Digital Recorder for Impulse Voltage Tests

Performance Progress, Type Tests and Calibration

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Abstract

The paper gives an short overview of the performance progress of digital recorder for impulse voltage tests since 1978.

The hardware of a new generation of digital recorders with 200 MS/s sampling rate, 14 Bit resolution and 50 MHz bandwidth is introduced, which are designed and optimized to fulfill all requirements for measuring of any impulse voltages including full and chopped lightning impulses, switching and current impulses as also AC and DC voltages as required for National metrological laboratories and accredited laboratories.

The results of essential type tests required in IEC 61083-1 and problems of applicability are discussed.

The results of the official calibration performed by the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig on the first TR-AS 200-14 digital recorder are shown.

Two of this digital recorders meantime are established as Reference Standards of Measurement at the PTB as also in our DKD Calibration Laboratory for electrical impulse parameter DKD-K-11701.

1. Introduction

It is a long time from the first digital recorder with stable analogue parameters, developed 1978 – 1981 and especially designed for the automatization of high voltage tests /1/ with a sampling rate of 20 MS/s and a resolution of 6-8 Bit until today. Commercial digital recorders at this time had no good performance with stable scale factors, they only were useful for showing the signal lapse.

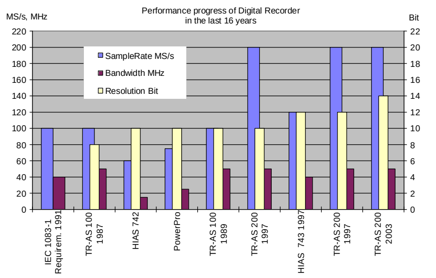


Figure 1: Performance Progress of Digital Recorder

Later in 1987, the first TR-AS 100-8 Digital Recorder was delivered to customers for h.v. impulse tests and was therefore the first system with 100 MS/s sampling rate (Figure 1), which fulfilled all requirements of the IEC 1083-1, published later in 1991 /2/.

A short time later in 1989 followed the TR-AS 100-10 Digital Recorder with 100 MS/s sampling rate at 10 Bit resolution which fulfilled all requirements of IEC 1083-1 in all respects for comparative measurements, too /3/4/.

The first systems with 12 Bit resolution and sampling rates of 120 MS/s respectively 200 MS/s followed in 1997 including self-adaptive evaluation software /5/ and automtization features /6/.

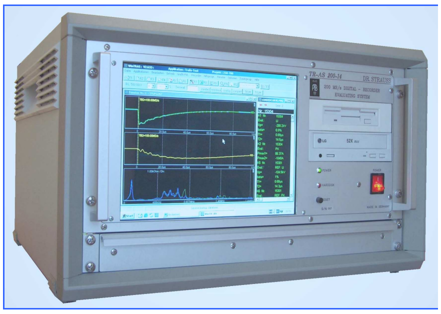


Figure 2: TR-AS 200-14 Desktop System with PTB Calibration Mark 2002 for Calibration Laboratory DKD-K11701

End of 2002 a new designed system with 200 MS/s and 14 Bit resolution, optimized response parameters and further significantly reduced noise was presented (Figure 2).

One system was delivered to the Physikalisch-Technische Bundesanstalt Braunschweig to get a new National Standard and another to the Calibration Laboratory DKD-K11701.

2. Hardware description TR-AS 200-14

The prooved Impulse Voltage Measuring Systems TR-AS, including the digital recorders from our own development and manufacturing, were consequently further developed and show now improved sampling rates up to 200 MS/s in realtime with 14 Bit resolution and 50 MHz bandwidth simultaneously in up to 16 measuring channels.

The new composit A/D-converter hardware system developed by DR. STRAUSS Ltd. generates raw data with up to 14 Bit resolution together with the highest available sampling rate of 200 MS/s and a full bandwidth of 50 MHz today.

A careful design using sophisticated programmable logic controllers and SMT optimizes the demanding requirements like high sampling rate, small risetime, minimized noise, short settling time, small measuring uncertainty and good long-term accuracy.

The high sampling rate of 200 MS/s and the high bandwidth of 50 MHz show increased accuracy and reduced standard deviations for the front time of full impulses as also for the peak and the time-to-chopping at front chopped impulses and allow therefore measurement of steep impulse voltages with reduced uncertainty, too.

The resolution increased to 14 Bit and a noise reduced to 0,02 % results in nearly smooth shapes without visible quantization steps and improves the results of diagnosis using difference method and transferfunction. The measuring electronic is specially designed considering the application in the h.v. testfield with extremly high electromagnetic distortions. The individual measuring channels comprising of input divider, measuring amplifier, A/D-converter and recorder memory are constructed modular and independently from each other, so easy assembly of 1 up to 4 channels is possible including a later upgrade depending on the application.

The 1600 or 2000 V input divider as the critical component is designed for high performance and long term stability including an overvoltage protection tested with 7 kV peak voltage.

The analogue bandwidth and risetime of the input divider as also of the direct input could be increased and amounts to 75 MHz and 5 ns respectively, so the analogue bandwidth and risetime overall for both corresponds to 50 MHz and 7 ns.

The direct input feeds a fully programmable measuring amplifier comprises 22 stages, which allows a very fine adaption in 80 %-steps according to a factor of 1.26 to the amplitude values to be measured. In this respect, signal amplitudes can be measured with optimal deflection from 2000 V downto 12 V using the input divider while signal amplitudes from 10 V downto 65 mV can be measured using the direct input.

3. Type Tests

The new systems were subject to several type tests which are described in the following.

Determination of static Integral Nonlinearity INL acc. to IEC 61083-1

The measurement was performed according to IEC 61083-1 applying a constant DC voltage in steps from $0{,}2 \cdot n \cdot 2^{-14}$ to the input increased from n = 1 to $5 \cdot 2^{14}$. For each DC voltage, a record of output was taken and the mean of 100 samples was calculated. The result is shown in the following Figure.

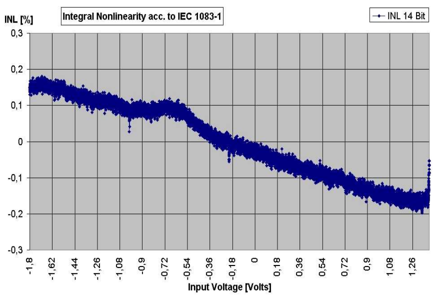


Figure 3: Integral Nonlinearity acc. to IEC 61083-1

Figure 3 show the problems of determination of the static integral Nonlinearity according to the actual Standard IEC 61083-1 arising for digital recorders with high resolution. For this recorder the number of records to be taken – e.g. for a 14 Bit recorder 81920 records – is so high, that the test duration increases significantly up to several hours. Therefore the test results do not show the INL but the long term stability of the digital recorder offset voltage matched with the long term stability of the DC calibration source.

Determination of static Integral Nonlinearity INL with Linear Ramp Method

With this alternative method a linear rising voltage from 0 to 100 % of full scale deflektion (f.s.d.) and a steepness of f.s.d./2^N inside 10 to 16 sampling values is applied to the input and a record is taken. For N=14 a record length of $16 \cdot 2^{14}$ = 256K is sufficient.

In a first step the record measured in channel CH1 is smoothed with a smoothing interval 1 of 10 samples into a virtual channel CH2 to eliminate the noise of the recorder but keep the quantization levels. Additional CH1 is smoothed with a smoothing interval 2 of 1280 samples into a virtual channel CH3 to eliminate the quantization levels of the digital recorder to get a smoothed lapse and keep possible non-linearities of the applied ramp.

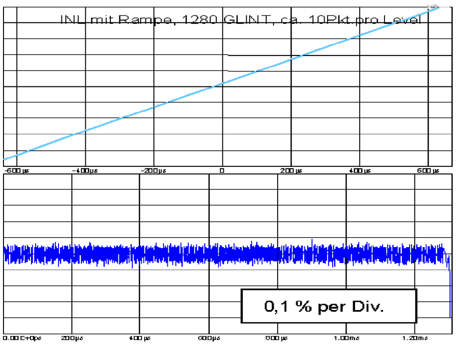


Figure 4: Determination of static Integral Nonlinearity INL with the Linear Ramp Method
Upper shape: linearly rising input voltage

Lower shape: TR-AS 200-14 INL of of typically 0,05 %

In a second step CH2 is subtracted from CH3 and the result corresponding to the calculated INL is displayed in a virtual channel CH4.

For the digital recorder TR-AS 200-14 a INL of 0,05 % was determined with the Linear Ramp Method (Figure 4).

The smooting interval 1 should correspond to the number of constant quantization levels to eliminate primalely the noise but without influence to the quantization levels itself.

The smooting interval 2 should be great with respect to the number of constant quantization levels to eliminate the individual quantization levels. It must be small enough to be without influence to possible nonlinearities of the applied signal ramp.

The resolution of the virtual channels of 16 Bit limits the accuracy of the method because the signal ratio of a 14 Bit recorder to 16 Bit is only 2 Bit, in a first approximation a uncertainty of 25% for the INL determined can be estimated.

In case of virtual channels extended to 32 Bit resolution improofed results can be expected.

Determination of the Differential Nonlinearity DNL under dynamic conditions

The determination of Differential Nonlinearity DNL under dynamic conditions follows according to IEC 61083-1 applying a triangular voltage with 4,25 MHz to the input of the digital recorder TR-AS 200-14. The measurement was referred to a vertical resolution of 12 Bit because the dynamic behavier of the composit A/D-converter hardware system make DR. STRAUSS show a decreasing resolution from 14 Bit downto 12 Bit for increasing signal steepness respectively signal frequencies above some 100 kHz. This behavier in analogue systems is well known as small and great signal bandwidth.

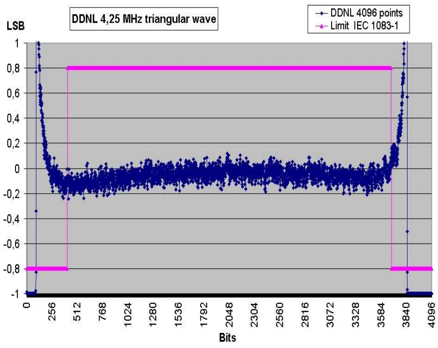


Figure 5: Differential Nonlinearity DNL under dynamic conditions referred to 12 Bit resolution

The result with < 0,2 LSB shown in Figure 5 is significantly below the limits required in IEC 61083-1 of 0,8 LSB.

The dynamic behavior of the A/D-converter implemented show a decreasing resolution for increasing signal steepness respectively signal frequencies without influence to the bandwidth. Therefore the resolution of 14 Bit for signal frequencies from d.c. up to some hundred kHz corresponding to impulse shapes similar to peak and tail of LI and SI is reduced down to 12 Bit for higher signal frequencies corresponding to impulse shapes similar to the front of LI and LIC. For steep voltages a resolution of 12 Bit show together with the high 50 MHz bandwidth and long term stable analogue input excellent calibration results.

The resolution of 14 Bit improofes the accuracy for full waves, for a.c. and d.c. and for comparative measurements advantageously.

Response Measurement

The response measurement was performed with help of a mercury relay directly at the 2000 V input.

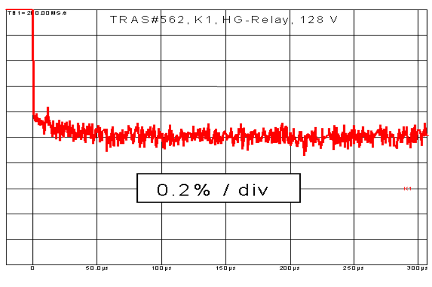


Figure 6: Step response - 50 times vertically magnified - show deviations of less than 0,2% from zero level

The first measurement was made taking one record with 200 MS/s to show the creeping behavior to the stationary zero level.

Figure 6 show the step response vertically magnified 50 times corresponding to 0,2% per division up to 300 µs. The complete system response has settled below 0,2% after some µs already and is stationary to infinity.

The second measurement was performed to calculate the response parameters according to IEC 60-2.

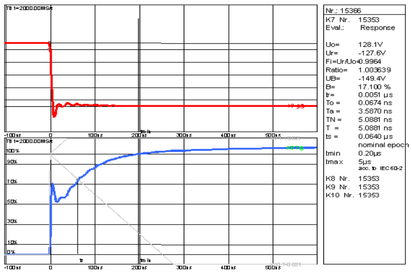


Figure 7: Calculation of the Response Parameters according to IEC 60-2 measured with 2 GS/s using the repetitive sampling method
Upper shape: response u(t) displayed up to 600 ns
Lower shape: response T(t) displayed up to 600 ns

The response u(t) show a minor overshoot of 17 % for less than 20 ns and optimized settling behavior within 64 ns settling time. The risetime is measured between 5 and 7 ns corresponding to 50 MHz bandwidth.

The first partial response time Ta is typically between 3,5 and 5 ns and the nominal response time T_N is calculated between 5 and 6 ns.

With this excellent parameters it can be expected that the measurement of impulse parameters should be possible with an uncertainty never reached in past.

Measurement of Internal Noise with FFT

For the determination of the internal noise level a sinusoidal input voltage of 1 MHz frequency and attenuated 60 dB of f.s.d. is applied, the internal of zero level was set to 50% f.s.d.. After taking the record the fast fourier transformation FFT was performed, the result is shown in a virtual channel and displayed as in following Figure:

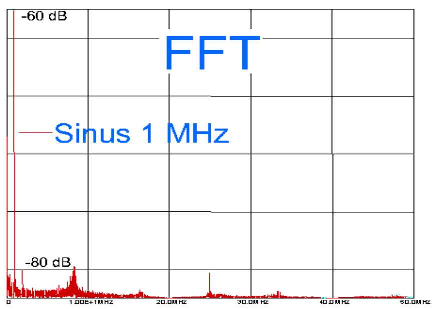


Figure 8: Measurement of Internal Noise with FFT

The Spectralline of the 1 MHz Sinus with known amplitude of 0,1 % f.s.d. shows directly the individual noise level of slightly above 0,01 %. This value corresponds to the noise level of 0,02 % determined according to IEC 61083-1.

Overload Recovery Test

The analogue broadband-amplifier was tested for his overload recovery behavier.

A squarewave voltage of approx. 3.2V was applied to the measuring input set to 4V range and 50% offset and recorded (Figur 9, red wave K5). Then the range was reduced to 2V correspondig 2 times overload and records were taken with 0% offset (blue wave K6) and 100% offset (green wave K1)

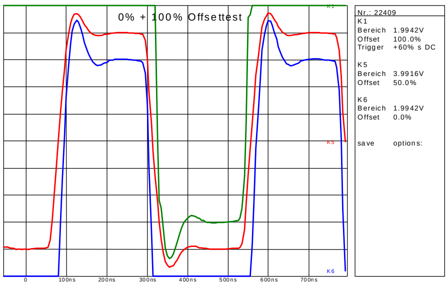


Figure 9: Recovery Test

The recovery of the blue as also the green wave shows no visible delay from the saturation areas <0% respectively >100%.

4. PTB-Calibration Results

The calibration of full waves LI and SI as also chopped waves LIC from 50 V to 1000 V peak was performed with the Reference Calibration Generator System KAL 1000.
The following two tables show calibration results with full lightning impulses LI 0.84/60 and chopped lightning impulses LIC with a time to chopping of Tc=0.5 µs for the digital recorder type TR-AS 200-14 calibrated by the PTB in 2002.

The calibration results for switching impulses SI show values for |dU| ≤ 0,3 % and for |dT1| and |dT2| ≤ 0,6 % similar to LI.

The calibration results for Step voltage with values for |dU| ≤ 0,2 % up to some 100 ms time interval allow calibration of AC and DC voltages, too.

The calibration results fulfill the expectations based on the optimized design of the response behavier of the complete system and especially of the 2000 V input divider.

The TR-AS 200-14 digital recorder can be recommended for Metrological Institutes as their National Standard for impulse measurement as also for AC and DC measurements.

References

1 W. Strauss: Automation of i.v. tests online with microcomputers and digital recorders, thesis TU Berlin 1983.

2 IEC Publication 61083-1: Digital recorders for measurements in high voltage impulse tests, Part 1 - Requirements for digital recorders, 2001

3 W. Strauss: Calibration of digital recorders for h.v. impulse tests, 7th ISH Dresden 1991, paper 62.03

4 H. Bachmann, et al: Field and EMC-tests of a digital h.v. impulse control and measuring system, 7th ISH Dresden 1991, paper 62.04.

5 W. Strauss: Selfadaptive evaluation software for high-voltage impulse tests, ERA-Report 96, MILAN, paper 5.4.

6 W. Hauschild, et al.: Computer-aided performance tests and checks for high-voltage measuring systems, ERA-Report 94-0776, paper 3.3.

LI	positiv			negativ		
Bereich	dU	dT1	dT2	dU	dT1	dT2
V	%	%	%	%	%	%
50	-0,2	-0,4	0,2	0,1	-0,5	0,5
64	-0,3	-0,2	0,2	0,0	0,0	0,3
80	-0,3	-0,5	0,5	-0,1	0,0	0,3
102,4	-0,2	-0,6	0,5	-0,1	-0,6	0,5
128	-0,1	-0,7	0,6	-0,1	-0,8	0,5
160	-0,1	-0,2	0,4	-0,2	-0,5	0,4
200	-0,1	-0,1	0.3	0,0	-0,4	0,3
256	-0,2	-0,4	0,5	0,0	-0,1	0,3
320	-0,3	-0,5	0,5	-0,2	-0,2	0;4
400	-0,4	0,0	0,6	-0,3	-0,2	0,4
500	-0,2	-0,2	0,4	-0,1	-0,1	0,3
640	-0,2	-0,4	0,6	0,0	0,2	0,3
800	-0,2	-0,2	0,6	0,0	0,4	0.4
1000	-0,2	-0,1	0,8	-0.1	0.2	0,5
1250	-0,2	-0,4	0,4	-0.1	0.0	0.4
1600	-0,1	-0,4	0,4	0.0	0.1	0.3
2000	-0,1	-0,5	0,3	0.0	-0,1	0.4

Table 1: PTB-Calibration with LI

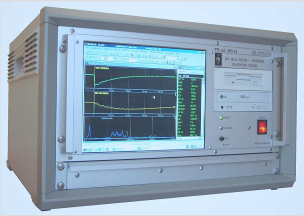
LIC	positiv		negativ	
Bereich	dU	dTc	dU	dTc
V	%	%	%	%
102,4	0.0	1.4	0.1	1.0
128	0.0	0.0	0.1	1.4
160	-0.3	0.0	0.2	0.2
200	-0.3	0.4	0.1	0.4
256	-0.2	0.8	0.2	0.2
320	-0.1	1.0	0.3	0.0
400	-0.4	1.0	0.0	0.0
500	-0.2	1.0	0.0	-0;2
640	0.0	1.0	0.4	-0.2
800	-0.1	1.0	0.1	-0.2
1000	-0.3	0.8	0,1	-0,4
1250	-0.1	1.0	0,2	-0,4
1600	0.1	0.8	0,3	-0,4
2000	-0.1	0.8	0,3	-0,4

Table 2: PTB-Calibration with LIC

5. Discussion at the oral session O.27.02 on Thursday, August 28th, 2003

DR. STRAUSS

Digitalrecorder TR-AS 200-14



- Desktop System
  for the PTB
  and with PTB-Calibration
  for the Calibration Laboratory
  DKD-K-11701
- 200 MS/s
- 14 Bit rated resolution
- 50 MHz bandwidth

DR. STRAUSS

Typetest TR-AS 200-14

- INL acc. to IEC 61083-1
- INL with Linear-Ramp-Method
- Differential Nonlinearity DNL under dynamic conditions
- Step-Response-Measurement
- Response Parameter acc. to IEC 60-2
- Measurement of internal noise with FFT
- Test of amplifier overload recovery
- PTB-Calibration with LI, LIC, SI, STEP: 4543 PTB 02

DR. STRAUSS

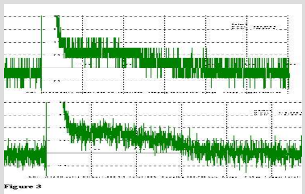
Digital Signalprocessing efficient?

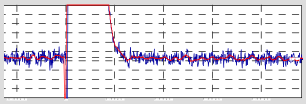
Resolution Enhancement (refere to HAEFELY website)
(www.haefely.com/measuring_diagnostics/hias743_additional.html)
By signal processing the resolution can be enhanced but at the same time the bandwidth of the system is significantly reduced. A resolution enhancement of + 2 bit reduces the bandwidth to less than 6% of the original. Therefore this process is mainly useful for research or switching impulses.

- The HiAS 743 system offers the following amplitude resolutions:
  - 12 bit (basic resolution: overall bandwidth 50 MHz)
  - 13 bit (+ 1 bit enhanced: overall bandwidth 12 MHz)
  - 14 bit (+ 2 bits enhanced: overall bandwidth 3 MHz)
- We think, **not in this way**, because TRAS Digital-Recorder have **full bandwidth 50 MHz** for 60 – 100 - 200 MS/s and for all rated resolutions from 8 – 10 – 12 or 14 Bit
- Digital Signalprocessing up to 16 Bit only adaptive to increase the accuracy of evaluation algorithm

DR. STRAUSS

Resolution and Noise





- Enlargement of recordings performed with HIAS 10 bit (top) and 12 bit (bottom) digitizers. The 10 bit digitizer shows the steps of individual bits.
  (Fig. 3 of paper 1.177.P4 "Requirements and Limitations of Digital Impulse Analysing System" by M. Loppacher, HAEFELY TEST AG Basel,Switzerland published on 11th ISH August 23-27, 1999, Montreal)
  noise 0.3% peak-to-peak
  [scale 0.15% per div]
- The 14 Bit digitizer type TRAS 200-14 make DR. STRAUSS have a A/D-converter system developed in house which shows also at 14 Bit resolution steps of individual bits, clearly separable from the noise 0,15% peak-to-peak
  [scale 0.1% per div]
- red shape: resolution enhancement to 16 bit by signal processing

Some digital recorder use digital signal processing for resolution enhancement from 12 to 13 or 14 Bit

the applied filter algorithm significantly reduce the bandwidt from 50 down to 12 respectively 3 MHz.

This method does not fulfill no longer the IEC 1083 requirements regarding bandwidth

We have developed an 200 MS/s analog-digital-converter systems with high bandwidt of 50 MHz upto 14 Bit resolution

We use digital signal processing upto 16 Bit only to increase the accuracy of evaluation algorithm

The picture show comparison
of HIAS 10 and 12 Bit recorders – green shapes
with the TRAS 14 Bit recorder – blue shape
vertically extremly magnified

The noise could be further reduced to 0,15% peak-to-peak

DR. STRAUSS

Overview of the PTB - Calibration

full lightning impulse LI	|dU| ? 0,4 %	|dT1| and |dT2| ? 0,6 %.
front chopped lightning impulse LIC	|dU| ? 0,4 %	|dTc| ? 1,4 %.
swithching impulse SI	|dU| ? 0,3 %	|dT1| and |dT2| ? 0,6 %
step voltage STEP	|dU| ? 0,2 %	up to 100 ms time interval

• never obtained calibration results for direct impulse measurements

DR. STRAUSS

Results of Calibration

- The Calibration results fulfill the expectations regarding
- the optimized step response behavier of the whole system – especially of the 2000 V input stage
- the bandwidth of 50 MHz – also at 14 Bit
- with significant reduced uncertainties for measuring of the time parameters