



ROTATING MACHINE PARTIAL DISCHARGE MEASUREMENTS VIA PREINSTALLED 80-pF-LINE-COUPLERS IN TERMS OF PICOCOLOMB (pC)

**Hendrik Elze, Stefan Kornhuber, Matthias Boltze
Doble Lemke GmbH**

ABSTRACT

At stator windings of rotating machines we have the effect that partial discharge signals from sources deeper inside the machine, away from the decoupling point, are pre-integrated and attenuated in amplitude due to the low pass behavior of the signal path along the winding.

Only the lower frequency contents remain at the measuring point in contrast to the higher frequency contents of the PD closer to the coupler.

Many rotating machines worldwide are equipped with 80-pF-line-couplers accessible for repetitive PD measurements. With the 50- Ω -load of the PD detector this forms a high pass of approx. 40-MHz. Usually, the mV-quantified PD measurements are done in the frequency range of several tens of MHz. Hence the internal discharges are measured with poor sensitivity, whereas the PD pattern is dominated by the end winding discharges.

More promising in that respect is the PD charge measurement in picocoulomb acc. IEC 60270. The reading of the PD activity is less depending on the pulse shape. That provides more sensitivity for internal discharges leading to a better reliable assessment of the entire insulation state.

The paper resolves the apparent contradiction to the 80-pF-line-coupler high pass behavior.

By signal conditioning it is possible to maintain the signal integration, necessary for charge-pC- measurement.

Additionally the test voltage signal can be derived for synchronization the phase resolved PD Pattern.

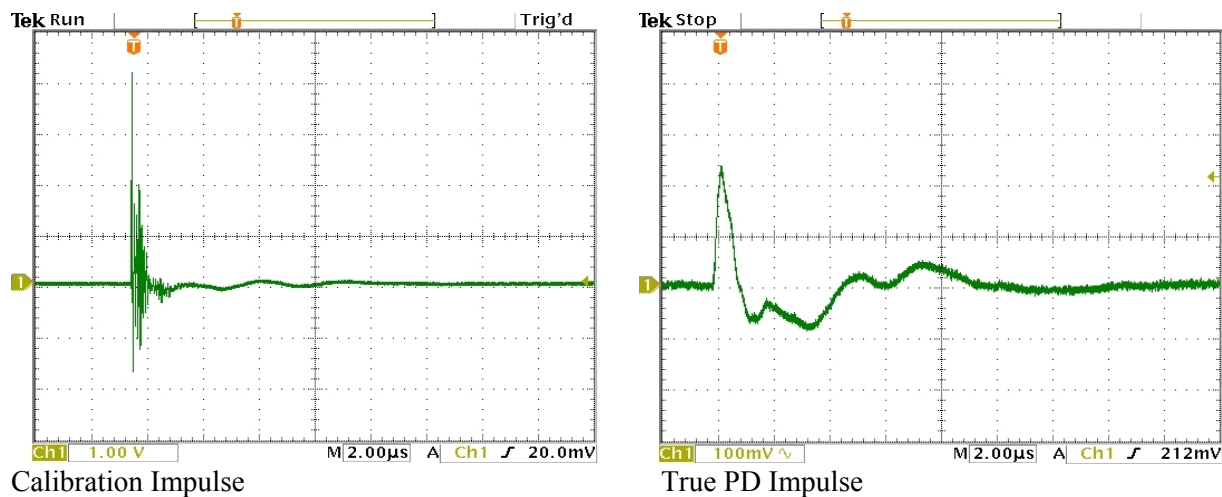
Comparative measurements at a generator stator with larger coupling capacitors illustrate the feasibility of charge measurements via 80-pF-line-couplers. Further ideas of characterization the integration behavior are presented and calibration questions are discussed.

INTRODUCTION

The measurement of the PD activity as charge in terms of pC provides on one hand the advantage to be sensitive for PD inside the winding away from the decoupling point. On the other hand it is necessary that not only the PD detector provides an appropriate integration behavior but also the whole signal chain including the PD coupler.

Figure 1 shows as example a calibration signal (calibrator, 10 nC, in parallel to the terminals) and a true PD signal gathered at the phase terminal of a generator stator winding (turbo generator, 11 kV, 41 MVA).

In opposite to the calibration impulse the true PD signal has a much longer pulse duration and is an indicator for the internal integration behavior of the generator winding itself, depending on the fault position.



Comparison of Calibration and True PD Impulse Gathered at 11 kV Stator Winding (41 MVA) with 100-nF-PD Coupler and Traditional Decoupling Quadripole
Figure 1

With respect to the above mentioned 80-pF-line couplers it is obvious that the high pass behavior would lead to a remarkable loss of signal-area (charge), when the PD signal (fig. 1 b) passes that coupler. This can be further illustrated if the high pass time constant of $80 \text{ pF} * 50 \Omega = 4 \text{ ns}$ will be considered in relation to the pulse PD duration of approx. $1 \mu\text{s}$. The mentioned line coupler shows a strong differentiating behavior.

The basic idea to overcome the loss of signal area is to compensate the high pass behavior by an appropriate low pass filtering of higher order in the signal path. So the charge can be recovered and the integration error minimized.

For that purpose a special line coupler matching unit was developed that includes such low pass filter ($f_2 = 500 \text{ kHz}$). That module provides furthermore an electronic op-amp circuit with low impedance input that integrates the capacitive coupler current and gives out the HV signal for synchronization the phase resolved PD pattern.

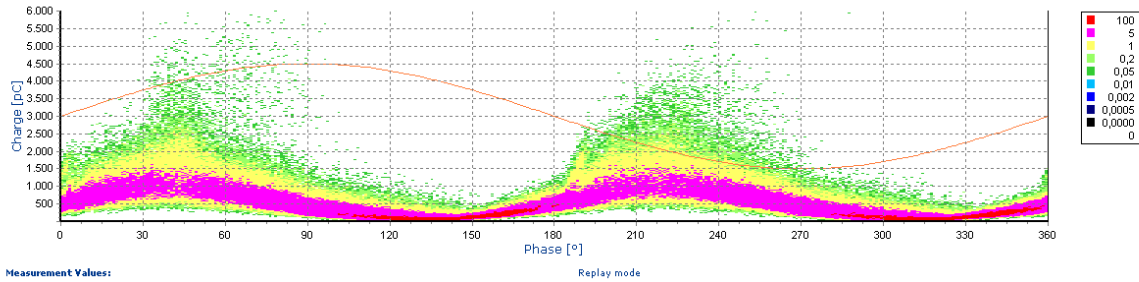
GENERATOR STATOR MEASUREMENTS

In order to verify that idea deeper comparative measurements at generator stator winding (mentioned above) have been conducted with the first main target to compare the measuring results in the frequency range up to 500 kHz (according to IEC 60270). The calibration procedure was performed according to standard by means of 10 nC calibrator in parallel to the phase terminal and ground.

The following coupler arrangements were investigated:

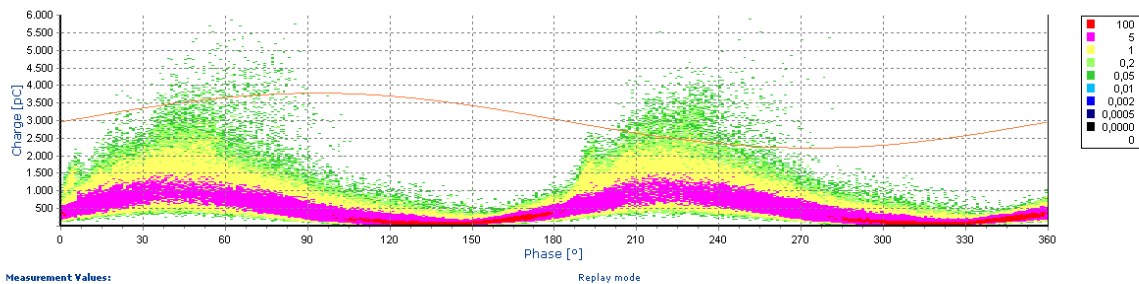
- 100 nF
- 2 nF
- 80 pF with line coupler matching unit (low pass active)

The figures 2 to 4 show the resulting phase resolved PD patterns and the belonging reading of the apparent charge Q_{iic} .



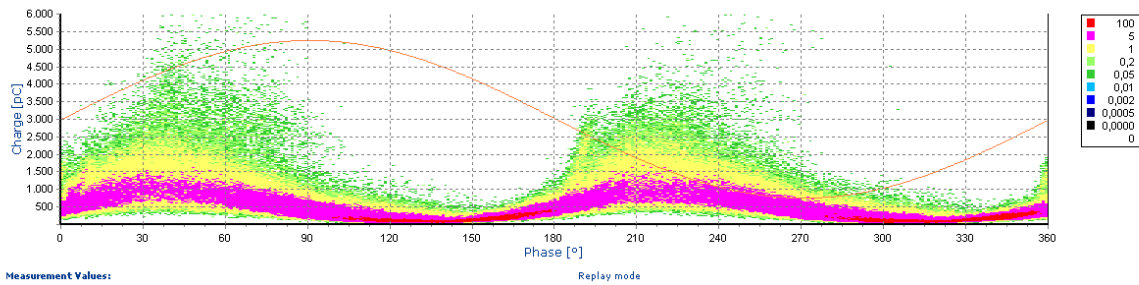
Output created with PD Smart software from Doble Lemke GmbH

100-nF-Coupling Capacitor and Measuring Impedance, $Q_{iec} = 4.24$ nC
Figure 2



Output created with PD Smart software from Doble Lemke GmbH

2 nF Coupler, Internal Measuring Impedance, $Q_{iec} = 4.16$ nC
Figure 3



Output created with PD Smart software from Doble Lemke GmbH

80-pF-Line Coupler with Matching Unit, 500-kHz-low-pass Active, $Q_{iec} = 5.07$ nC
Figure 4

The good correlation of the obtained patterns and the measured apparent charge values is the first indicator of the feasibility of charge measurements using the 80-pF-line couplers.

INVESTIGATION WITH LARGER BANDWIDTHS

Under real on site measuring conditions it is often impossible to apply the measuring bandwidth restrictions of IEC 60270 because of noise issues. In order to improve the signal to noise ratio the upper frequency limit has to be raised up to the MHz region. For that case it is possible to deactivate the internal low pass filter of the mentioned line coupler matching unit.

In order to evaluate the consequences for the charge measurements the investigations at the generator stator winding were continued. Table 1 gives an overview about the results. The first row shows the coupler arrangement and the upper line contains the upper frequency limit adjusted at the PD detector.

Table 1
Apparent Charge Values of the Stator Winding versus Bandwidth of the PD Detector

Q _{iec}	500 kHz	2 MHz	10 MHz
100 nF	4,2 nC	2,5 nC	530 pC
2 nF	4,2 nC	1,3 nC	550 pC
80 pF	1,6 nC	600 pC	220 pC
80 pF with low pass (500 kHz)	5,1 nC	4,9 nC	4,8 nC

Marked fields: Reading in accordance to the apparent charge.

At comparison of the indicated charge values the general trend is visible that the measured charge decreases with larger upper frequency limit, except the last line. Independent on the settings of the PD detector the upper frequency limit f_2 of the total signal chain is maintained at 500 kHz provided by the low pass.

At the 80-pF-coupler without low pass the charge reading is lower even in the IEC frequency range of the detector, due the high pass behavior and the loss of signal area.

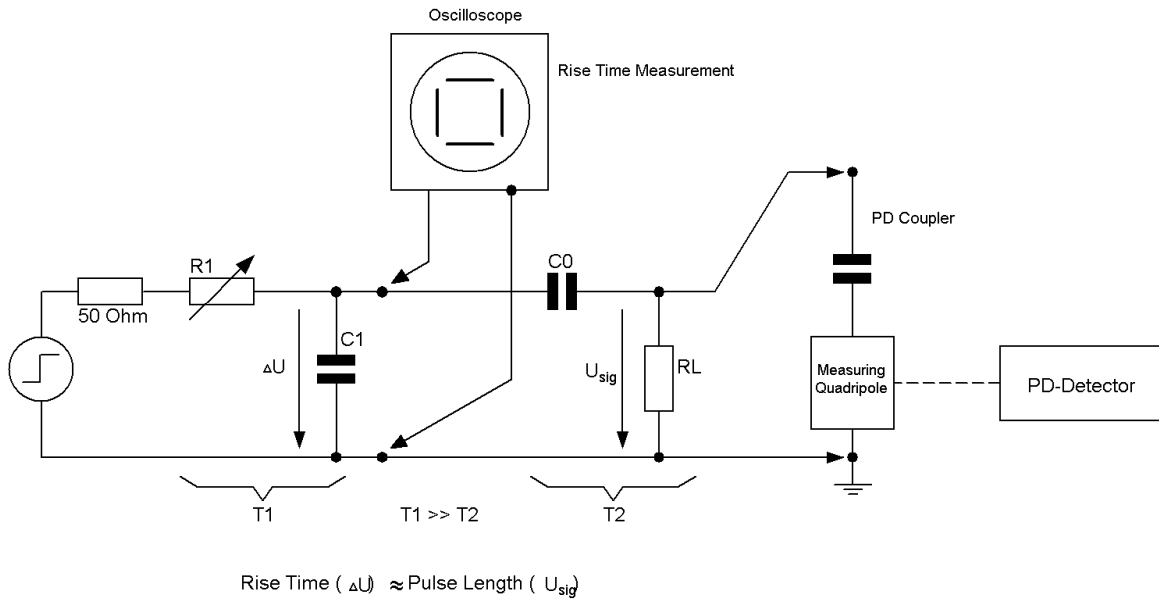
These results give a first impression of which integration errors can be expected under real on site conditions where the measuring frequencies have to be matched according to the actual circumstances.

The results are an example since they are depending on the individual PD signal shape (ref. fig. 1) and must not be generalized.

DETERMINATION OF THE INTEGRATION BEHAVIOR, INTEGRATION ERRORS

As consequence the next target was to apply a simple solution to characterize the integration behavior of the whole measuring arrangement Coupler / PD detector.

According to fig. 5 a simple circuitry was found that permits the generation of artificial PD pulses of **constant charge** and **variable duration**.



Determination of the Integration Behavior for Each Measuring Arrangement
Figure 5

The low pass $R1 / C1$ shapes a low pass, via $R1$ the time constant $T1$ and hence the rise time of the step response on the incoming step signal can be adjusted. By means of the connected oscilloscope the rise time can be determined and read out. The following elements $C0 / RL$ form a high pass. Provided by the very small time constant $T2$ this can be considered as pure differentiation stage. The resistance value of $R1$ is small enough to avoid interactions from the connected PD coupler. The resulting voltage drop across $R1$ (U_{sig}) represents the desired needle pulse with constant area (charge) and variable duration.

That pulses were injected into the corresponding couplers and the pulse duration was increased until the charge reading at the PD detector reaches 63% ($1 - e$).

In that way the so called Integration time $T1$ was defined and determined for each individual measuring configuration. Table 2 contains the determined values:

Table 2
Integration Time, Overview

$T1$	500 kHz	2 MHz	10 MHz
100 nF	1,1 μ s	260 ns	120 ns
2 nF	973 ns	221 ns	115 ns
80 pF	235 ns	125 ns	66 ns
80 pF with low pass	1,25 μ s	1,1 μ s	980 ns

Marked fields: Reading in accordance to the apparent charge (ref. table 1).

From the displayed results is visible that the integration time $T1$ is very short at the 80-pF-coupler that finally results in an integration error that is not negligible (ref. table 1). The charge reading at the PD detector would deviate, especially in case that the actual PD impulse shapes are much longer than the calibration pulses.

The 80-pF-coupler in combination with the low pass filtering shows again much better results. By this means can be easily demonstrated that it is possible to perform proper charge measurements even with small coupling

capacitance. The integration error would stay within reasonable limits. Integration times around 1 μ s correspond to the apparent charge measurement acc. IEC 60270.

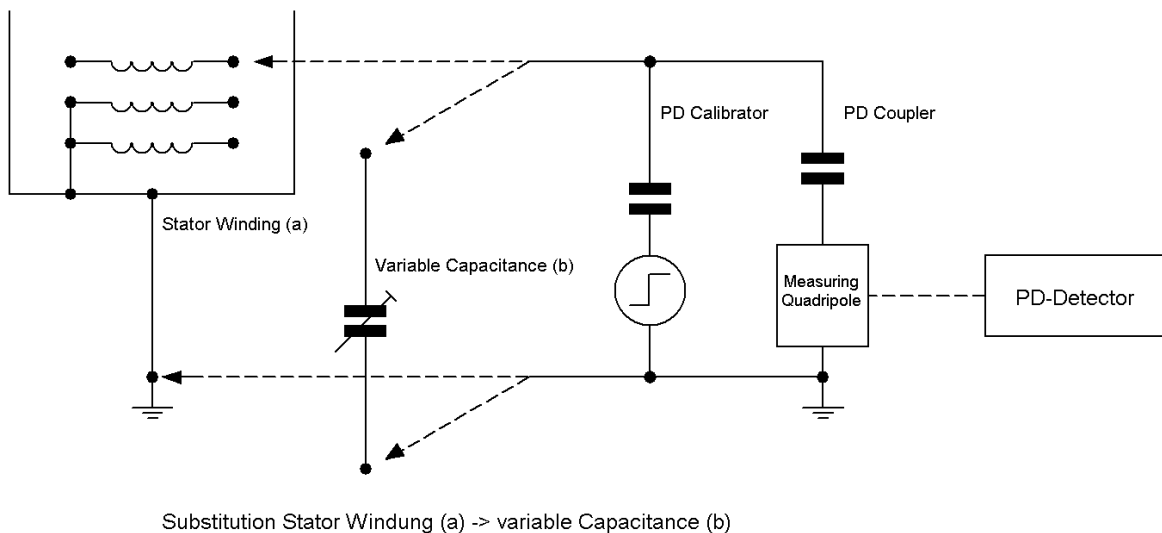
DETERMINATION OF THE APPARENT LUMPED CAPACITANCE OF THE STATOR WINDING

It should be mentioned that in general the application of small coupling capacitances lead to decreasing of measuring sensitivity. According to the classical capacitive equivalent circuit of the IEC 60270 the charge amount transferred to the measuring circuit is increasing the bigger the coupling capacitance is in relation to the test object capacitance.

In case of any generator winding it makes no sense to refer to the total winding capacitance because it does not act as lumped capacitance in the relevant frequency range of PD measurements.

Furthermore the question arises for the equivalent lumped capacitance of the generator winding that appears in the total measuring arrangement including coupler, detector and calibrator, depending on the measuring configuration, bandwidth etc.

In order to determine the mentioned capacitance a simple substitution method according fig. 6 was applied:



Determination of the Integration Behavior for Each Measuring Arrangement Figure 6

After each calibration of the measuring configuration the stator winding was disconnected and substituted by a variable low voltage capacitance. Its capacitance value was tuned until getting the same reading as before with the generator winding connected. The resulting capacitance values are plotted in table 3.

Table 3
Apparent Lumped Capacitance, Overview (total winding capacitance: 190 nF)

T_1	500 kHz	2 MHz	10 MHz
100 nF	29 nF	20 nF	4,2 nF
2 nF	22 nF	7,5 nF	2,8 nF
80 pF	8,6 nF	2,7 nF	324 pF
80 pF with low pass	19,5 nF	19,2 nF	19,7 nF

Taking into account the dimension and price of PD coupling capacitors it can be stated that the benefit is very limited if the coupling capacitance exceeds that of the test object, in the actual case the lumped capacitance of the generator stator winding. The measuring sensitivity would not increase essentially.

The determined capacitance values are specific for the stator winding under test and the measuring configuration; nevertheless we can generalize as follows: 100 nF as coupling capacitance is not necessary, 10 nF seems to be adequate but is in reality not the optimum compromise considering the dimensions and price. PD couplers around 1...2 nF represent obviously the best efficient solution. 80 pF couplers are not recommended for new installation but are preinstalled at various machines. In order to cope also with these couplers the matching unit solution was created.

PD CALIBRATION

At all on-line PD measurements there is the principle challenge that the test object terminals are not accessible for calibration purposes. The installation of on-line calibrators is not common.

But for trending purposes there is the need to have the measuring results comparable in terms of charge as pC. Finally it does not matter for trending if the results are the same as calibrated according to IEC 60270 but the results of repetitive measurements must be basing on the same scale factor of the measuring PD detector. So it is recommended to perform at least an indirect calibration in parallel to the input of the PD detector connection to the coupler terminal box.

Taking the previous results into account it is further recommended, not simply to inject charge pulses directly from the calibrator. In order to get a scale factor in the same range roughly of the IEC calibration the pulse should be injected via a capacitive charge divider. This should consist of a parallel capacitor of 10 nF to simulate the lumped capacitance of the stator winding and a e.g. 80-pF-capacitor in order to simulate the coupler capacitance (resp. the actual coupler capacitance).

The proposed calibration procedure does not guarantee the accordance to apparent charge calibration of IEC 60270 but fulfils the main task of PD calibration in general. The measuring results will be reproducible and comparable.

CONCLUSION

The detection of partial discharges deeper inside of a generator stator insulation requires the transition to charge measurements with respect to IEC 60270. I.e. a sufficient integration behavior of the entire measuring arrangement must be given. At many generators are on line couplers preinstalled with strong high pass behavior that hampers the charge measurement. An additional module with switchable low pass of higher order was applied to overcome the obstacle. Comparative PD measurements at a real test object verified the feasibility of comparable charge measurements even with a coupler of very small capacitance. The integration time T_1 was introduced as measure to evaluate the integration ability of the measuring setup. That value was determined for different measuring configurations with different couplers and processing bandwidths. The results revealed, as expected, that the integration time decreases and the integration error increases if the total upper frequency limit increases and the coupling capacitance decreases.

In principle it is possible to measure the PD activity in terms of pC even in the MHz region with some concessions to the integration error; the measured value might be below 50% of the actual one.

This is less critical if the calibration is performed thoroughly before each measurement. A calibration adaptor is proposed for indirect calibration in for getting scale factors similar to that of the IEC-calibration.

A method was applied to determine the equivalent lumped capacitance of a generator winding. Basing on the generalized results recommendations were given for the selection of capacitance values of generator on-line PD couplers.

¹Doble Lemke GmbH
Zschoner Ring 9
01723 Kesselsdorf/Dresden
Germany
Email: elze@doble-lemke.eu
Email: kornhuber@doble-lemke.eu
Email: boltze@doble-lemke.eu

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