THE CDA TECHNOLOGY

CONTENTS

ABSTRACT

This chapter deals with the sophisticated CDA technology developed by LEMKE DIAGNOSTICS GmbH. It is intended for quality assurance tests of new cables after installation and predictive PD diagnosis tests in the framework of preventive maintenance. The available test facility is designed for testing medium voltage (MV) power cables and its accessories up to 36 kV rated voltage.

The non-destructive CDA technology has well been proved in practice and can be considered as a cost-benefit tool for improvement the reliability of power cable networks. Due to the comparatively low test level and transient stress the ignition of new weak points in the cable dielectric will never happen by applying the CDA-technology.

1. INTRODUCTION

To improve the reliability of installed power cables, the usual destructive breakdown test under AC, DC and VLF voltages is increasingly substituted by non-destructive PD diagnosis test. From a physical point of view the PD measurement should be executed under power frequency AC voltage in order to recognize PD faults occurring under service stresses. However, conventional AC test transformers are not qualified to perform such tests cost-effectively, due to the transportation problems caused by high weight and dimension of the apparatus and also the power demand for energizing the large cable capacity, which leads to very expensive costs.

The power demand and hence the weight and dimensions can be reduced effectively, if conventional transformers are substituted by AC resonance test sets. Nevertheless, they are also very expensive and therefore not economical for on-site testing of power cables in the medium voltage range. They are therefore only used for after-laying tests of high voltage (HV) cables in the voltage class of 110 kV and above. Therefore, alternative test equipment, which reduce the expenditure for on-site testing of MV cables are presently world-wide under discussion.

2. FUNDAMENTALS

The power demand for energizing the capacity of installed power cables can essentially be reduced by the application of very low frequency (VLF) test voltages [1; 2; 3] or switching impulse (SI) voltages as well as oscillating (OS) voltages [4; 5;6 ;7 ;8; 9].

The current practice in destructive breakdown testing under VLF voltages in the range of 0.1 Hz is also connected to crucial problems. For XLPE cables, for instance, the VLF test level must essentially exceed the stress level under service voltage and, additionally, a test duration up to one hour is required for identification of harmful imperfections in the extruded insulation [10]. Under such high and long overvoltage stress it could happen, that unintentionally new defects may ignite, so that the before undamaged cable will fail under service condition.

If instead of destructive breakdown tests non-destructive PD tests are executed under VLF voltages it has to be taken into consideration, that any recognized PD event may not happen at power frequency operation voltage. This is mainly caused by the transition from the capacitive-governed field strength distribution under power frequency to the resistive-governed field distribution under VLF.

Different to VLF voltages the electrical field distribution and hence the PD occurrence under transient voltages become comparable to those under power frequency service voltage, if the significant time parameters are chosen in the range of milliseconds. Therefore, switching impulse voltages [6; 7] and oscillating voltages [8; 9] are much more efficient than VLF for recognition of dielectric imperfections.

Based on this knowledge, fundamental studies dealing with the PD occurrence under transient voltages of different shapes has been performed. The result of the investigations was a non-conventional transient voltage, which can easily be generated, even if the test object capacitance is comparatively high. When applying this, the PD behaviour is comparable to that under power frequency test voltage. So it is proved, that optimum conditions for PD ignition are insured, if first a pre-stress is applied, using a slowly rising voltage in the range of about 10 seconds, and after that the voltage decreases much faster, i.e. in the range of about 10 milli-seconds. During the tail time the main stress is caused, so that PD may ignited in dielectric imperfections. Hence, the PD detection is performed during the tail time, i.e. at decreasing voltage stress [11; 12].

This transient voltage stress adopts the advantage of both, the VLF test voltage, which requires a low power demand, and the power frequency voltage, which ensures the optimum conditions for the recognition of dielectric imperfections by PD measurements. As mentioned above, the analysis of PD events is done at decreasing test voltage, i.e. when the cable capacity is discharged. Therefore , this new diagnostic tool is called CDA technology, which means Complex Discharge Analyzing. The significant time parameters of the CDA test voltage are evident from Fig. 1.

Fig.1: Significant time parameters of the CDA test voltage

The front time t_1 for charging the cable capacity is in the order of 10 seconds, as already mentioned. This keeps the power demand as low as in the case of VLF test voltages. The tail time t_2, at which the cable capacity is discharged, takes about 10 milliseconds. This corresponds to the significant time difference between the positive and negative crest value of the power frequency (50 / 60 Hz) voltage. Fundamental studies showed, that the PD occurrence is not influenced remarkably if the given values for the time parameters t_2 and t_2 change within several tens of percentages, which simplifies essentially the design of the CDA test equipment.

3. TEST PHILOSOPHY

The above mentioned optimum conditions for the recognition of PD faults under CDA test voltages can easily be explained on the basis of the "a-b-c-model" for PD ignition, already presented in the Fig. 4 of chapter I. The capacitive current flowing through the capacitance C_b of the dielectric column and charging the capacitance C_c of the gas-filled void after each PD event, is governed by the steepness of the applied test voltage.

As mentioned previously, the front time t_1 of the CDA voltage takes about 10 s and the tail time t2 about 10 ms, respectively. That means, the voltage steepness and hence the capacitive current through C_b charging C_c is about 1000 times higher, when the test voltage collapses. This provides an optimum condition for PD ignition in imperfections of solid dielectrics, as will be discussed now.

For this purpose let us first compare the PD occurrence in a gas-filled void under CDA voltage with those under power frequency stresses, already presented in the sub-clauses 2.2. and 2.3. of chapter I. If the CDA voltage rises slowly during the front time t_1 and the critical field strength E_{bg} for PD ignition is exceeded, the first PD pulse will happen. According to the "a-b-c-model", shown in Fig. 4 of chapter I, the capacitance C_c is suddenly discharged. Because of the slowly rising CDA voltage the capacitive current through C_b is also accordingly low. Therefore, it takes a comparatively long time, - several seconds - for charging C_c up to again the critical breakdown field strength E_{bg}. Under this condition the ohmic conductivity of the dielectric material can not be longer neglected, as for 50 / 60 Hz stresses, where this charging time is about 1000 times shorter.

Because the repetition rate of the subsequent PD pulses is governed not only by the capacitive but also by the resistive current through C_b, the PD Process changes not only quantitatively but also qualitatively. This effect is forced by so-called micro-discharges, which are typically for slowly rising voltage stress. Consequently the evaluation of the PD activity during the front time t_1 of the CDA voltage is not recommended from a practical point of view. This fact has also to be taken into consideration for PD test under VLF stress. The appearing PD phenomena are significantly different to those under power frequency voltage.

We wont to pay further attention to PD events, which appear during the tail time t_2 of the CDA test voltage, when the cable capacity is discharged within about 10 ms. This is 1000 times shorter than the front time t_1 and consequently the capacitive current through C_b increases about 1000 times. Under this condition the resistive current component through C_b can be neglected and the PD mechanism appearing at t_2 are comparable to those under power frequency voltage. Hence, the detected PD signals during the tail time t_2 are equivalent to those under AC operation voltage.

In this context it has also to be noted, that the PD inception voltage under CDA voltage stress is lower than those under other transient test voltages, such as switching impulse (SI) voltages [6; 7] and oscillating impulse (OI) voltages [8; 9]. The reason for this is, that during the long front time t_1 of the CDA voltage charge-carriers are already produced by the first PD pulse and the micro-discharges. Hence, the time lag for generation the primary electrons is very short [7], and the PD may ignite without any significant time-delay during t_2 , when the cable capacity is discharged.

If compared to other predictive diagnosis tools the new developed CDA technology is characterized by the following benefits:

1. Low voltage stress:
   - a test level of 2 x U_0 is sufficient for recognition of dangerous PD faults

2. No time consuming:
   - only 5 CDA test voltage shots are required for each of the 3 test voltage levels (1.0 x U_0 ; 1.5 x U_0 and 2.0 x U_0)

3. Low power demand:
   - the long front time t_1 of about 10 seconds keeps the current for charging the power cable capacity below 10 mA

4. Low weight:
   - the weight of the complete CDA facility for MV cables (30 kV)

is about 600 - 800 kg

5. Modular and mobile design:
- the CDA facility can easily be installed in a test van

6. Network-independent power supply possible:
- the power demand is about 2 kVA

7. Capability for PD fault location:
- the mapping of PD faults bases on wide-band PD measurement and the implemented automatic PD location software

4. PRACTICAL APPLICATION

4.1. The CDA test circuit

The block diagram of the CDA test circuit is shown in Fig. 2. It is modular designed and contains the main components:

- HV equipment
- Computer-aided control and measuring system
- Protection system
- Connecting cables

Fig.2: Block diagram of the CDA test circuit

The connection to the power cable to be tested is done via a HV cable of 50 m length, which is PD-free up to 50 kV. With respect to the location of the PD faults based on the measurement of the time difference between the direct and the reflected PD pulse, the PD coupling unit is designed for a measuring frequency in the MHz range.

4.2. Performing practical CDA tests

One of the main target for developing the CDA technology was to keep the test voltage stress as low as possible, in order to avoid the ignition of new dielectric defects during the test. Therefore it is not only applicable for quality assurance tests of new or repaired cables but also for predictive diagnosis tests of aged cables after longer service time. In this context it should be emphasized, that the below recommended test parameters base on extensive practical experience. Up to now more than 900 km (single phase) MV power cables has been tested. If required, it could be adjusted in accordance to the growing knowledge by the customer.

4.2.1. Quality assurance tests after new installations or repair

The main goal of PD tests of power cables after installation or maintenance is to check the proper assembling work of the accessories, such as joints and terminations. For this the following test parameters are recommended:

parameter	extruded insulation	paper insulation
test voltage level	2 * U_0	2 * U_0
polarity	negative	negative
shot number	5	5
accepted PD level	< 50 pC	< 500 pC

If the detected PD level exceeds the above specified values, the PD source has to be located for further detailed evaluation. The procedure for PD fault location is presented in sub-clause 4.3 of this chapter and also in sub-clause 4 of chapter I.

4.2.2. Predictive diagnosis test of aged cables with respect to preventive maintenance

Different to new or repaired power cables the PD test of aged cable should be started at comparatively low test voltage level in order to avoid a non expected breakdown. Therefore the following preliminary test parameters are recommended:

parameter	extruded insulation	paper insulation
test voltage level	0.7 * U_0	0.7 * U_0
	1.0 * U_0	1.0 * U_0
	1.5 * U_0	1.5 * U_0
	2.0 * U_0	2.0 * U_0
polarity	negative	negative
shot number	5	5
accepted PD level	< 50 pC	< 2000 pC

If the detected PD level exceeds the above specified values, the PD fault must be located for further evaluation. The procedure for this is presented now.

4.3. PD fault location

After the cable data are stored to the computer, first the calibration routine is proceeded. This serves not only for quantifying the detected PD pulses in pico-Coulomb (pC) but also for the PD fault location. The traveling wave propagation velocity $v_0/2$ of the tested power cable is determined, as well.

After that the HV test under CDA voltage can be executed applying the above listed test levels. Due to the negative polarity of the charging voltage, which refers to the front time t_1 of the CDA voltage, a positive voltage rise occurs during the tail time t_2, when the cable is discharged and the PD detection is executed. As a measuring example Fig. 3 shows the obtained PD pattern for a mass-impregnated paper cable of 20 kV.

Fig. 3: PD pattern of a mass-impregnated power cable subjected to

a CDA test voltage of 1.5 * U_0 = 19 kV

To localize dangerous PD faults cables the traveling wave principle is used. For this a wideband digitizing unit for time-domain reflectrometry is therefore installed in the system. As already reported in sub-clause 4 of chapter I, for the PD pulses the cable appears to be a dielectric waveguide. Therefore, the PD pulse at the point of origin is divided into two equal parts in accordance to the differential characteristic impedance of the cable.

According to Fig. 21 presented in chapter I the time difference t_{A12} between the direct pulse and the pulse reflected at the far end is a measure for the geometrical distance x_{PB} of the PD fault from the far end. Hence, the distance to the near end x_{PA}, where the coupling unit is connected, can be expressed by the formula:

$$X_{PA} = X_{PA} - t_{A12} * V_K / 2$$

A seperate fault location amplifier supplies the highspeed digitizer with the received PD signal. The signals are converted with a digital dynamic of 10 or optional 12 Bit and sampling rate of 100 Ms/s. A typical PD pulse reflectogram is displayed in Fig. 4. This record results from Fig. 3, where the highest PD pulse was zoomed accordingly.

Fig. 4: PD pulse reflectogram of the maximum PD pulse displayed in Fig. 3

The computer-based system is also able to run the impulse-echo evaluation for several complete PD sweeps. Hence, not only the PD fault with the highest magnitude is detectable but also multiple faults can be located. All localized PD faults are extracted, evaluated and mapped automatically. Thus, the PD mapping diagram represents the PD pulse magnitude as a function of its particular position versus the number of the localized PD pulses. A typical PD position map is shown in Fig. 5. An example for an identified PD fault in a cable joint using the CDA technology is shown in Fig. 6

Fig. 5: PD fault position map for a medium voltage cable (20 kV) for the test voltage level of 1.5 x U_0 = 19 kV

Fig. 6: PD fault identified by the CDA technology

To improve the localization sensitivity and accuracy a number of high sophisticated features are realized additionally by the hard- and software:

- A continuous pulse averaging and an adjustable threshold level can be applied to reduce continuous interferences, impulse oscillations and background noise.
- A FFT feature assists the user finding harmonic radio interferences. Supported by this harmonic analysis, a selection of digital filters can be adjusted optimally.
- The rise time of the pulses is used to discriminate between near and far end PD sources.

- For a position-independent determination of the PD quantity apparent charge a transmission-loss-adjustment is automatically executed for all located PD pulses. Running a cross-correlation function with the injected calibration signal the dielectric frequency-dispersed signal is digitally reproduced.

5. INSULATION CONDITION ASSESSMENT

5.1. General remarks

For PD assurance tests of HV equipment after manufacturing the magnitude of the "apparent charge " according to the relevant standard IEC 270 [13] is specified. Therefore, it would be useful from a practical point of view to apply this well proved PD quantity also for condition assessment of installed power cables.

However, from a physical point of view the magnitude of the PD quantity "apparent charge" is not correlated to the geometrical size of insulation imperfections. Hence it is stressed in the relevant literature, that the PD severity can not be assessed by a critical magnitude of the "apparent charge". Without going into details it can be stated, that this conclusion seems only realistic for extruded dielectrics, such as XLPE, but not for mass-impregnated paper insulation.

For extruded dielectrics without interfaces the breakdown strength is reduced in general as longer the radial extension of imperfections is. On the other hand, the apparent charge of PD pulses increases not significantly with the extension of imperfections, so that the insulation detoriation can not be judged by the measured PD level, as already mentioned. The reason for this is, that in the polymeric insulation no any barriers exist, which may stop the treeing process. Therefore, at a critical length of the trees finally an insulation breakdown may happen, initialized by transient overvoltages under service condition.

Different to polymeric dielectrics in mass-impregnated paper cables the radial grow of discharge channels may be stopped, due to the barrier effect of the laminated insulation. Therefore, PD channels may only propagate further, if the apparent charge of PD pulses increases up to a critical magnitude, required for the degragation of the orthogonal paper barrier. Based on this the following approach for classification the PD severety for mass-impregnated power cables subjected to CDA-voltages is proposed.

5.2. Classification of the PD severity

As well known, PD events may become dangerous, if they exceed a critical level and appear continuously in each half cycle of the service voltage. According to fundamental studies this will happen, if the PD events appear also under the CDA voltage at a test level of 1.5 * U_0. Therefore, this magnitude is used for the following approach like a reference test level.

Based on the physics of partial discharges it can be distinguished between the following fundamental types of internal PD:

1. glow-like PD
2. streamer-like PD
3. steam-like PD
4. leader-like PD
5. spark-like PD

The transition from one type to the other one will only happen, if a critical pulse charge is generated, as already reported by TOEPLER in 1933 [14]. Based on this the following preliminary approach is used for classification the PD severity:

PD class 0: qm < 2000 pC

Under this condition only glow-like and streamer-like discharges may appear. Those cause no any significant detoriation of the paper insulation, even if the PD events appear permanently. Nevertheless a trend assessment is recommended, especially if overstresses under service condition appeared.

PD class 1: 2 000 pC < qm < 10 000 pC

Under this condition the concentration of the streamer-like discharges cause a local increasing of the temperature, resulting into a steam-like discharge channel. It causes a progressive degradation of the insulation boundaries and may become critical after longer time. Therefore, the trend development should be monitored by periodically repeated CDA tests. Recommended for this is after about one year or even after high overstresses in service.

PD class 2: 10 000 pC < qm < 50 000 pC

Under this condition leader-like discharges are formed. Those cause a forced insulation degradation, which may become critical within a short time. Therefore, maintenance work is recommended as soon as possible.

PD class 3: qm > 50 000 pC

Under this condition spark-like discharges may appear which may cause an insulation breakdown if an overvoltage appears. Therefore, the maintenance work must be done immediately.

Due to the stochastics of PD phenomena not only the magnitude of individual PD pulses but also the repetition rate (frequency) at each CDA test shot has to be taken into consideration. The higher PD pulse frequency will cause a stronger insulation degradation. Based on practical experiences the following preliminary sub-classes has been introduced, which refer to the standard procedure, i.e. 5 shots at each CDA test voltage level:

PD sub-class a: **PD pulse frequency: 2 - 3**

PD sub-class b: **PD pulse frequency: 4 - 6**

PD sub-class c: **PD pulse frequency: > 6**

For better understanding of the given classification of the PD risk let us consider a practical example: The PD status map showed for a joint at the position 275 m a very strong PD activity. The maximum PD magnitude was estimated as high as 16 800 pC. This value corresponds to the above presented **PD class 2.** The PD pulse frequency ranged between 4 - 6. This corresponds to the **PD sub-class b**. From this follows the **PD severity 2b**. That means, the PD risk is comparatively high and the maintenance should be done as soon as possible.

It has to be stressed again, that physics of PD phenomena appears very complex. Hence, the above presented approach has to be considered as a preliminary proposal for the assessment the PD risk. In this respect it must be mentioned, that the PD pattern is strongly affected by the ambient conditions, especially by the temperature of the cable insulation. This influences the viscosity of the mass-impregnation and hence the existence and geometrical size of the voids as well as the partial gas pressure. With respect to comparable test conditions it is therefore recommended, to perform the PD tests as close as possible to the operation temperature, i.e. immediately after the outage of the cable to be tested.

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