HAEFELY HIPOTRONICS

Technical Document

PD performance of UHV-DC test equipment

C.-H. Stuckenholz, M. Gamlin, P. Mraz
Haefely Hipotronics, HV and Tettex Instruments Division

TD-104

HAEFELY HIPOTRONICS

Designed by Tettex INSTRUMENTS

precision. swiss made.

HIGH VOLTAGE TEST SOLUTIONS

PD PERFORMANCE OF UHV-DC TEST EQUIPMENT

C.-H. Stuckenholz[1*], M. Gamlin[1], P. Mraz[1]
[1]Haefely Test AG, Birsstr. 300, 4052 Basel, Switzerland
*Email: Stuckenholz.carl-hendrik@haefely.com

Abstract: The demand for reliable, economical and environmentally friendly energy is steadily increasing. This requires the transportation of energy over long distances at acceptable cost and losses. Recent improvements in the industry have allowed higher DC transmission levels at reduced costs and consequently the importance and total number of DC transmission have grown. Although voltage levels have been pushed as high as 800 kV, discussion is ongoing for even higher voltage levels. For research and production it is mandatory to have appropriate test equipment. Although DC test generators have been built since decades, the demand for low PD test systems and laboratories has increased lately. The industry standard for PD testing is the IEC 60270 ed. 3.0. The intention of the paper is to start the discussion in the HV community on these topics. The better understanding of PD behaviour for DC equipment will help to build more reliable equipment necessary for the reliable energy demand of the future.

1 INTRODUCTION

The demand for reliable, economical and environmentally friendly power has been steadily increasing over the past years. The power generation is located at geographically defined places far away from the public, industrial and private end users. This requires the efficient transportation of the energy over long distances. HVDC transmission has proven to be an efficient solution for this purpose. Consequently the transmission voltage levels have increased over the past years and with them the testing requirements for the installed components.

The testing of UHV-DC equipment, especially converter transformers, reactors and bushings, is accompanied by partial discharge measurements. Although the importance of DC PD measurement is increasing, literature and experiences on DC PD performance is hard to find. As a manufacturer of test equipment and power equipment, it is especially important to have low PD level test equipment to avoid any impact on the acceptance tests of the UHV-DC power equipment. During the last 5 years several test systems between 1 MV and up to 2.2 MV DC have been erected.

The intention of the paper is to start and intensify the discussion on DC PD performance in the HV community and to gain a better understanding of the processes being involved. The test objects have to work reliable for up to 30 years in environments which are less controlled than the typical HV test lab.

2 DC PD TESTING - THEORY

An overview of tests and test standards has been presented in [1]. The standards for converter transformers, bushings and reactors are very similar and will be the main focus of this paper.

2.1 Requirements for Test Objects and Test Systems

The PD testing is separated into a Withstand Test (WT) and a Polarity Reversal Test (PRT). The differences between the different apparatus test standards are the PD level and the number of pulses [2-4].

Withstand Testing [WT]:
higher test voltage level than during PRT
120 min positive, no negative

Polarity Reversal Testing [PRT]:
lower test voltage level than during WT
90 min negative, 90 min positive, 45 min negative

The test time for the PD is during the last 30 min of the 2 hr test. The number of allowed pulses varies and is lower for the bushings. During PRT the requirements are different with the converter transformer PD only measured directly after the completion of each polarity reversal (PR) while the smoothing reactors and bushings have to be measured during any 10 min and 30 min time window respectively excluding the polarity reversals.

All three standards allow for one 30 min extension during WT, in case the PD criteria are not met. The standards for converter transformers and bushings request to disregard pulses that are proven to be external to the test object, the standard for the

smoothing reactors does not explicitly allow for the reduction of the pulse count [2-4]. It can be concluded, that the PD acceptance criteria is the highest for the bushing testing, as it has the lowest allowed number of pulses during the longest time span.

Based on above standards, a universal PD specification for UHV-DC test systems was derived. Table 1 gives an overview of the times and acceptance criteria [1]:

WT: No more than 5 pulses with magnitudes 500 pC ≤ x < 1000 pC during the last 30 min of a 2 hour test at U_{WT}.

PR: No more than 5 pulses with magnitudes 500 pC ≤ x< 1000 pC during any sliding 30 min window of the test time at U_{PRT}, excluding the PR periods.

Table 1: Details of acceptance criteria [1]

	Converter Trans formers	**Smoothing Reactors**	**Bushings**	**Test systems**
IEC	**61378-2**	**60076-6**	**62199**	
Withstand Testing				
Time frame	Last 30 min *(Last 10 min)*	Last 30 min *(Last 10 min)*	Last 30 min	Last 30 min
Count Level	≤ 30 pulses ≥ 2000 pC *(≤ 10 pulses ≥ 2000 pC)*	≤ 30 pulses ≥ 2000 pC *(≤ 10 pulses ≥ 2000 pC)*	≤ 10 pulses ≥ 2000 pC	≤ 5 pulses 500 pC ≤ x < 1000 pC
PR Testing				
Time frame	30 min after PR *(Last 10 min of 30 min period)*	Any 10 min window without first 5 min of polarity	Any 30 min sliding window except reversal periods	Any 30 min sliding window except reversal periods
Count Level	≤ 30 pulses > 2000 pC *(≤ 10 pulses > 2000 pC)*	≤ 10 pulses ≥ 2000 pC (≥ 500 pC shall be recorded)	≤ 10 pulses ≥ 2000 pC	≤ 5 pulses 500 pC ≤ x < 1000 pC

2.2 PD behaviour under DC voltage

The physical principles of partial discharges under DC stress have been discussed in [1,5]. Kreuger states for the inception voltage a PD pulse rate of 1 pulse / min, which is the allowed pulse rate for converter transformer and smoothing reactors. For low level PD test equipment, it is essential to control the internal and external PD. Since the internal insulation design of the coupling capacitor is rather simple compared to the insulation design of the test objects, internal PD has not been an issue with the test systems. The external design however is more complex. External discharges, corona discharges, have been defined into two classes, geometrical corona and field enhanced corona [6].

1. Geometric corona:
- Determined by macroscopic shape of electrode
- typically random distribution around the highly stressed part
- PD often > 1000 pC
- noisy, detectable with UV camera
- inception level high

2. Field enhanced corona:
- Caused by surface irregularities
- typically appears in one spot
- PD can range from detection limit to > 1000 pC
- inception level as low as 50 % of geometric corona possible

The geometric corona must be handled during the design phase of the electrodes and system. Due to the long test times, the large electrode surfaces, isolation volumes involved, changing climatic conditions, dust, etc., field enhanced corona is not predictable. PD pulses will eventually occur with a certain statistical probability. It will require significant efforts to control the surroundings to reduce the statistical probability and to prevent these discharges. The necessary inception field strength for field enhanced corona can be as low as 50 % of the field strength for geometric corona [6]. For low numbers of allowed PD pulses and equivalent charge, these pulses must be avoided since one discharge event might let fail the acceptance test.

2.3 PD measurement

The standards refer to PD measurement according to IEC 60270. Since the counts of pulses and the level of the pulses are defined, they need to be precisely measured. Some standards allow to disregard the pulses when they can be proven to be external. At the current stage of development, this will require alternative PD measurement techniques, however the proving is still very difficult.

2.3.1 Electrical PD measurement acc. IEC 60270

Electrical PD measurements are the most common measurements. Only they allow for the determination of the apparent charge and the number of pulses as required by the relevant apparatus standards. Since the apparent charge level will be calibrated before the actual measurement, the acceptance throughout the industry is very high. DC PD measurements have important differences to the AC measurement, which are not completely reflected in current PD measurement and calibration techniques.

According to [7] PD detectors must have a pulse train response according to Table 2.

Table 2: Pulse train response acc. IEC 60270

N (1/s):	1	2	5	10	50	≥100
R_{min} (%):	35	55	76	85	94	95
R_{max} (%):	45	65	86	95	104	105

The pulse train response is valid for equidistant pulses with a pulse repetition frequency N, the reading shall be between R_{min} and $R_{max.}$. For DC PD measurements, the allowed pulse rate is typically around 1 pulse/min or even less. Therefore the pulse train response is not applicable, as is stated in Note 4. This means, weighting acc. IEC 60270 must be deactivated in the PD detector software. Current PD calibrators submit pulses with a higher repetition rate, therefore during the calibration process it cannot be verified if the pulse train response has been deactivated in the software and is functioning properly.

The PD detector must be set to the fixed amplitude of interested, auto-ranging is not possible since the dynamic behaviour is too fast for the PD detector to switch between ground noise level and amplitude. The calibration level "should, in lieu of other specifications, be understood to be from 50 % to 200 % of the specified PD magnitude [7]." With DC PD testing, a calibration of the detector may become difficult. For example IEC 60700-1 and IEC 62501 for different type of valves define different numbers of PD pulses on PD levels from 300 pC to 2000 pC [8,9].

Some PD detectors allow the setting of the dead time. Since this parameter has a major influence on the counting, it will be discussed more in detail in Chapter 3.

The purpose of the calibration is "to verify that the measuring system will be able to measure the specified PD magnitude correctly [7]." It must be questioned, if this approach is sufficient for a calibration where a charge level **AND** a pulse count determine pass or fail of a test object.

2.3.2 Alternative PD measurement

Alternative PD measurement techniques can be based on the effects of PD, which are mainly the radiation of sound, ultra-violet light and electro-magnetic waves. These alternative test methods cannot measure the apparent charge and pulse count to make them comparable to the electrical PD measurement. Additionally it may be very difficult to synchronize the PD event with the single PD counts on the electrical detector. According to the authors experience the advantages and disadvantages of the different methods with current technology are summarized below:

UV-Camera:
+ Detection of geometric corona
+ Detection of field enhanced corona (dirt on surfaces)
- Limited field of view
- Line of sight is mandatory
- Limited time resolution
- Statistical noise

Directional microphone:
+ Detection of geometric corona
+ Detection of field enhanced corona (dirt on surfaces)
- Exact localization difficult
- Limited time resolution
- Limited "field of view" of horn
- Dynamic range of impulses
- Typically without recording, no proof

UHF-Sensors
+ Large "field of view"
+ Localization possible down to some cm
+ High time resolution
+ Synchronization with electrical PD possible
- Rather complicated
- 3-dimensional measurement very demanding
- Manual evaluation is slow and with higher probability for errors
- Setup of sensors requires great care
- Distinction between internal and external pulses may require additional (internal) UHF sensors

These alternative methods are useful tools for the identification of hot spots of field enhanced corona and to verify the general test setup before the test. The tools can give strong indication, where events take place. However when proving of a discharge event is necessary on a single count basis, the UHF-Sensor might be the only applicable technology. At the moment the UHF-technology was proved conceptually, a commercial product with automated and fast evaluation is not available yet.

When relying on alternative methods to distinguish between external and internal pulses and deciding between pass or failure, these methods will need calibration/verification as well.

3 INFLUENCE OF DEAD TIME

Some PD detectors allow for the setting of the dead time. The purpose of the dead time is to reduce false PD information due to wrong evaluation. Fig. 1 shows an example wave shape for a PD pulse measured with a detector with 1.5 MHz bandwidth.

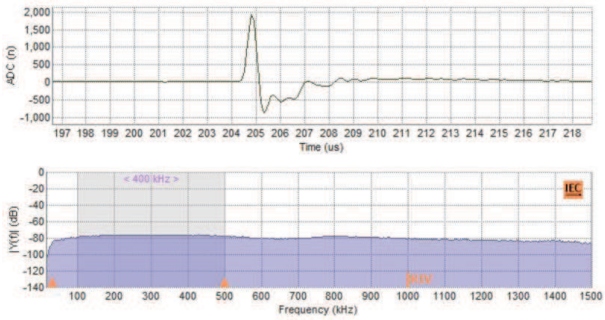

Fig. 1.: PD pulse in time and frequency domain

The shape of the measured PD pulse is mainly determined by the following aspects:

1.: PD measurement system with its inherent and adjustable filter characteristics
2: Impedance characteristics of test object
3: PD travelling path
4: PD type

As a rule of thumb, a narrower bandwidth of the filter will cause more oscillations and therefore a longer pulse duration. The test setup of the circuit consists of a coupling capacitor C_C (1 nF) in series with a Tettex AKV 9310 quadrupole. It is connected to a test object capacitor C_T (2.2 nF). The calibrator Tettex KAL 9250 was injecting into C_T. The PD detector Tettex DDX 9121b was equipped with an older software with dead time setting and the current software with automatic pulse detection.

The calibrator was set to burst mode. The pulse repetition frequency PRF is then defined by the internal frequency (0.1 – 1500 Hz) or the number of pulses per cycle (1 – 32) with the cycle length being derived from light synchronization [10]. The number per cycle was set to 1 pulse/cycle. This pulse repetition rate is very slow, especially compared to real discharges as for example corona discharge. Fig. 2 – 5 shows the results for 100 pulses. With 1 µs, the detector was not able to determine the polarity of the impulse correctly. The pulse width is only 4 µs, therefore a dead time setting of 5 µs is sufficient for this setting and 10 µs and auto detection will not show different results.

The pulse count for 1 µs dead time shows 195 counts and it shows the pulses with positive and negative polarity, although the pulse was only injected positive. With the dead time set too short, undershoot/ringing can be identified as wrong PD pulses with the same or opposite polarity. With the dead time set to 5 µs or above all pulses were correctly counted.

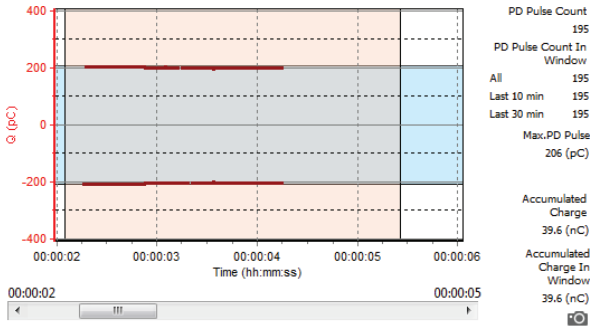

Fig. 2.: Dead time = 1 µs, 195 counts

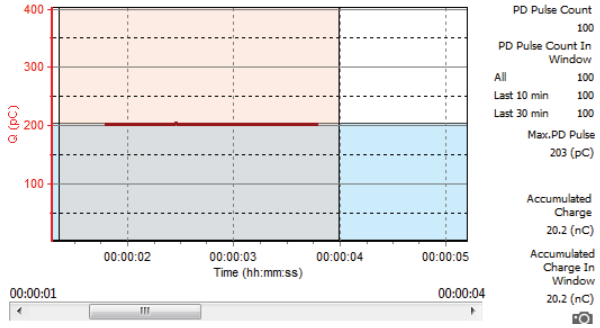

Fig. 3.: Dead time = 5 µs, 100 counts

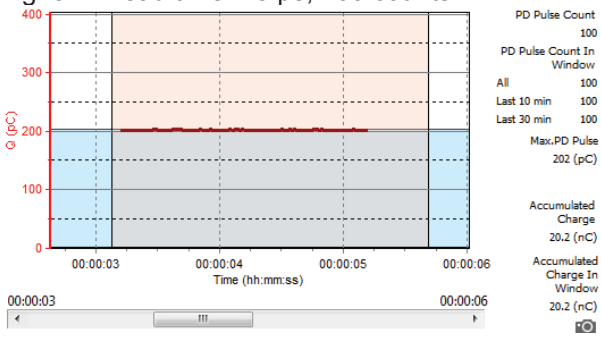

Fig. 4.: Dead time = 10 µs, 100 counts

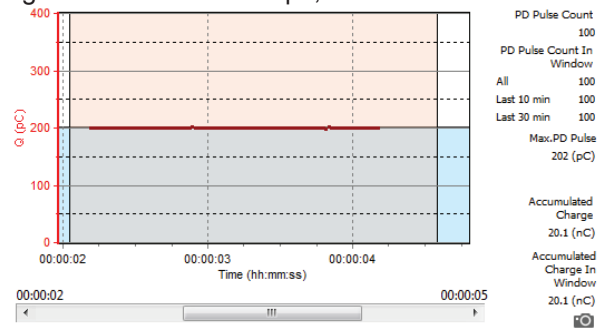

Fig. 5.: Automatic pulse count, 100 counts

From above results the calibration with the dead time of > 5 µs seems to be acceptable. However an example with a rod-plane arrangement shows, that the pulse repetition frequency is significantly higher than the pulse rate from the PD calibrator. For that reason, pulses may not be detected when the dead time is set too long, see Fig. 6.

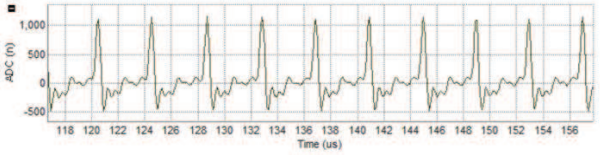

Fig. 6.: Pulse shape for rod plane arrangement

With the dead time set to 10 µs, 2 of 3 impulses will be ignored which is 4000 pulses per period for this example.

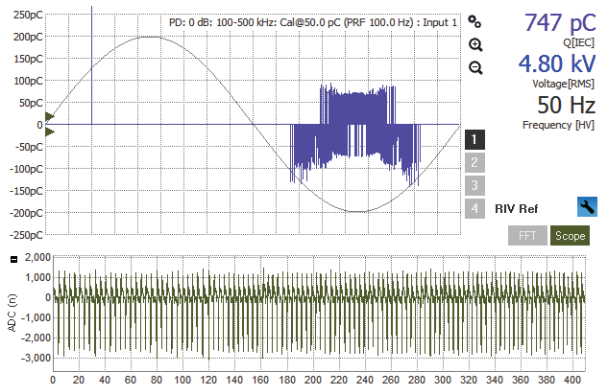

Fig. 7.: Rod plane arrangement,10 µs dead time

Fig. 7 shows, that with the changing repetition rate during the voltage increase/decrease of the cycle, the detector starts to detect different polarities of the pulses again, which is physically not possible. With a fixed Based on these findings, PD detectors with fixed dead time are physically not capable of doing a correct PD counting. Ceretta et al. report on PD measurement on cast resin transformers [11] where they found oscillations of a PD pulse increasing the duration, as measured with the calibrator, by an order of magnitude to 500 - 600 µs, Fig. 8.

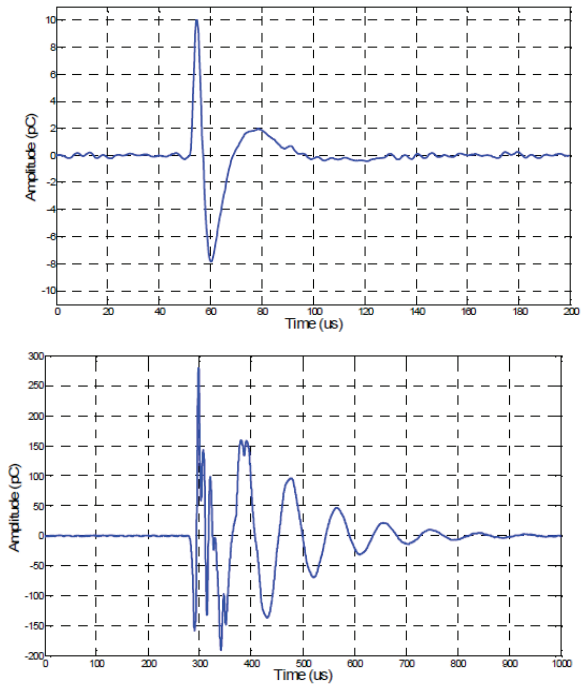

Fig. 8.: Response to calibration pulse (top) Response to PD pulse [11]

Even a dead time setting of 100 µs would not have been sufficient for this pulse and create positive and negative pulse counts. Long oscillations like these will reduce the time resolution of subsequent pulses and give possibly origin to superposition errors [11].

The implementation of a smart algorithm seems to be an appropriate way. However it must be ensured and verified, that these algorithms from different vendors will result in the same count numbers. Especially with the possibility of superposition errors the quality of an automated evaluation may vary. Since major components of these algorithms are done in the software, it may be a suitable approach to use synthetically generated test data to verify the software evaluation like it is done with the software for impulse testing [12]. The IEC 61083-2 includes a test data generator (TDG) which is based on artificial and measured waveforms to qualify the evaluation software by given tolerances. The pulse detection and counting may be done at different stages within the signal processing, therefore a pure software based TDG approach may not be satisfactory and an additional hardware TDG may be necessary.

4 DC PD TESTING – EXPERIENCE

The test results are presented from an acceptance test for a HV DC test system for 1800 kV. As pointed out in Chapter 2, some standards allow to disregard external pulses if they can be proved to be external. With current technology, a “water-tight” proving is not possible, the tools can only give strong indications where the pulses occurred.

During PRT at ± 1600 kV a total of 28 counts was detected. After approx. 16 min an audible discharge occurred with a total of 16 counts and a peak level up to │8530 pC│. The remaining 12 counts were recorded during the different stages of the PRT, the level did not exceed │200 pC│. Table 4 shows the results for the discharge event.

The PD level and time stamp have been exported from the saved test data. The smallest time division of the test data of this PD recorder is 1 ms. The duration of the discharge event can be estimated to 200 ms and the total number of counts was 16. 3 counts were below 2000 pC. Of the remaining 13 counts, 4 counts (count 4, 7, 10, 12) were identified as positive pulses, however the positive pulses never occurred alone but always in a time frame together with a negative pulse.

Although the discharge was recorded with a PD detector with a smart detection algorithm, the positive counts seem to be measurement errors. Without the transient recording from an oscilloscope it is impossible to distinguish, if these counts have been real counts or are due to some evaluation error.

Table 4.: PD count for audible event

Time [ms]	PD level [pC]	Count > 2000 pC
982238	-625	
	-5812	1
982256	-5978	2
982267	-6150	3
	5225	4
982308	-6514	5
982321	-6710	6
	5685	7
982339	-7037	8
982361	-1827	
	-7108	9
982392	6204	10
	-8530	11
	7243	12
982430	-483	
	-7366	13

The allowed count level for a bushing is 10 pulses > 2000 pC within any 30 min sliding window during the complete polarity reversal test excluding the polarity reversal periods, so the only 1 audible discharge created a pulse count of 13 within 200 ms with 4 counts giving strong indication that they are measurement errors. Considering the 4 positive counts as valid, the bushing failed, considering them as measurement errors the bushing passed.

The alternative measurement techniques would not have helped in the decision making. Their time resolution would not allow to differentiate the single counts. With the camera and ultrasonic showing only a part of the system, one must always question if a discharge event was taking place at the same time at a different location. The manual evaluation of the UHF-sensor measurement would not have been able to cover all the counts.

5 CONCLUSION

With the demand for HVDC power transmission increasing over the last years, the DC PD measurement became more and more important. The increased importance is not yet reflected in the standards. As pointed out, there is strong evidence that current calibration processes and measurement devices are not yet capable of correctly measuring DC PD with the requirements for pulse level AND pulse count. Additionally, further research must be done to clarify if AC definitions can be applied to DC conditions as well. When a single discharge can create several pulse counts, it is not creating a problem in an AC test. But with the DC tests only allowing for certain pulse count numbers, it is essential if a discharge event from an electrode creates 1 count or 10 counts and if these 10 counts must be referred to as pulses as in the standards. Some standards allow to disregard external pulses when they can be proved to be external. With currently available technology a proving is not possible and there will be always discussions between manufacturers and customers. The intention of the standards and the acceptance criteria is to ensure the quality of the test objects. Therefore a precise and correct PD measurement with apparent charge and pulse count is mandatory. The introduction of a suitable TDG for the PD measuring instrument qualification should be discussed.

REFERENCES

[1] C.-H. Stuckenholz, P. Lequitte, M. Gamlin, R. Connell: “PD Requirements for testing HV DC equipment and their impact on HV DC test equipment”, Proceedings 17th ISH Hannover, C-002, 2011.

[2] IEC 61378-2 ed. 1.0 (2001-02), Converter transformers: Part 2: Transformers for HV DC applications

[3] IEC 60076-6 ed 1.0 (2007-12), Power transformers Part 6: Reactors

[4] IEC 62199 ed. 1.0 (2004-05), Bushings for d.c. applications

[5] F. H. Kreuger, Industrial High DC Voltage, Delft University Press, ISBN 90-407-1110-0

[6] M. Larsson, O. Hjortstam, H. Faleke, L. Arevalo, D. Wu, L. Ming: “Corona at Large Coated Electrodes”, Proceedings 23rd Nordic Insulation Symposium, Trondheim, 2011

[7] IEC 60270 ed. 3.0 (2000-12): High voltage test techniques – Partial discharge measurement

[8] IEC 60700-1 ed. 1.2 (2008-11): Thyristor valves for high voltage direct current power transmission

[9] IEC 62501 ed. 1.0 (2009-06): Voltage sourced converter valves for high-voltage direct current power transmission

[10] Tettex KAL 9520 manual

[11] C. Ceretta, R. Gobbo, G. Pesavento: “Effect of integration error on partial discharge measurements on cast resin transformers”, Proceedings 16th IMEKO TC4 Symposium, 2008

[12] IEC 61083-2 ed. 2.0 (2013-03): Instruments and software used for measurement in high-voltage and high-current tests – Part 2: Requirements for software for tests with impulse voltages and currents

The original version of this article was published in ISH 2015 proceedings: 19th International Symposium on High Voltage Engineering, Pilsen, Czech Republic, 2015

Locate our local sales representative at

www.haefely-hipotronics.com

OFFICES:

Europe
Haefely Test AG
Birsstrasse 300
4052 Basel
Switzerland

☎ + 41 61 373 4111
🖷 + 41 61 373 4912
sales@haefely.com

China
Haefely Test AG Representative Beijing Office
8-1-602, Fortune Street
No. 67, Chaoyang Road, Chaoyang District
Beijing, China 100025

☎ + 86 10 8578 8099
🖷 + 86 10 8578 9908
sales@haefely.com.cn

North America
Hipotronics, Inc.
1650 Route 22 N
Brewster, NY 10509
United States

☎ + 1 845 279 3644
🖷 + 1 845 279 2467
sales@hipotronics.com