Investigations on a Combined Resonance/VLF HV Test System – Partial Discharge (PD) characteristics at VLF and DAC voltages

F. Petzold, H.T. Putter, D. Götz, H. Schlapp, S. Markalous
SebaKMT GmbH
Baunach/Radeburg, Germany
petzold.f@sebakmt.com

Abstract—The necessity of HV cable testing is a given fact. So far two testing methods, 24-hour soak or resonance testing are commonly used. This paper describes a comparison of test power demand dependent from voltage shape and test capacitance as well as the power consumption of test systems for different test techniques. Furthermore an optimised technology for combining advantages of resonance and VLF principle is described and case studies of field applications of this technology are discussed. Moreover this paper presents the results of investigations regarding the noise sources created by the HV equipment and the methods for successful reduction and suppression to levels below 10 pC, which is a relevant value for on-site PD measurements. Case studies from field application show a good comparability of PD measurement results obtained with DAC and the optimised resonance/VLF technology. The new test equipment demonstrates that withstand testing on test objects with capacitances up to 25 µF are very successful and monitored PD testing as well as diagnostic PD testing are conclusive.

Keywords—test techniques, partial discharge PD, commissioning and maintenance testing

I. INTRODUCTION

For commissioning and maintenance testing of high and extra high voltage cable systems, ACR test systems are commonly used. The logistic in using ACR systems is often difficult, because for testing higher test capacities (longer cables) up to 4 or more test systems must be used in parallel to be able to meet the capacitive demand of the cable. The costs for such testing and necessary space on site, is one of the reasons why in a lot of commissioning cases only a 24 hour soaking test at operating voltage is preferred/ performed.

From power utilities worldwide alternative HV test methods are requested. In 2012 CIGRE has established two working groups [1, 2]. B1.38 to evaluate alternative test methods/HV sources for withstand testing and D1.48 to consider the behaviour of HV insulating materials under VLF (very low frequency) voltage. The discussion about other voltage shapes than 20 to 300 Hz AC for withstand testing also needs to consider the capability of the alternative technologies for testing long lengths of cables with high test capacitances. The comparability of PD measurements between 50 Hz and alternative types of test voltages is also a criterion. This is not only important for diagnostic testing on aged cables systems, but also for commissioning testing on newly installed cables to check the quality of workmanship.

II. COMPARISON OF POWER DEMAND OF TYPICAL EXCITATION VOLTAGE EQUIPMENTS

Power consumption is one parameter in which complexity and effort of test equipment could be estimated. In general the increase in power demand (depends on length of cable) is proportional to the complexity of handling the heating and the current flowing. The following four test systems are compared.

- Resonance test set at 50/60 Hz, assuming Q = 150.
- Resonance test set at lowest frequency according to standards 20 Hz, assuming Q = 150.
- Very low frequency (VLF) sine wave test set, using 0.1 Hz. Usually the test power consumption could be assumed as 1.3 times higher as the required power.
- Very low frequency (VLF) cosine rectangular test set, using fundamental frequency of 0.1 Hz. By the usage of the resonance choke for energy storage in the polarity change, a factor of 1/7 times the required test power could be assumed.

Another alternative waveform which is a well proven method for maintenance testing, the damped AC (DAC) voltage waveform is not included, because currently it is not accepted as a full stress test for cables and is in most cases only used for cable maintenance programs. The IEEE 400.4 [3] working group is currently working on a standard for using DAC as test voltage source for commissioning testing.

In order to compare the test systems two examples are chosen. It is assumed that the cables will be tested according the standard IEC 60502-2 and IEC60840 (MV and HV cable test standard), with three times respectively two times the nominal voltage (2U0 for resonance testing).
The test power is computed as follows:

A. Windfarm cable, 33 kV, 25 μF test load, testvoltage 3U0 for both resonance and VLF voltage

B. AC export cable Baltic 1, 150 kV, 61 km length, test load 12.8 μF, testvoltage resonance 2U0, VLF 3U0

Because of the storage of energy in the inductance of VLF CR test systems it is possible to build systems with low power consumption. This fact helps to downsize the test equipment.

III. COMBINING RESONANCE AND DAMPED AC

In several publications the operating principle of VLF cosine rectangular (VLF CR) testing system are described [4, 5]. Fig. 3 shows a schematic circuit of a VLF CR system. It is composed out of two DC sources, a positive (+U) and a negative (-U). A special switch (W) conducts either one of the sources or keeps them isolated of the remaining circuit. The inductance (L) and the internal supporting capacitance (CS) built the basis of the resonance part. The losses of the internal resonance circuit are represented by (R).

The main issue of the system is given by the correct timing of the switching. Fig. 4 shows a schematic timing diagram of the VLF cosine rectangular testing mode at a ground frequency of 0.1 Hz. In the plateau phases B and D the voltage remains constant, which means either the positive or the negative source is connected via the switch (W), switch (S) is open. In the resonance phases, A and C, the switch (W) is set to isolate the source from the resonance circuit. Switch (S) closes and a polarity reversal takes place with a frequency of (1).

\[
\begin{align*}
\text{f}_{\text{ring}} &= \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot (C_S + C_{\text{Testobject}})}}
\end{align*}
\]

Fig. 4. Timing diagram of VLF CR test cyclus.

There the main difference in voltage generation of VLF CR and DAC takes place. At VLF CR mode the resonance phase is stopped by opening switch (S) at the correct time. The sources recharge to the nominal voltage given by the control of the system. In DAC mode the switch (S) is kept closed, so a resonance circuit with a certain frequency (1) is generated. The attenuation of the oscillation is given by the losses of the internal components of the generator in addition to the losses of the test object. Fig. 5 shows a DAC distribution.

The combined system allows both voltage wave forms in one system. Even a combination of the voltages is generally possible. Fig. 5 furthermore demonstrates that two charging methods for DAC voltage generation are possible. Charging by following B, could be understood as a usual application for doing PD diagnosis. But by combining the waveforms depicted in Fig. 4 and Fig. 5 a DAC voltage could also be released out of a VLF CR before. Moreover it should be noted that as there is a positive and a negative power source, the DAC charging phase could also be positive or negative, or when doing DAC withstand testing be a combination of both to get rid of eventually possible space charge. The main strength of the combined power source is its application, as for withstand testing generally a continuous voltage application is recommended (which is the VLF CR mode), with maintenance testing normally a non-destructive voltage wave shape is recommended (which is the DAC mode).
IV. DEALING WITH NOISE AND INTERNAL PARTIAL DISCHARGES (PD)

Basically many different sources of noise with similar frequency spectrums as compared to partial discharges can be found at the in VLF CR and other test systems. The noise sources can be divided in the following groups:

- Internal discharges like corona, or surface discharges
- Thyristor switching noise
- EMC noise from the part at the PCB of the control like voltage regulators, the control of the thyristors, etc.

The main goal of PD measurements is to measure the PD in the defects of the object under test, not the PD generated by the voltage source itself. Even with internal PD in the voltage source we can still localize PD within cables; however we cannot determine the partial discharge inception voltage properly (PDIV). As the PDIV is one of the most important criteria for the decision making process, it becomes clear that the internal PD from the voltage source should be eliminated.

The internal discharges like corona and surface PD can be filtered out/ minimized by a good HV design and a hardware filter. Since the noise produced by the switching of the thyristors has phase stability, it can be canceled out by fixed window gating. The IEC60270 standard allows time window gating, if the windowing does not exceed 2% of the complete period of the excitation voltage. Moreover the IEC60270 standard gives guidance for reducing noise. The EMC noise can be filtered out/ minimized by using a proper hardware filter. The design of the hardware filter obviously depends on the excitation voltage type. (current, voltage demands). The noise of the MV VLF CR test sets has been reduced by the hardware and software filters to a PD level below 10pC. For field tests this level is more then enough as background noise is normally in a region of 50…100pC.

V. CASE STUDIES

The discussed case studies are examples of measurements on MV cables as HV VLF CR test sets do currently not exist. The case studies on MV cables are still representative as the PD behavior on both MV and HV cables will be similar. The case studies basically show the comparability of the PD results measured with DAC voltages and VLF CR voltages. Moreover an example will be given about a 3-phase PD monitored VLF CR test. This is especially useful for commissioning testing of newly installed cable circuits, to save valuable testing time.

A. Paper-mass impregnated cable of 1096m length

Fig. 7 shows the test setup at a medium voltage cable station. The setup consists of the combined VLF CR and DAC voltage source and a filtering and PD coupling device, which is connected directly to the object to test. The PD measurement system was built conform the IEC 60270 standard [6]. The source and the measurement device are controlled by software on a notebook.

The first test object is a cable dominated by paper-mass insulation. It is known that paper mass cable tend to have more PD activity, because of lack of impregnation. This leads to distributed voids in the insulation, which let expect high partial discharge activity. Fig. 6 shows the cable sections and the accessories.

![Fig. 6. Cable section plan; mixed 10kV cable with 12 splices.](image)

Fig. 7. Test setup combined VLF CR and DAC voltage source and PD measurement device.

Fig. 8 shows the PD mapping after PD measurement. It could be seen that the same defects were triggered with both wave shapes, while the repetition rate and PD values differs slightly between the defects. The PD inception voltages showed good correlation. See table 1.

![Fig. 8. Top: PD mapping with DAC voltage < = 10kV peak. Bottom: PD mapping with VLF CR voltage < = 10kV peak.](image)
<table>
<thead>
<tr>
<th>PDIV</th>
<th>VLF CR in kV</th>
<th>DAC in kV peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1</td>
<td>L2</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

### B. PE cable of 385m length

The second example is a field test performed on a 3 single core PE cable having 1 joint, see Fig. 9 and Fig. 10. The first test which has been performed was with DAC voltage. Fig. 11 shows that there is a PD concentration in the joint at 120m, phase 3 only.

![Fig. 9. Test set-up for test on 20kV PE cable.](image)

![Fig. 10. Cable section plan; PE 20kV cable with 1 splice.](image)

After the DAC diagnosis a 3-phase VLF test with monitored PD has been performed. The result can be seen in Fig. 12. Apart from the same weak spot as detected with the DAC voltage wave shape also some PD in the cable insulation at 270m has been detected. This cable did not pass the VLF withstand test, it broke down after 5 minutes in phase 2 (failure in the insulation, water tree problems).

![Fig. 11. PD mapping of three cable phases done with DAC voltage <= 29kV peak.](image)

![Fig. 12. PD mapping 3-phase VLF CR test @ 3U0. No differentiation between phases possible anymore.](image)

### C. PE cable of 653m length

The third example has 2 sets of joints, one set at 215m and one at 260m, see Fig.14. Cable is a 20/12kV 3 single core PE cable. The outcome of the DAC diagnosis up to 1.7U0 has shown PD in all phases at the joint at 215m. The second set of joints is completely PD free. The PDIV in all joints is above operating voltage. The PD mapping is given in Fig. 15.

![Fig. 13. PD defect of the joint at 120m.](image)

![Fig. 14. Cable section plan; PE 20kV cable with 4 splices (2 sets of 2).](image)

After the DAC diagnosis a three-phase VLF CR test with monitored PD has been performed. Interesting outcome of this test was, that the PD free joint set seen at DAC up to 1.7U0, was also PD free up to 3U0, see Fig. 16. Furthermore PD has been detected on both ends, which could be reflected back to the cable still connected to the bus bars.

![Fig. 15. PD mapping performed with DAC voltage up to 1.7U0.](image)
VI. CONCLUSION

There is a need for new testing methods for HV cables, as of capacitive demand, as of size, weight and power consumption. Current available test systems can cover the capacitive demand; however 3 or more systems need to be connected in parallel. This is in most cases economically not feasible, logistically not possible or because of space constraints/road blocks not possible (e.g. in downtown areas). The VLF CR technology seems to be a good alternative as of its low power consumption, only 1/7 of the required test power demand is needed. The VLF CR technology has already proven its functionality in the MV range, in the HV range research is currently performed.

One of the problems of the VLF CR voltage wave shape is the noise created which could influence the PD measurements. This has been thoroughly investigated, solved and tested on MV VLF CR test sets.

Modern VLF CR test sets are nowadays also able to generate a DAC voltage wave shape. The DAC wave shape is ideal for maintenance testing on service aged cables. The case studies show the comparability of PD results between the proven DAC voltage wave shape and the VLF CR wave shape (measured during polarity reversal). Therefore it can be concluded that the VLF CR wave shape is an ideal alternative for commissioning testing with a monitored PD measurement as shown in case study B and C. Moreover based on the case studies it is know that when joints are installed properly that they could also be PD free up to 3U0, which is of importance for the commissioning testing of MV cables. Further investigation is still needed to support these findings.

VII. DISCUSSION AND FUTURE WORK

There are currently two working groups investigating alternative test methods/ HV sources for withstand testing (B1.38) and the D1.48 considering the behavior of HV insulating materials under VLF voltage. For withstand testing the voltage levels should be thoroughly investigated. With MV cables there is a difference between 50Hz testing and VLF testing (2U0 versus 3U0), although some research work have proven that the growth rate of the electrical trees at 2U0/50Hz is far lower than 3U0 VLF [7, 8]. As with HV withstand testing after installation the voltage level even goes down to only 1.1U0 (for 500kV cables [9, IEC 62067]) this effect on the testing time should be investigated (lower growth rate of electrical trees). For long onshore cables we have the possibility to couple out the PD at the accessories, but what to do with offshore cables where it is not possible to couple out PD at the accessories itself, or to localize PD based on the TDR principle? Over here we need to rely on the withstand test only (with PD detection, but can we still see PD from 40km? If yes, with what sensitivity?)

REFERENCES

[1] Cigre WG B1.38, After laying tests on AC and DC cable systems with new technologies
[8] E. Gockenbach, “The selection of the frequency range for high-voltage on-site testing of extruded cable systems” IEE Electrical Insulation Magazine Vol. 16 No. 6, pp. 11-16.
[9] Ed. 1: Power cables with extruded insulation and their accessories for rated voltages above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) – Test methods and requirements