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A New Approach for VLF Withstand Testing and Cable Fault Pre-Location

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Abstract

They need to be tested to ensure the reliable operation of power cables. While cable testing, pre-damaged cable insulation may break down, resulting in an arc, which enables the location and repair of the damaged cable section. For this purpose, various cable fault location methods have been established. After an arc occurs these methods are applied with an additional cable fault location equipment. This paper introduces a new approach, where cable testing and cable fault pre-location are combined to test the device's feasibility a field study was conducted, which is presented in this paper.

Keywords: APL, Arc Pre-Location, Cable Fault Pre-Location, Simultaneous Cable Testing and Fault Pre-Location, VLF Cable Testing

Abbreviations and Acronyms: **ADC:** Analog to Digital Converter, **APL:** Arc Pre-Location, **ARM:** Arc Reflection Method, **DUT:** Device Under Test, **HV:** High Voltage, **ICM:** Impulse Current Method, **PD:** Partial Discharge, **PDTD:** Partial Discharge & Tan Delta, **PILC:** Paper Insulated Lead Cable, **TD:** Tangent Delta, **TDR:** Time Domain Reflectometry, **VLF:** Very Low Frequency, **XLPE:** Cross-Linked Polyethylene

1. Introduction

A secure supply of electricity and a reliable power system operation can only be guaranteed if the transmission cables are in a sound state. Therefore, regular or condition-based cable testing should be performed. Various test methods have been established to examine the condition of power cables[1-3]. A precise, reliable and commonly used test method is Very Low Frequency (VLF) cable testing. VLF testing is an offline voltage withstand test and is described and recommended in standards such as IEEE 400.2 or CENELEC HD 620 S2 as well as CENELEC HD 621 S1. The target of the voltage withstand test is to detect weaknesses in the cable insulation, when the cable is offline, to avoid a cable insulation breakdown during operation. While a healthy cable passes the voltage withstand test unharmed, a cable with already damaged insulation will break down during this test, resulting in an arc[3].

In case of a fault, it is of great importance that the fault is located rapidly. Fast fault location can accelerate cable repair, reduce outage durations and avert economic losses[4]. VLF test sets generally show the voltage value at which the cable breakdown occurred as well as the elapsed test time, but they do not provide any information about the fault location.

For the localization of the breakdown, further tests and equipment are needed - typically carried out by a specially trained testing team with a cable fault location van. Cable fault location vans may not always be available when they are needed, because they are often a limited resource of Distribution Network Operators (DNO). With such vehicles, a driver's license for a gross vehicle weight over 3.5 tons might be required. Additionally, equipment within a test van is usually permanently fixed and cannot be used externally. If the vehicle breaks down, the equipment becomes useless. This can lead to longer downtimes of the cable. On the contrary, portable devices are not dependent on the availability of test vans.

This paper introduces an approach, where the functions of VLF testing and cable fault pre-location are combined, including an automatic fault pre-location evaluation algorithm only requiring personnel with basic VLF testing

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training. This paper aims to assess if this approach generally works and if so, how accurate the fault pre-location can be. To answer this question, a prototype was built, where an arc pre-location function was integrated into an existing VLF tester. In-house measurements were conducted, which proved that this approach works under laboratory conditions. In a subsequent field study, this device was used to test several service-aged cables. In the case of an arc, this device also pre-located the distance to the arc. The results show that within this field study, a combined VLF withstand testing and arc pre-location with only one device was possible and provided useful distance information.

2. Cable Fault Location

Since there are several types of faults in underground cable systems, cable fault location depends to a great extent on applying the appropriate technique or a combination of techniques. With no less importance, competent engineers and service providers (mainly for guidance) are required to provide the accurate method[5].

Fault location methods can be categorized into the following principles: impedance-based, travelling wave-based and learning-based[4]. Furthermore, the fault location methods can be divided into single-ended and multiple-ended methods[4]. Here measurements are performed at one or respectively multiple terminals. Various travelling wave pre-location methods have been established. They can be categorized into pulse reflection-based methods and transient methods[6]. In this paper, we present a single-ended transient-based fault location method.

This method is based on an effect that appears when a cable insulation breaks down, due to stress induced by an electrical field. If an insulation breakdown occurs during high-voltage testing, this will result in an arc. Such an arc has usually a very low impedance which will burn for a short period and discharge the cable capacitance. Furthermore, it initiates a high-frequency wave which travels from the arc position in both directions towards the cable ends. These transient waves are then reflected with the same or inverted polarity, depending on the impedance at the cable ends and return to the arc location[7]. If the arc is still present, the transient wave will be inverted and travel again to the cable ends and so forth until the pulse amplitude decays due to damping within the cable[5,8].

The waves hereby propagate with a velocity typical to the cable. The propagation velocity is dependent on various variables like the cable's insulation type, age and temperature[5]. Furthermore, it is also frequency dependent[8,9] which adds an uncertainty factor since the frequency spectrum of the travelling wave may not match the frequency spectrum the cable velocity was measured with.

These travelling waves can be captured at the high voltage source, to determine the distance to the fault location. Typically the period time from the first full wave is measured in the time domain, *i.e.*, a manual selection with cursors to measure Δt from one positive pulse to the next positive pulse. Figure 1 shows an example of such a signal.

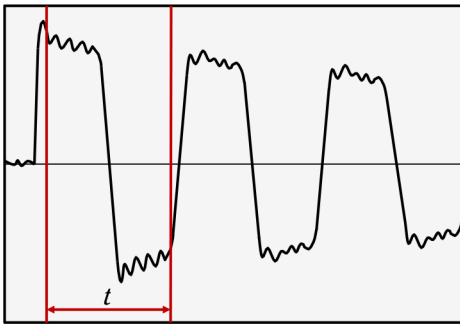


Figure 1. Example of a captured signal with placed cursors.

This manual method to identify the period has numerous disadvantages like inaccuracy due to sampling rates, display resolution, user skills, ignition delay, *etc*[7].

To calculate the distance to the arc *(l)* in m, the following equation (1) is used, with period time *(t)* in s and the cable's propagation velocity *(v)* in m/s[5,7].

$$l = t\frac{v}{4} \qquad [1]$$

3. VLF Tester with Integrated ARC Pre-Location Function

For this field study an established VLF tester and integrated Arc Pre-Location (APL) function were used. As a VLF source, a VLF high voltage test set from b2 Electronics GmbH was used. The test equipment was an HVA45TD, which is a small and compact device providing sinusoidal voltage up to 34,6 kVrms @ 0,1 Hz[10]. This allows to test cables with a voltage rating of 20 kV up to 3 x U0. The integrated APL function consists of hardware and software. The hardware is a small circuit board that captures high-frequency transient waves which are present when a breakdown occurs. The APL software analyses the captured transient waves, to determine the distance to the arc. Figure 2 shows the schematic of the VLF tester including the high-frequency signal acquisition of the APL function.

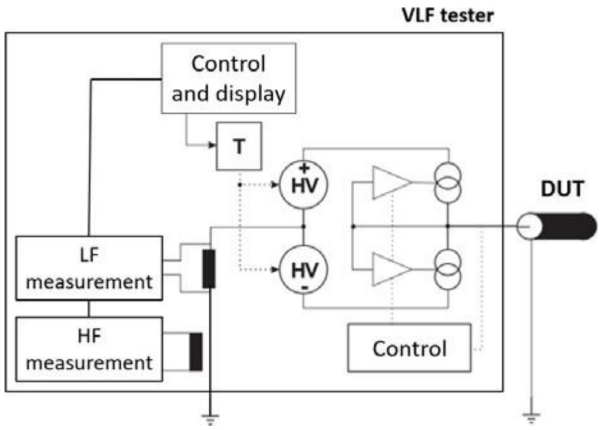


Figure 2. Schematic of a VLF tester including a high-frequency signal acquisition.

4. APL Hardware

The APL circuit board uses a coil to capture transient waves. The coil is placed on the low-voltage side of the VLF tester instead of the high-voltage side. At this position, the coil can capture transients coming from the high-voltage cable without having the disadvantage of requiring thick insulation. This approach is similar to ICM (Impulse Current Method)[5].

The APL reads the induced voltage signal from the coil into an analogue circuit that integrates the signal since:

$$u_{coil} \alpha L\frac{di}{dt} \qquad [2]$$

and

$$\int u_{coil} \alpha L * i \qquad [3]$$

This means the integrated voltage signal *(ucoil)* in V is proportional to the inductance *(L)* in H times the actual transient current *(i)* in A we want to measure.

This signal is then processed via a bandpass filter and read in via an ADC (Analog to Digital Converter). In this field study the signal is sampled with up to 10 MHz to see if it is an appropriate choice.

4.1 APL Algorithm

The software algorithm processes the data as follows:

***Sampling and framing*:** The signal is transferred from the ADC into a cyclic buffer, from which frames are selected based on the signal-to-noise ratio, concurrently to the ongoing sampling. To determine how long the relevant frame of the decaying signal is, we monitor how long the signal persists above the noise level.

***Fast Fourier Transform (FFT)*:** A FFT is performed on the selected frame. The obtained spectrum is then compared to the present noise level. Consequently, the highest spectral peaks are selected.

***Correlation of fundamental waves*:** A correlation of the selected frequencies with the original frame is then performed in the time domain. The correlation values are subsequently ranked. This ranking order was found to deviate from the ranking of the FFT amplitudes and appears to be a better criterion for a good match between the raw frame and the found frequency. This way the FFT pre-selects dominant frequencies, which are then tested via correlation.

***Plausibility check*:** A plausibility check is performed for the dominant frequencies. First, the determined correlation ranking is considered. If the differences in correlation are small, the FFT rank is again considered to decide on a near tie. Then with the known cable length and the cable's propagation velocity a frequency range is determined in which the dominant frequencies must lie. Frequencies out of this range are then discarded. From the remaining frequencies, the most plausible one is selected.

***Distance result*:** To evaluate the raw signal, the APL function determines the frequency, instead of the period time. Since period is the reciprocal value of frequency, the following equation (4) is used to calculate the distance to the arc:

$$l = \frac{v}{4f} \qquad [4]$$

where, f is the frequency in Hertz. The APL uses the most plausible frequency for the distance calculation.

Figure 3 shows the algorithm flow chart. This scheme describes the used software version for the field study.

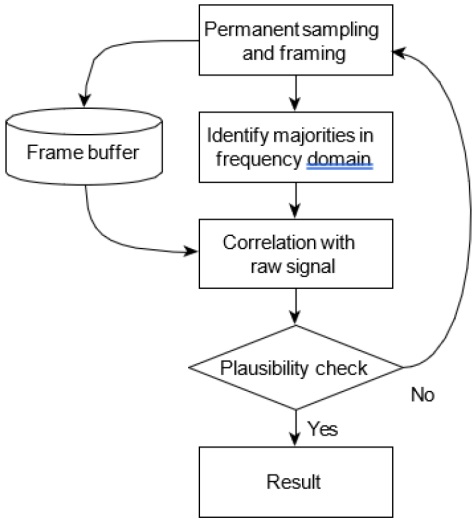


Figure 3. Software process description of the APL function.

4.2 APL Measurement Verification

To verify the quality and accuracy of the recorded signals of the APL circuit board, third-party high-frequency current measurement equipment was used (PEM CWT03). This measurement equipment is rated for frequencies from 67 Hz to 30 MHz and has inductive coupling. This inductive coupling was placed in parallel to the coil used for the APL setup. This signal was then sampled with 20 MHz and read into MATLAB® for processing. The performed processing is analogous to the APL algorithm, described in Figure 3. With this setup, it was possible to verify that the APL hardware records the same signal as the presented third-party solution.

4.3 APL In-House Test Setup

Before performing the field study, the functional principle was tested in-house under well-known conditions at the b2 laboratory. For these development tests, a VLF tester with the integrated APL function was used and HV tests with a designated cable were conducted. This cable consisted of segments that range from 100 m to 800 m in length so that a total length of up to 2.7 km could be arranged. A spark gap was then connected to a junction of any two segments, to simulate a fault from the inner core to the shield.

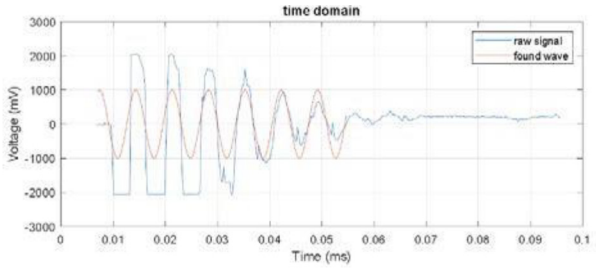


Figure 4. Raw arc signal with an overlay of the plausible frequency.

Figure 4 shows measured raw data (raw signal) with an overlay of the plausible frequency (found wave). With this setup, we were able to test the APL function.

5. Field Study

To check the in-field usability of a combined VLF testing and fault pre-location approach and to evaluate the quality of its measurement results, a field study was conducted. For this purpose, seven service-aged medium voltage cable sets were tested. A local distribution network operator in Germany provided the Devices Under Test (DUT) to carry out this field study.

5.1 DUT Description

For this field study, there were seven 20 kV medium voltage cables with three phases (L1, L2 and L3) available. The total cable lengths varied from 159 m to 722 m. These cables consisted of several cable sections, linked with joints. Some cables had all sections of XLPE insulation, while other cables had sections with different insulation types such as XLPE and PILC. These cables had cross sections from 95 mm^2 - 150 mm^2. The joints in the tested cables had a systematic fault known by the distribution network operator and tended to break down during VLF withstand testing using 3 x U0. Some of the joints were defective because of moisture ingress. Others had insulation breakdown faults in the joints. The majority of these joints were expected to break down during testing making it the ideal opportunity to test the arc pre-location function of the VLF tester.

5.2 DUT Testing Procedure

To obtain breakdowns along the cable, they were tested according to a predefined procedure. First, the cable's propagation velocity was measured with a partial discharge diagnostic system (PDTD60-2) and a calibrator, that was used to inject a pulse at the near end. Afterwards, the PDTD60-2 was used to locate the joints and to perform a Partial Discharge (PD) measurement which can run in parallel to the VLF test and the APL, to identify weak spots along the cable. The consequent VLF withstand test was conducted according to the distribution network operator's internal guidelines, which allow a test voltage of 3x U0. When a breakdown occurred, the APL function determined the distance to the arc, which was later compared to available independent measurements.

Procedure

The procedure was as follows:

- Cable propagation velocity (v) measurement
- Joint position measurement
- VLF withstand test
  - Arc → check APL result → repeat test to get multiple measurements
  - No arc → test next phase
- Arc location verification
  - Third-party system → breakdown position
  - ARM → breakdown position
  - PD → joint position

5.3 APL Distance to Arc Verification

As a basis for the verification, corresponding cable plans were used. The distances contained in the cable plans are usually accurate to +/- 1 m, according to the DNO.

Further on, these plans contain information about the whole cable set and its properties like terminations, cable types, cable section lengths, joint types and positions. The performance of measurements other than APL was also assessed and compared. For this, the following independent measurement systems were used:

The arcs were also recorded with the external reference system PEM CWT03 and evaluated with MATLAB® according to the same algorithm, as described in the APL algorithm paragraph. As a second measurement method, the traditional fault pre-location method ARM (Arc Reflection Method[5]) was used. For this a cable test van of the DNO was available. The last method used was the PD measurement. During the cable set calibration step of the PD measurement, the joint positions can be determined. Since the breakdowns occurred at the cable joints, this measurement was used for the performance comparison. These three independent measurement methods evaluated the APL performance (Table 1).

Table 1. Result overview

Cable plan information	Cable set number	1	2	3	4	5
	Total length [m]	467,1	415,7	181,3	721,5	158,9
	Defective joint [m]	178,7	109,7	167,6	169,8	122,4
APL measurement result	Avg. [m]	177,7	117,5	-	159	114,1
	Std. deviation [m]	10,7	4,9	-	-	1,7
	# Samples used	6	2	0	1	7
Comparison measurements	ARM [m]	173	114	168,5	-	-
	PDTD60-2 [m]	180,1	108,3	170	167,8	129
Difference to cable plan	APL [%]	-0,6%	7,1%	-	-6,4%	-6,8%
	ARM [%]	-3,2%	3,9%	0,5%	-	-
	PDTD60-2 [%]	0,8%	-1,3%	1,4%	-1,2%	5,4%

6. Results

In the following part, the results of the conducted in-house measurements at the b2 laboratory and of the conducted field study at the distribution network operator in Germany are reported. The APL field study results are then compared with established methods as mentioned previously. Subsequently, observed effects are described.

6.1 In-House Measurements

The in-house measurements show that the measurement error of the APL system lies below the targeted range of +/- 10% (which is the common uncertainty range of ICM methods[5]). This was tested for fault distances between 100 m to 2700 m, independent of the overall cable length (Figure 5).



Figure 5. Measurement error of the APL function in the laboratory.

The measurement error hereby decreased with increasing distance to the fault.

6.2 Field Measurement

During the field study 7 cable sets with 3 phases each were tested. Therefore, 21 individual cables were available for testing. 11 of these cables broke down with an arc during the 3 x U0 VLF withstand test. The faults, which were localized with the APL, later pin-pointed and excavated for repair, were in a range of 110 m to 179 m. All the faults were at or inside the joints.

The 11 cables with joint breakdowns can be classified into the following three categories:

- For 7 cables, the algorithm could retrieve the distance to the arc.
- In 1 cable both information about the cable length (L/2) and the fault distance were present in the signal. The automatic distance evaluation failed due to this.
- In 3 cables the transient signal only contained information about the cable length (L/2) or had a fault characteristic, that persisted in returning ambiguous signals (Figure 8).

Table 1 summarizes the measurements for each cable set where at least one breakdown occurred (5 cable sets in total). If the fault distance could not be determined in one phase, the next phase was tested. This was sufficient to repair the cable set since all joints were at the same position for all three phases of the cable set.

At the cable set number 3 only one phase arced but returned ambiguous data which could be rejected with the plausibility check. Hence no sample was used.

At the cable set number 4 only one arc could be recorded and the APL managed to determine the correct fault location from this single arc. After this single arc, the fault could no longer be ignited. This shows the benefit of simultaneous arc pre-location and VLF testing, provided by the proposed method without additional effort.

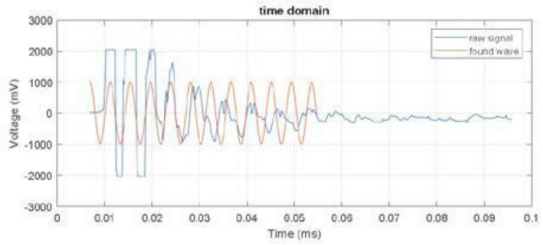


Figure 6. Example of an arc recorded by the APL of cable set 1 with frequency overlay.

To demonstrate one of the measured raw data, Figure 6 shows a captured transient wave (raw signal) from cable set number 1 and the corresponding frequency (found wave), determined by the APL function.

6.3 Measurement Comparison

We observed, that the APL did perform just as well as the external reference system PEM CWT03 described in the APL distance to arc verification section. Either both the APL and the external unit did find the distance to the arc or neither of them did. This confirms that the used APL hardware is accurate for recording the transient waves. For this comparison, 32 data sets from 9 different cables were used.

The APL distance to arc measurement was compared with the available joint position from the cable plans. The performance of the ARM and the PD measurements was also assessed. Table 1 shows the different measurements and compares their accuracy.

The APL measurements deviated up to 7,1% from the cable plan values, which corresponds to a maximum difference of 11 m in this setup. For three cable sets the ARM measurement data was available. The results show that there was up to 3,9% difference between the ARM measurement and the cable plans. The measured distance to the joint from the PD measurement differed from the cable plans up to 5,4%.

7. Further Findings and Discussion

Additionally, we obtained further interesting information regarding breakdown characteristics, arc burn time as well as fault conditioning effects, and gained some experience with a traditional fault pre-location method.

7.1 Observed Breakdown Characteristics

The cable joints had various breakdown characteristics. The breakdown was sometimes not reproducible when repeating the same VLF test right after a breakdown. Sometimes repeated breakdowns could not be achieved, even when increasing the voltage to the distribution network operator's specified maximum permissible testing voltage (3 x U0 and even 3.2 x U0 in one case). This was the case as cable set 4 was tested and only one arc could be ignited.

The VLF tester used in this field study can measure Tan Delta (TD) simultaneously with the performed VLF test. In some tests, a decrease in TD could be observed. A decreasing TD value over time, during a voltage hold phase, is usually associated with moisture ingress[11]. The fault hereby disappears when the moisture has dried out, indicated by a lowered TD value. Such a phenomenon was observed with some cables.

In this case, the APL proved its advantage of requiring only a single arc to perform arc pre-locations. This is especially advantageous when arcs cannot be repeated, which was the case with some of the cables tested during this field study. With the usual separation of cable testing and fault pre-location, this fault would not have been easy to find. The found distance with the APL function could be associated with a joint which later was confirmed as the cause of the fault by pinpointing.

7.2 Short Arc Times

A phenomenon observed was that on some cables the arc, caused by the breakdown, extinguished before the stored energy in the cable was depleted resulting in arc burning times of under 10 µs. This led to a signal that contained the distance to the arc only in that first period followed by a phase where the transient wave contained a period length of half the cable length (L/2) when using the same evaluation algorithm. The observed length is due to the fact, that the signal can now travel the whole cable length after the arc is gone.

When this occurred, the extraction of the correct distance to the arc was challenging. Whether this phenomenon is common or just a seldom occurring case specific to these joints, requires further investigation. This insight showed us a phenomenon we did not observe during the in-house measurements.

Meanwhile, when repeating arcs, two clusters of distances were observed, one at L/2 and the other at the defective joint (Figure 7). With knowledge of this phenomenon, one can prioritize the one not near L/2 in the plausibility check.

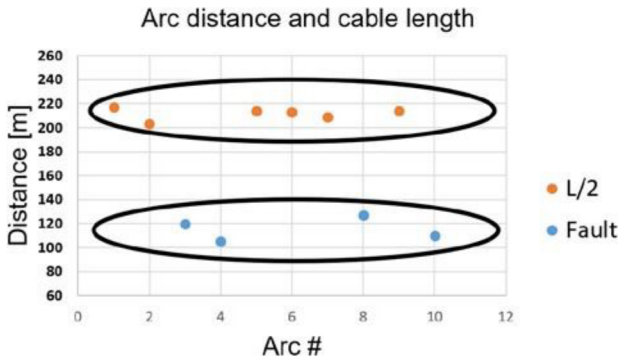


Figure 7. Repeated APL measurements containing the arc distance of around 117 m and L/2 with a cable length of L = 416 m.

7.3 Fault Conditioning Effect

Some arc events produced ambiguous signals such that no distance could be determined from them. Too much damping made the signal disperse. Such damped arc shapes are already described in the article[7]. The more distinctive the arc signal is, the better the arc distance detection performs. Figure 8 shows recorded raw data of various arc qualities.

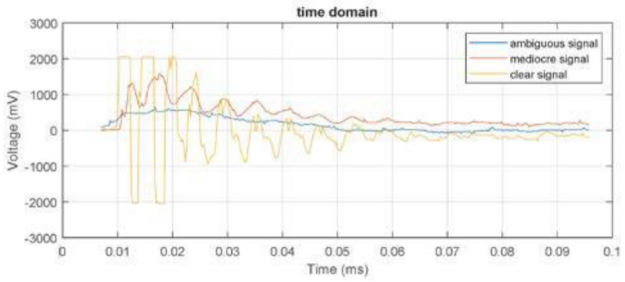


Figure 8. Recorded signals with varying quality.

In cases of ambiguous signals, fault conditioning effects can be exploited. On some cables, the recorded transient shape evolved when multiple breakdowns were caused. The recorded signal evolved from a smoothed-out wave to a very clear transient wave. In these cases, after an average of 3 arcs a clear image was obtained.

Other cables, with faults in the same joint type, did yield a clear transient signal at the first arc. When analyzing the defective joints, after replacing them, different fault patterns were observed. This might be the reason for the different behaviours under high voltage. These examples of experienced phenomena show how broad the behavior of arcing cable faults can be and this is exactly why a field study was conducted to test the APL system on real faults and in operational conditions.

7.4 Experiences with a Traditional Fault Pre-Location Method

The ARM method required manual placement of cursors to pre-locate the faults. In this study, it was known that the breakdowns occurred at the joints. Therefore the user may tend to place the cursor where a joint is. This biases the obtained values toward the a priori known cable plan values.

Sometimes the ARM method required repeated thumping before it returned the desired transient images. For some cables, the maximum voltage of the ARM method of 32 kV was not sufficient to trigger an arc. Then a VLF withstand test at higher voltages was performed to condition the fault and the ARM method was repeated, expecting a now lower breakdown voltage than 32 kV. This limitation is not present with the integrated APL, since the maximum voltage is only limited by the capabilities of the used VLF device.

8. Conclusion

This paper reports on a new approach of combined VLF testing and arc pre-location. To prove the approach's functionality and in-field usability, in-house measurements as well as a field study were conducted. The in-house measurements show that the APL can repeatably locate the distance to the arc in laboratory conditions. The field study shows that combined VLF testing and arc pre-location in a single device work and can deliver useful information to the user without further instruments. The comparison of the APL measurements shows that the results vary in a range of up to 7%, which is comparable to the accuracy of established ICM methods.

9. Outlook

If there is a breakdown during the VLF test nowadays, a cable test van and a specially trained person to locate the fault must be organized. It may be that the cable test van of the distribution system operator is already busy or that no one has an appropriate driver's license to drive a vehicle with more than 3.5 tons of gross vehicle weight. The APL function integrated into the portable VLF tester enables pre-location at the moment of the breakdown. Field testing has shown that this is accurate enough to pinpoint the location of the fault within one joint. A simple surge generator and a ground microphone can be used for pinpointing so that in most cases the test

van could be dispensed with such. This approach would enable distribution network operators to repair faults more quickly, optimize their operating procedures and thus save money.

10. Acknowledgement

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