ENSURING THE FLOW.

VLF sine 0.1 Hz – Universal voltage source for testing and diagnostics of medium-voltage cables

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1. Introduction

More and more operators of medium-voltage networks are faced with the challenge of delivering high availability and reliability at lowest possible costs. Evaluation of the network condition offers valuable information for cost-optimum management, grid expansion and maintenance. With the help of information on the cable condition, we can for example, identify highly aged cable routes and prioritise these during maintenance. But even in newer cable routes, the cable diagnostics delivers information on hidden faults, such as defective joints, water ingress and much more.

Testing cable routes is essential in order to utilise the potential of condition evaluation. Network operators that would like to carry out diagnostics tests (see Section 2 Diagnostics procedures) in addition to power-on tests, are subsequently concerned about achieving significant diagnostic results with as little time and at the lowest cost as possible. In addition, they strive for the highest possible significance of the measurement results.

Among other things, the significance of the measurement results depends on the voltage source of the testing and measuring device. Various sources are available on the market, including 50 Hz resonance systems, VLF sine 0.1 Hz (VLF = Very Low Frequency), DAC (DAC = Damped AC) and VLF Cos-Rect (Cosine Rectangle).

The quality of the respective voltage sources - more precisely, quality of the measurement results that can be achieved with these sources - has already been a subject of several studies and even test engineers discuss the relevance of the voltage source for tests on field. In this paper, we will interpret the results of a few studies. In addition, we will present the methods or method combinations that could be useful in practice.

Moreover, we will show the impact that the selection of the voltage source and the possible test and measurement methods with it could have on everyday practice, the cost factors that must be observed while deciding on the measurement technology and how the daily relevant criteria are affected in practice.

2. Diagnostic procedure

While the withstand voltage test basically only results in an “Ok” or “not Ok”, cable diagnostics deliver information on the cable condition and on the ageing behaviour. The dissipation factor measurement (also called tan delta measurement) and partial discharge measurement (PD test) have proven to be especially convincing cable diagnostic procedures.

Dissipation factor measurement (tan delta)

The dissipation factor measurement is a non-destructive and integral procedure, and is hence useful for assessing the entire tested cable route. It can be applied for plastic-insulated cables, paper pulp insulated cables as well as for mixed lines. Prerequisite for the interpretation of measurement results is to know the structure of the cable route. The dissipation factor measurement typically comprises several measurement cycles: As a rule, 6 to 10 measurements are performed at 0.5 x U_0, 1.0 x U_0, 1.5 x U_0 and 2 x U_0. The following information can be derived from the dissipation factor measurement:

- The tan delta mean value (MTD) of measurements in the individual voltage steps delivers information on water trees, i.e. damages caused by water in the insulation of plastic-insulated cables. (These water trees can become electrical trees where partial discharges and breakdowns may occur). At the same time, the mean value gives information on the thermal or chemical ageing behaviour of the cable route.
- The tan delta standard deviation (STD) of measurements in the individual volt-

age steps can be used to collect indicators of partial discharges (PD) or to detect moist joints, for example.

- The mean value difference (DTD) in the various voltage steps is helpful to detect water trees, partial discharges and vaporisation effects (e.g. at terminations).
- Furthermore, inadequate insulation of paper pulp insulated cables due to water penetration can be detected with the dissipation factor measurement.

The significance of the tan delta measurement depends on the measurement accuracy and resolution. For example, we need a measurement accuracy of about $1*10E^{-4}$ to be able to detect an increase in the dissipation factor during measurement on a plastic-insulated cable (see Fig. 1).

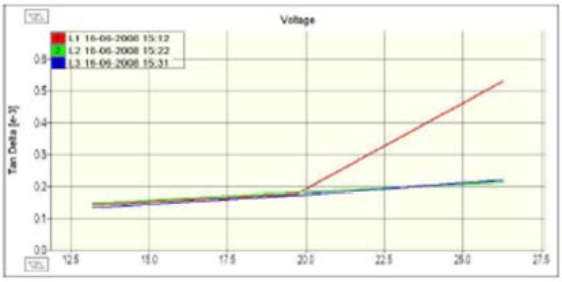

Fig. 1: The increase in the dissipation factor of phase 1 from $0.2 * 10^{-3}$ at $1.5 \times U_0$ to $0.5 * 10^{-3}$ at $2 \times U_0$ delivers information on a "hidden" fault. A subsequent PD test indicates a defective cable termination.

Partial discharge measurement (PD)

The partial discharge measurement is a non-destructive procedure where the measured values can be assigned to a specific location on the cable route. The following faults can be detected with the help of the inception voltage (voltage at which partial discharges occur for the first time) as well as the measured PD level during a specified test voltage:

- Permanent damage in the cable sheath due to external effects, perhaps during the course of groundwork
- Defects in new and old fittings, for example, defective joints or fittings
- Defects affecting the insulation-effect in the insulation of plastic-insulated cables, such as electrical trees
- Insufficient paper pulp insulation due to drying or water penetration

For the purpose of comprehensive cable diagnostics, it is thus desirable to be able to carry out both diagnostic procedures - dissipation factor measurement and partial discharge measurement - in addition to a cable or cable sheath test.

3. Voltage sources - requirements and characteristics

To achieve a successful condition-based maintenance, the testing and measuring devices must satisfy a catalogue of requirements. The essential requirements for the voltage source are:

- Suitability for cable tests / withstand voltage tests
- High measurement accuracy during dissipation factor measurement (see above)
- Significant results during the PD test (inception and extinction voltage, PD level and phase-resolved PD pattern) and good localisation of the PD
- High reproducibility of results to guarantee the comparability of staggered measurements and various cable routes in the network
- Possibility of applying various methods in parallel and to combine the results of the test/measurement automatically so as to save time
- Light in weight, easy to handle, easy connection, easy operation, short test duration

Requirement	VLF sine	CLF Cos-Rect	50 Hz resonance systems	DAC
Withstand voltage test in compliance with IEC, VDE (CENELEC), IEEE	yes	yes	yes	yes, IEEE standard in preparation
Load-dependent test signal	yes	Swing phase varies in the region of 30-250 Hz acc. to IEEE400.2 [8], reload phase varies depending on load	Test frequency depends on cable length	Test frequency depends on cable length
tan delta measurement accuracy	high ($1*10^{-4}$)	unsuitable for tan delta	high	medium
tan delta sensitivity / comparability	high	unsuitable for tan delta	medium, sensitivity less than with VLF	medium, load-dependent
PD localisation possible	yes	yes	yes	yes
PD level and PD pattern comparable with measurement at 50 Hz	yes	not yet studied in detail	yes	yes
PD inception voltage comparable with measurement at 50 Hz	yes	not yet studied in detail	yes	yes
Compact voltage source	yes	yes	no	yes

Table 1: Comparison of various voltage shapes with regard to different practice-relevant requirements.

Table 1 shows a comparison of the various voltage sources in relation to the above mentioned requirements. From the table it is apparent that the VLF 0.1 Hz sine voltage as single voltage source meets all the stipulated requirements, i.e. is suitable even for measurement of partial discharges and the dissipation factor measurement (tan delta). With regard to the withstand voltage, almost all popular voltage sources on the market have been found suitable in theory and in practice.

However, one must note that here it depends on the voltage shape: To achieve reliable results independent of the load (cable route), an ideal sinusoid is of advantage. For this, it is important that the voltage source, as far as possible, always delivers the same signal shape and frequency to avoid any influence on the PD test or tan delta measurement, for example. The aim is to minimise the influence of the voltage source on the measurement result. This allows the user to compare the measurement results and thus to fine-tune decision-criteria for evaluating the condition of cable routes. The VLF sine voltage source is particularly suitable for this.

With regard to the measurement of the dissipation factor, it is apparent that due to the high precision and sensitivity, a VLF sine measurement has an edge even over the 50 Hz measurement. At low frequency, the tan delta values for the PE-insulated cables are higher - with this, an increase in the tan delta can be detected better (more sensitive). It must be further mentioned that only sinusoidal voltage sources are suitable for a precise tan delta measurement. And from this, as mentioned above, the 0.1 Hz sine has been proved to the extent that standards and limit values (IEEE 400.2-2013) for this measurement are available. Among other things, this is due to the fact that we have acquired more experience with the VLF sine in the meantime.

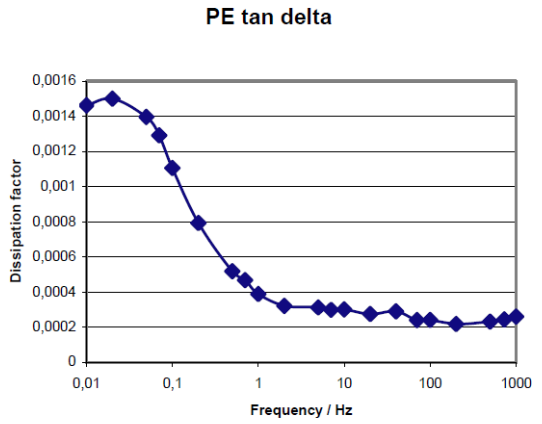

Fig. 2: A higher tan delta value is measured at low frequencies (Graph source: [7])

Various scientific publications have already discussed the suitability of different voltage sources (VLF sine 0.1 Hz, 50 Hz, DAC, VLF Cos-Rect) for the partial discharge measurement. For example, the behaviour of various voltage sources has been studied on the following test samples:

- Artificially created faults on cable routes and cable terminations
- Dirty outdoor cable terminations, fault in outer duct / deflector
- Cables in use
- Defective joints
- Aged and worn plastic-insulated cables and joints

Depending on the publication, the behaviour of two or more voltage sources was compared, particularly in view of the comparability of the measurement results with those tested at operating frequency (50 and 60 Hz). To sum up, the following result can be derived from the publications (also see [1] to [6]):

According to [6], the comparison of measurements with 2 x U_0 on 6 worn joints resulted in 5.5 times the PD level with approx. 5,500 pC (as opposed to about 1,000 pC at 50 Hz and VLF sine) for a VLF Cos-Rect voltage source.

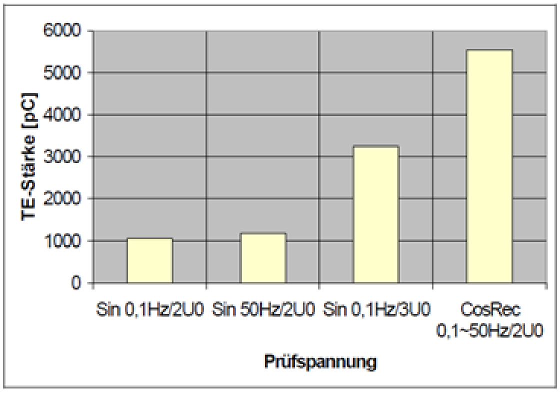

Fig. 3: PD strengths of six joints (plug-in technology); [6]

These higher measured values mean that a measurement with the Cos-Rect voltage source presents a higher load for worn joints. However, for proper diagnostics, it is important that the cable and accessories are not unduly loaded or even damaged by the measurement. In addition, in [6] it has been determined that the waveform of the test voltage has a greater impact than the increase in the level from 2 x U_0 to 3 x U_0 (compare sine with Cos-Rect). It is also apparent that sine 50 Hz and sine 0.1 Hz show almost identical levels.

Until now, scientific studies have been conducted only on PD tests with a VLF Cos-Rect voltage source. Practical experiences on the suitability of the VLF Cos-Rect voltage shape for the PD test especially with worn cable routes are still not available.

With reference to the PD tests with VLF sine, all mentioned publications state that the PD inception voltage can be compared with the voltage of the 50 Hz measurement when tests were conducted on field objects (i.e. not artificially prepared objects). In artificially created faults, the inception voltage during the VLF test and the 50 Hz test occasionally differed from each other, which is why [4] comes to the conclusion that faults and test bodies created artificially in the laboratory are not suitable for selecting the optimum voltage source.

With regard to the PD level and the PD pattern (distribution of measured values), the publications similarly showed that results with VLF sine 0.1 Hz are comparable with the results of 50 Hz measurements. This likewise applies for worn joints in plug-in and heat shrinking technology. There were no relevant differences even in the location of partial discharges.

With reference to a comparison (4 cable routes with total of 42 different faults) between VLF sine 0.1 Hz, 50 Hz resonance system, 20-400 Hz resonance system and DAC (Cos-Rect was not used here), during the test on various medium-voltage cables we conclude for example [2], that no single technology seems better than the other (*"Under the conditions in which this project was carried out, the experimental results show that no single partial discharge testing technology for installed MV cable systems provides significantly better results than the others.")*.

No clear correlation was evident between the PD strength or the inception voltage and the voltage source in the [2] described study *("The possible relationship between the magnitude of the partial discharges and the type of high voltage source used was investigated, but no relationship was found between them due to the high dispersion of results. The same conclusion was reached on studying the possible relationship between the PD inception voltage levels and* *the type of voltage source used. It was not possible to establish any correlation")*.

While choosing from the [2] studied voltage sources (VLF sine 0.1 Hz, 50 Hz resonance system, 20-400 Hz resonance system and DAC), the user must preferably consider practical criteria such as possible accomplishment of tasks, weight, versatility and easy handling. Table 1 shows that of the four types of voltage sources – VLF sine, VLF Cos-Rect, 50 Hz and DAC – only the VLF sine voltage source satisfies all the requirements when considering the cable test as well as the tan delta and PD test. With regard to the tan delta measurement, the VLF sine has a favourable impact owing to its higher sensitivity.

4. Consequences during practical use

For practical use, other aspects besides measurement accuracy and reliability must be taken into consideration. The following aspects are important during use in the field:

- Easy transport and easy connection of measurement technology
- Staff expenses, training
- Time required for the connection
- Time required for the measurement
- Cost-benefit ratio
- Relevance of measurement results for future maintenance

Under these aspects, the VLF voltage sources can register low weight and its compactness as plus points compared to a 50 Hz voltage source. Furthermore, as the VLF sine source is considered for cable testing and diagnostic measurements (tan delta and PD), network engineers can perform all relevant measurements on new and old cables only with one voltage source.

Unlike the use of various voltage sources for different methods (e.g. Cos-Rect for withstand voltage test and OWTS for PD test), there are clear time benefits while using one voltage source, such as VLF sine: connection times are cut by half. While using one voltage source, it is also possible to apply test and measurement methods in parallel, e.g. during the Monitored Withstand Test:

Monitored Withstand Test or Monitored Withstand Diagnostics (short MWT) means the partly simultaneous implementation of cable testing and cable diagnostics with the tan delta methods. As the test engineer must connect only one device for the MWT and then start a related workflow, he can perform the usual test after installing a new cable or repairing a cable route and simultaneously determine the cable condition in a short time. A combination of testing and diagnostic measurement - the MWT - offers the following benefits:

- Easy test setup, easy flow (no additional connections and no introduction to MWT needed)
- Shorter test duration if the cable is in good condition
- No cable overload
- Result evaluation in real time
- Interpretation of cable condition with Smiley sign on display
- Precise results on cable condition

Even the partial discharge measurement can be similarly integrated in a measurement and test cycle so that a PD test hardly requires any additional time. Information from the integral dissipation factor measurement and the local partial discharge measurement is complementary and gives network and maintenance engineers more criteria for evaluation.

For the test engineer, using an easy and light voltage source for the cable testing and diagnostics means that he can measure more cable routes in the same time than while using different voltage sources. In other words: the condition of almost twice the number of cable routes can be determined in the same time, which is of advantage for condition-based maintenance.

Standard deviation	Result	Measurements required	Measures required	Comment
< 0.010	• Cable in good condition • Water trees • Only less PD	• tan delta • PD	• None, as in good condition	• Standard deviation tan delta low • No PD, no high PD
0.010 to 0.080	• Water trees and PD • Only PD	• tan delta • PD	• Moderate ageing with regard to water trees • PD concentration must be analysed	• Moderate water trees – No immediate measures • Replace joints in case of PD concentration
0.080 to 0.500	• Water penetration in joints	• tan delta • PD shows no high values	• Only the tan delta shows the effect • PD values decrease due to water penetration, PD cannot be used as criterion	• Sheath fault location can display the location of wet joints because leakage currents occur there • Joints with indication of low PD must be found (in spite of low PD values)
> 0.500	• High water penetration in joints	• tan delta • PD are largely eliminated in the relevant joints	• Only the tan delta shows the effect • PD displays no weak points / immediate replacement of joint • Check PD calibration graph	• Sheath fault location can display the location of wet joints because leakage currents occur there

Table 3: Guideline for interpretation of standard deviation of tan delta.

5. Practical example

This example shows why it is important to keep the option of a dissipation factor measurement and a partial discharge measurement open: typically, defective joints for example, wrong accessories or those with electrical conducting faults, can be detected with the PD test. However, this is not the case with wet joints. In this example, during tests in a network in Hong Kong, the tan delta measurement delivered information on this.

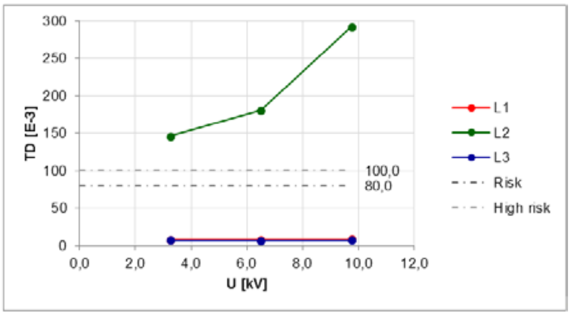

Fig. 4: Dissipation factor measurement on three-phase cable: Conductor 2 shows a high standard deviation.

STDTD	$0.5U_0$ (kV)	U_0 (kV)	$1.5U_0$ (kV)
	3.5	6.5	10
L1	0.068	0.036	0.060
L2	4.453	2.313	9.343
L3	0.063	0.004	0.050

Table 2: Measured values for Figure 4:

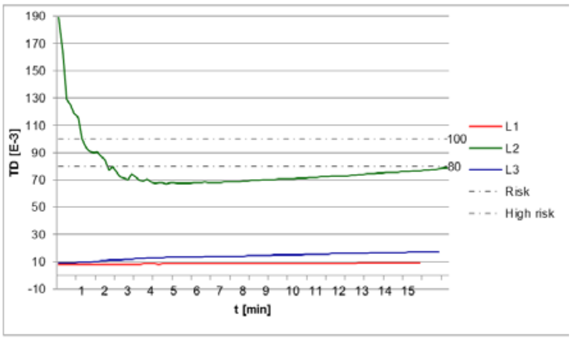

Fig. 5: Drying effect of moist joints during a MWT

The tan delta standard deviation on conductor 2, identified in Fig. 4, strengthens the suspicion of a moist joint, as the PD test cannot detect any PD activity (too much moisture). The MWT, i.e. the combination of cable testing and tan delta measurement over 15 minutes, conveyed that the joint had dried up and that the tan delta had clearly dropped (Fig. 5). This reinforced the suspicion of wet joints.

6. Effects of the voltage source – Example E-Werk Mittelbaden

About ten years ago, the Elektrizitätswerk Mittelbaden Netzbetriebsgesellschaft mbH (short E-Werk Mittelbaden) carried out a comparison of VLF 0.1 Hz sine and a 50 Hz method for the PD test based on over 40 cable routes. As the 50 Hz method produced too many highly varying evaluations and especially more negative prognosis at the time, which until today were not considered as losses, the company decided on the VLF 0.1 Hz sine method. In the meanwhile, the VLF measurement with sine voltage has been established in hundreds of tests. This was evident in the diagnostic measurements, performed on 240 kilometres with 500 partial routes in the 20 kV network of the E-Werk Mittelbaden, on paper pulp insulated and mixed cable routes.

At the E-Werk Mittelbaden, such cable routes with a VLF sine 0.1 Hz have been diagnosed by means of PD, and since about seven years, also by means of the tan delta measurement. According to Werner Brucker, Director of network operations, both these diagnostic procedures produced a good overall view of the age and condition of the network. Partial routes classified as dangerous will be replaced soon. The isolation of defective partial sections resulted in huge savings, as the entire cable run didn't have to be replaced.

In practice, the VLF measurement has proven to be suitable during the commissioning tests of new or modified cable systems for locating faults precisely, and in future for detecting faults in the accessories with a simultaneous PD test so that the work involved for troubleshooting, such as installation faults, or during maintenance, e.g. excavation work, can be kept to the minimum.

Brucker emphasises the weight and suitability for daily use as an essential advantage of the VLF sine voltage source. The 0.1 Hz technology can be transported and operated by any employee, which would not have been possible with a 50 Hz system.

The use of a test car with two persons is required very rarely, as the portable measurement and testing device is enough for most cable lengths. A test car would be necessary only during the seventh measurement or so.

E-Werk Mittelbaden saw a clear cost advantage by applying the VLF 0.1 Hz technology: measurements could be easily performed by a single employee in a short time. Due to the short connection time and test duration as well as the need for fewer people, several cable routes can easily be tested per year. Routes identified as critical during the measurements or partial sections will be scheduled for repair or replacement. Maintenance budgets can thus be deployed specifically. With the knowledge of weak points in the network and the condition-based maintenance, in spite of the growing cable stock, running the medium-voltage network with a low failure rate and in a cost-optimised manner has been successful.

The maintenance plan at the E-Werk Mittelbaden is approx. EUR 4 million, of which

EUR 2.5 million are relevant for the distribution network. The costs for cable diagnostics at present are € 90,000/year.

From the comparative tests conducted before procuring the VLF equipment, Brucker knows that there were distinct differences between VLF 0.1 Hz sine and 50 Hz measurements for his tests.

In practice, a changeover seemed no longer relevant, as the E-Werk Mittelbaden became very familiar with the VLF 0.1 Hz measurements and its interpretation, and is able to use measured values with high reliability for classifying cable routes. Even the prognosis whether a cable route is in danger in the short or medium term is possible with relative accuracy due to the wealth of experience, thus making it easier to prioritise maintenance measures accordingly.

7. Conclusion

The use of a VLF sine voltage source opens up the possibility of a single person performing cable tests and diagnostics of a cable route and with portable equipment. In scientific studies and in the field, the VLF sine showed that it is a suitable voltage source for cable testing, PD and tan delta measurement and that the achieved measurement results can be compared with results of tests performed at operating frequency. In addition, the ideal, load-independent sine form proved to be of benefit when it pertains to the reproducibility of results and when load-independence is desired (independence from measurement of cable lengths). Thus, comparisons of measurement results can be performed easily and more experience on condition evaluation of cable routes can continue to be acquired.

Thus, the VLF sine measurement offers the opportunity to measure more cable routes by using the same means and time and to collect more information on the network condition. This comes with various advantages:

- Specific allocation of maintenance budget
- Cost savings by isolating faulty partial sections
- Lower failure rate
- Positive effect on the cost structure in ratio to the network failure rate
- Quality of new cable routes (detection of installation faults before any actual failure)

Against this background, the discussion about the comparability of the VLF sine measurement results with other voltage shapes acquires academic importance. The universality of VLF sine measurement has proven its suitability in various networks (Europe, overseas, on plastic-insulated cables, paper pulp insulated cables, mixed routes…) and delivers ample and precise results, thus enabling the network and maintenance engineer to make a reliable evaluation of the cable routes.

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