2.4, will evaluate the non-linearity of the time base. The integral non-linearity of the time base shall be less than 2% of $T_x$. If the integral non-linearity is between 2% of $T_x$ and 0.5% of $T_x$, then the time base shall be calibrated for each record. If the integral non-linearity is less than 0.5% of $T_x$, then only periodic calibration is needed.

4.4.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, Signal generator WaveTek Model 185; Frequency counter PM6665.

4.4.2 Calibration process
Sine waves were applied to the 390 AD. The frequency of the sine wave generated by signal generator was calibrated by the frequency counter. Fig. 18 shows the measured oscillogram (circles, represent each sampling point) and simulated sine waves (line) with a frequency of 2,0030MHz. The signal applied on the 390 AD has a frequency of 2,004523MHz. Therefore the time base difference will be 1,0/2,003 - 1,0/2,004523 = 0,37 ns, which is less than 0,5% of $T_x = 0,5 \text{ \mu s}$ (the minimum time interval between 30% and 90% peak value for a lightning impulse).

**4.4.3 Conclusions and uncertainties**

The time base difference which is less than 0,5% of 0,5 \text{ \mu s} (the minimum time interval between 30% and 90% peak value for a lightning impulse), which fulfils the requirement of IEC1083-1.

The uncertainty in a frequency measurement at 2,004523 MHz is ±0,06 Hz for coverage factor of 2.

![Oscillogram](image.png)

*Fig. 17 Oscillogram (dot) and simulated sine wave form (line) with a frequency of 2,0030 MHz.*

**4.5 Rise time**

This test specified in IEC 1083-1, sub clause 2.2.5, will evaluate the rise time of a digital recorder. The rise time shall be not more than 0,03$T_x$, where $T_x$ is the time interval to be measured for a lightning impulse.
4.5.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, Tektronix square-wave generator Type 107.

4.5.2 Calibration process

Square waves with rise time less than 0.5 ns were applied to the 390 AD. Fig. 18 shows the measured oscillogram. The rise time from 10% and 90% of the settle level is 18 ns which is treated as the rise time of the 390 AD.

In order to ensure that the time parameter of lightning impulses can be measured within the required accuracy, according to IEC 1083-1, the rise time of a digital recorder should be less than or equal to 0.037τ. Thereby, for the 390AD, the possible measurable interval time τ shall be larger than or equal to 0.6μs (0.037τ>0.018 μs) which gives the front time of τf=1.0 μs. In another word, the 390 AD digital recorder can not be used for measuring a lightning impulse whose front time is less than 1 μs. Furthermore, another criterion that must be met with regards to a full lightning impulses with oscillations superimposing on the front. The rise time of a digital recorder shall also be less than or equal to 1/2πfmax, where fmax is maximum frequency of the oscillation superimposing on the front of a full lightning impulse. Thereby, for the 390 AD the possible measurable oscillation frequency will be 8.8 MHz.

![Fig. 18 Oscillogram obtained for the rise time calibration, the dots represent the sampled points.](image-url)
4.5.3 Conclusions and uncertainties

The rise time of the 390 AD is 18 ns.

The square wave generated by Tek square wave generator was checked by Tektronix oscilloscope 7603. The rise time of the square wave (time interval of 10%-90% peak amplitude) is less than 3 ns.

4.6 Measurement of the impulse scale factor

This test specified in IEC 1083-1, sub clause 2.2.6.2, will determine the impulse scale factor and evaluate the impulse scale factor, which shall be constant within ±1% over the time interval of 0,5T₁ to 2T₂ for a full lightning impulse; over the time interval of 0,5T₁ to 2T₂ for a chopped lightning impulse.

4.6.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, Multi-product calibrator Fluke 5500A, Step generator from Helsinki University of Technology, DC power supply.

4.6.2 Calibration process

Two alternatives have been given in IEC1083-1 for the measurement of the impulse scale factor, the pulse calibration (sub clause 2.2.6.1) and the step calibration (sub clause 2.2.6.2). A pulse calibrator may have too large uncertainty and has to be calibrated before it can be used for the calibration purpose. Contrary, the step calibration is much more precise than the pulse calibration because a known and traceable DC voltage with high accuracy and stability can be used as the reference voltage. Hence, the step calibration was used in our calibration for determination of the impulse scale factor.

The step generator [6] from Helsinki University of Technology was used as a switching device. The switching time is less than 6 ns. Fig. 19 shows the circuit diagram of the step calibration. Fig. 20 shows the diagram illustrating the transition to zero level and variation of the impulse scale factor. Time parameter T₁, T₂ are illustrated in Fig. 1. Considering the tolerance of the full standard lightning impulse, time parameters for the step calibration are T₁=0,84 µs and T₂=60 µs.
Fig. 19 Circuit diagram for the step calibration.

Fig. 21 shows the recorded oscillogram with only the first five microseconds. The applied DC voltage is 90 mV. Twenty-five measurements were performed. $O(t)$ was read at every sample in the time interval of [0, 84 $\mu$s, 120 $\mu$s], each $O(t)$ was found to be within $\pm 1\%$ of the mean value $O_s$. Curve 1 in Fig. 22 shows mean value $O_s$ in the time interval [0, 84 $\mu$s, 120 $\mu$s] for each of these twenty-five measurements. $O_{sm}=89.7655$mV is the mean value of $O_s$ for these twenty-five measurements. The impulse scale factor is defined as the quotient of the input DC voltage 90 mV and mean value $O_{sm}$, thereby the obtained impulse scale factor in the time interval [0, 84 $\mu$s, 120 $\mu$s] is 1,0026.

For a chopped lightning impulse, replace $T_2$ by $T_c$ (2 to 5 $\mu$s, see Fig. 1 (b)); $T_I$ is defined in the same manner as for a full lightning impulse. The evaluation of each $O_s$ of each twenty-five measurements was performed in the time interval of [0, 84 $\mu$s, 10 $\mu$s] ($T_c$ is selected to be 5 $\mu$s ). The mean value $O_{sm}$ is 89,7776 mV, thereby the obtained impulse scale factor is 1,0025. Curve 2 in Fig. 22 shows mean value $O_s$ in the time interval of [0, 84 $\mu$s, 10 $\mu$s] for each of these twenty-five measurements.

4.6.3 Conclusions and uncertainties

The impulse scale factor for a full lighting impulse and chopped lightning impulse are 1,0026 and 1,0025 respectively, which are also within $\pm 1\%$ during the required time interval.
The uncertainty for applied DC voltage at 90mV is ±9.7 μV for a coverage factor of 2.

Fig. 20 A step response illustrating the variation of the impulse scale factor. Outputs $O(0.5T_1)$, $O(t)$ and $O(2T_2)$ correspond to times $0.5T_1$, $t$ and $2T_2$ respectively. $O_s$ is the mean value of $O(t)$ over the time interval $[0.5T_1, 2T_2]$.

Fig. 21 Oscillogram obtained for the step calibration (only showing first 5 μs). The sampling rate of the 390AD is 30 MSa/s.
4.7 Interference test

This test is specified in IEC 1083-1, sub clause 2.2.7, will evaluate the electromagnetic compatibility of a digital recorder. The maximum deflection from the reference line in the interference test shall be not more than 1% of the full scale deflection.

4.7.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, voltage divider, Marx generator, etc.

4.7.2 Calibration process

Digital recorders are more sensitive to interference during high voltage impulse tests. Hence special measures have to be taken to enable the digital recorder to perform adequately in impulse measurements. However, a digital recorder may be subjected to the interference which results from very different causes, such as the type of tests, the measuring cable, arrangement of the set-up, the shielding effectiveness of a control room, etc. The interference test on a digital recorder should be considered to be a whole system evaluation instead of only evaluation of a single digital recorder. Therefore, the interference test on the digital recorder has to be evaluated on site. This interference test will be performed in the high voltage laboratory of Chalmers University of Technology.
4.8 Ripple

This test specified in IEC 1083-1, sub clause 2.2.8, will evaluate any ripple effect from the supply line or other sources on a digital recorder. The effect of ripple shall be less than 0.4% of full scale deflection for a digital recorder only used for the evaluation of impulse parameters; 0.1% of full scale deflection for a digital recorder used also in a test where a comparison measurement is required.

4.8.1 Instrumentation

Digital recorder 390 AD; Computer with GPIB card, Multi-product calibrator Fluke 5500A.

4.8.2 Calibration process

A DC voltage was applied to the 390 AD. The sampling rate should be sufficiently slow for the oscillogram to span one cycle of the power frequency. Fig. 23 shows an oscillogram obtained at a sampling rate of 10 kSa/s.

![Oscillogram of a DC voltage measured with low sampling rate, 10kSa/s.](image)

For obtaining the ripple effect, high frequency signals should be filtered away. A digital IIR filter with order of 6 was programmed in Matlab. Fig. 24 shows the spectrum of this low pass filter, which gives 3 dB attenuation at 150 Hz. After application of the digital low pass filter on the data shown in Fig. 23, the obtained low frequency signals are given in Fig. 25. The maximum peak-to-peak variation of the filtered signals is 0.38 mV. The effect of the ripple is taken as half the peak-
to-peak value, thereby, the ribbon is 0,19 mV which is less than the 0,1% of the full scale voltage (0,2V).

![Graph showing frequency response of a designed digital IIR low pass digital filter.](image)

*Fig. 24 The spectrum of a designed digital IIR low pass digital filter.*

![Graph showing a low frequency signal with time interval 0.1 to 0.2 s.](image)

*Fig. 25 The low frequency signal merged in Fig. 24 shown for time interval 0.1 to 0.2 s.*

4.8.3 Conclusions and uncertainties

The effect of the ripple is less than the 0,1% of the full scale voltage (0.2 V), which fulfils the requirements of IEC 1083-1.

The applied DC voltage uncertainty at 90 mV is ±9.7 μV for a coverage factor of 2.
5. Input sensitivity

The 390 AD has an input sensitivity range from ±100 mV to ±50 V with 1-2-5 sequence, 9 steps. This test will verify the linearity and absolute error of the different input sensitivities (not required in IEC 1083-1).

5.1 Instrumentation:

Digital recorder 390 AD; Computer with GPIB card, Multi-product calibrator Fluke 5500A.

5.2 Calibration procedures:

DC voltages with different amplitudes were applied to 390 AD for covering ±90% of full scale voltage for each input range. Fig. 26 shows the absolute error $\varepsilon$ of each input range.

5.3 Conclusions and uncertainties

The absolute errors for different scales are shown in Fig. 26. An accuracy of different scales is less than ±1% of full scale.

The uncertainty for applied DC voltages may refer the specification of Fluke 5500A in Appendix.
Fig. 26 The absolute error in mV for different input sensitivities of the 390 AD versus the percentage of the full scale voltages
6. General evaluation

Summarising the calibration mentioned above, table 1 shows the performance characteristics of the 390 AD digital recorder: here, f.s.d stands for the full scale deflection which is 0,2V; c.b.w stands for the code bin width.

Table 1

<table>
<thead>
<tr>
<th>Basic parameter</th>
<th>390 AD</th>
<th>Requirement for impulse evaluation</th>
<th>Requirement for comparison measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling rate</td>
<td>60 Msa/s</td>
<td>≥ 60 MSa/s</td>
<td>≥ 60 MSa/s</td>
</tr>
<tr>
<td>Rated resolution</td>
<td>10 bit</td>
<td>≥ 8 bit</td>
<td>≥ 9bit</td>
</tr>
<tr>
<td>Full scale deflection</td>
<td>0,2 V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Performance Test

1. Direct voltage calibration

Static integral non-linearity

less than 0,45% of f.s.d

within ±0,5% of f.s.d

within ±0,5% of f.s.d

Static differential non-linearity

0,3 per unit c.b.w

within 0,8 per unit c.b.w

within 0,8 per unit c.b.w

2. Differential non linearity under dynamic conditions

0,6 per unit c.b.w (assuming 9 bit)

within 0,8 per unit c.b.w

within 0,8 per unit c.b.w

3. Internal noise level

0,25 % of f.s.d

0,4% of f.s.d

0,1% of f.s.d

4. Time calibration

less than 0,5% T_x

0,5% T_x

0,5% T_x

5. Rise time

18 ns

less than 0,03 T_x

less than 0,03 T_x

6. Impulse scale factor

less than 0,1%

0,1%

0,1%

7. Interference test

Need to be done

1% of f.s.d

1% of f.s.d

8. Ripple

less than 0,1% of f.s.d

0,4% of f.s.d

0,1% of f.s.d
Conclusions and discussions

The 390 AD with an 10 bit vertical resolution and a sampling rate of 60 MSa/s was calibrated. The calibration process and analysis are presented. The limits of uncertainty given in the performance test of IEC 1083-1 are met for a full lightning impulse measurement and a chopped lightning impulse, however, the front time of measured lightning impulse should be longer than 1 µs. The internal noise level of the 390 AD is 0,25% of full scale deflection which exceeds the limitation for the 390 AD used in a test where comparison measurements are required.

The interference test will be performed at a later date in Chalmers University of Technology. A more investigation on the internal noise level test will also be performed to find out influence of disturbance sources.

A step generator used for calibration of impulse scale factor (section 4.6) was also constructed in SP. The rise time of the output pulse is about 3,5 ns. Therefore, from now on, we can perform the calibration on a digital recorder by our own means. Furthermore, a pulse calibrator which can generate lightning impulses will be constructed and evaluated. After that, a digital recorder can also be evaluated directly by measuring lightning impulses, which is the alternative test for determination of impulse scale factors stated in IEC 1083-1.

Since each calibration step contains large amount of data, the data processing may easily require as much, or even more, time than the calibration itself. Therefore, much work needs to be done to make the calculation programs standardised and optimised.
References


[6] “Step generator”, High voltage institute, Helsinki University of Technology, Finland
Appendix

Instrumentation and main specifications:

1. Multi-product Calibrator

Flukes 5500A, series number SP 502130

DC voltage specifications

<table>
<thead>
<tr>
<th>Ranges</th>
<th>Absolute Uncertainty ±(% of output + μV)</th>
<th>Stability, 24 hours ±(ppm output + μV)</th>
<th>Resolution (μV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-329,999 mV</td>
<td>0,006%</td>
<td>5 ppm</td>
<td>1 μV</td>
</tr>
<tr>
<td>0-32,999 V</td>
<td>0,005%</td>
<td>4 ppm</td>
<td>3 μV</td>
</tr>
<tr>
<td>0-32,999 V</td>
<td>0,005%</td>
<td>4 ppm</td>
<td>30 μV</td>
</tr>
<tr>
<td>30-329,999 V</td>
<td>0,0055%</td>
<td>4,5 ppm</td>
<td>300 μV</td>
</tr>
</tbody>
</table>

2. Frequency Counter

Frequency count PM6665, series number SP 502664
Totally uncertainty from 1MHz to 10 MHz: ±0,03 ppm for a coverage factor of 2.

3. Signal generator

WaveTek Model 185, series number SP 500343
Maximum frequency 5 MHz with triangular wave, sine wave, square wave output.

4. Square-wave generator

Tektronix square-wave generator Type 107

The square wave generated by Tek square wave generator was measured by Tektronix oscilloscope 7603. The rise time of the square wave (time interval of 10%-90% peak amplitude) is less than 3 ns.

5. Step generator from Helsinki University of Technology

Switching time: less than 6 ns, maximum input DC voltage 20 V.
6. 390 AD control program

Fig. A-1 shows the flow chart of the 390 AD control program and Fig. A-2 shows the interface of the program. All the other control programs used in the calibration are based on the 390 AD control program.

Fig. A-1 The flow-chart of the 390 AD control program
Fig. A-2 The interface of the 390 AD control program