Breakdown Behaviour of Damaged Low-Voltage Cables: Laboratory Experiments and Field Experience

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Abstract

Faults in Low-Voltage (LV) cables commonly develop from earlier inflicted damage. Outages can be preceded by high-current transients of duration too short to activate protective devices like fuses. This paper explores such early signatures of possible upcoming faults both by laboratory experiments and in a field study.

Upon exposure of moisture the breakdowns and their voltage and current characteristics are investigated for two LV cable types (OIP and PVC). In laboratory tests, a clear intermittent behaviour is observed. Typical breakdown signals show a current transient igniting around the voltage peak and its extinction is usually close to the voltage zero crossing. LV grid faults should be distinguished from events occurring in connected households. Though signal patterns can be comparable, a distinction can usually be made, mainly based on current peak values because of the interruption characteristics of household miniature circuit breakers.

A pilot study involving 23 connections in the LV grid has shown similar signals as obtained in the laboratory tests. Typical cable fault related transients were observed beforehand. This indicates a correlation of such transients and the likelihood of an outage. A large variation of the time to an outage was observed ranging from several hours to several months.

1. Introduction

Compared to high-voltage and medium-voltage grids, the Low-Voltage (LV) grid has received little attention in terms of condition monitoring. This can be understood from the perspective that both the number of customers involved in an outage and the impact on the Customer Minutes Lost (CML) are relatively low. On the other hand, according to a study performed by a Dutch utility, the costs involved are almost a factor three higher, as indicated in Table 1. This is related to the complexity of the highly meshed LV grid. Moreover, a fault is often of an intermittent nature which complicates locating its origin.

Intrinsic degradation is not expected to be a major issue because of the low electric field stress, but faults may develop from an earlier inflicted damage depending on environmental conditions, e.g. presence of moisture. A damaged part (e.g. by digging activities) can be submerged in (ground) water. Corrosion will take place, in particular when aluminium cable conductors are applied. With less moisture present water may slowly accumulate until a process similar to dry-band arcing [1] occurs, upon which the moisture evaporates and the insulation is restored. The development of this mechanism to a fault depends on the presence of a thin water layer. Whether such layer is formed is affected by many, not fully understood, conditions. Influencing factors include water conductivity, temperature, voltage difference, soil properties, etcetera [2,3].

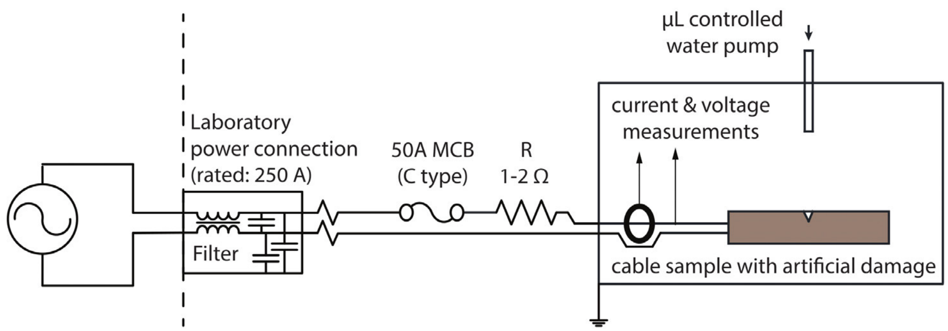
Ideally, ageing mechanisms would provide measurable signals to be employed for monitoring the condition of the LV grid. The topology of the grid is strongly meshed, providing electricity to households, meaning that any high-frequency signal arising from aforementioned ageing mechanisms will be reduced in amplitude at each branching connection. It will be severely attenuated and hard to detect e.g. in the noisy environment of a substation where the main LV cable ends. Simulations of propagation of such signal based on a simplified network with components with modelled and experimentally verified characteristics are provided in [3]. Therefore, the focus is directed to faults which are of intermittent nature. In this paper, characteristics of such faults are studied both under controlled laboratory conditions (Section 2) and from a pilot project with installed sensors in the LV grid (Section 3).

Table 1 - Indication of repair costs and CML for the medium and low voltage grid of a single grid operator over 2015 (2.7 million customer connections).

Grid level	**MV**	**LV**
Estimated costs per outage (€)	7000	2300
Number of outages/year	627	5500
Average CML/outage (minutes)	38000	2500
Total costs/year (M€)	**4.4**	**12.7**

2. Laboratory study

A breakdown does not necessarily cause a permanent outage. Low voltage outages can have an intermittent character. Such faults, sometimes referred to as high impedance faults, have been described in literature, e.g. [4,5]. Often, after breakdown, the insulation recovers within several milliseconds when a voltage zero crossing is reached. The energy contained in the breakdown arc disturbs the original conductive path leading to self-healing behaviour. Depending on the impedance of the grid and short circuit current of the transformer, such faults may not cause an outage directly as the current is too low and of too short duration for a fuse to break. This leads to intermittent



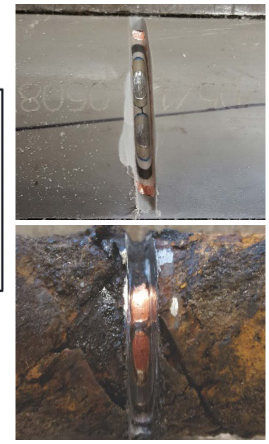


Fig. 1 - Schematic representation of laboratory setup for breakdown measurement of artificially damaged cable sections upon controlled exposure to water droplets. Artificial damage to PVC insulated (right-top) and OIP insulated (right-bottom) cable sections.

current pulses starting around the voltage peak and ceasing at the subsequent zero crossing.

2.1. Experimental setup

Experiments have been conducted on samples of PVC insulated cable with 95 mm^2 aluminium conductors and on OIP insulated cable samples with 35 mm^2 copper conductors. Artificial damage was inflicted by using an angle grinder. Damage in the form of a slit was made of such depth to reach the minimum distance between two conductors. For the PVC and OIP insulated cables this distance was 3.0 and 1.7 mm respectively (Figure 1). Nominal voltage (400 V_{RMS}) is applied to the two affected conductors via resistors connected in series to limit the short-circuit current. To prevent unwanted outages the test setup current was limited such that a 50 A circuit breaker would not break (the connection was rated at 64 A). Current and voltage measurements were conducted as close to the damaged cable section as possible (about 10 cm distance). The current is measured using a current probe with a bandwidth from 5 Hz to 2 MHz. The voltage is measured using a differential probe with bandwidth from DC to 20 MHz. Development of the fault was enforced by means of repeatedly exposing the damaged spot to water droplets. The rate was set to 90 s interval between successive drops (this appeared a practical value to achieve result within a reasonable test duration). The water conductivity was set to 2 mS/cm. This is higher than for average ground water conductivity (0.7 mS/cm, [6]), but was chosen for obtaining faster results. Its value was low enough not to cause a direct breakdown. A comparison was made with lower water conductivity as verification, showing no significant difference except for the shorter time till breakdown.

2.2. Breakdown transients

Discharges are observed along the surface of the damaged spot upon water exposure. These discharges cause degradation of the insulation material which forms an increasingly conductive path over the insulation surface. After sufficient development this path causes a short circuit between two conductors. The breakdown generally starts around the peak voltage. The conductive path gets disturbed by the energy associated with the arc and it can no longer support the breakdown after the arc extinguishes when the voltage is too low (around the zero crossing of the voltage).

A typical transient as measured with the PVC insulated cable is given in Figure 2. The current follows the amplitude profile of the line voltage and the arc voltage remains relatively constant, suggesting that the arc conductance is proportional to the arc current. Shortly before the arc voltage zero crossing, the arc current reaches zero. An offset is observed in the current magnitude just after crossing zero, due to the current probe having a pass-band characteristic starting at 5 Hz. As the arc extinguishes when a voltage is still present, a transient recovery voltage is observed when the current reaches zero.

Voltage and current patterns have been recorded for up to 100 breakdowns to study the development of a fault. For the PVC cable sample, this took approximately 3 hours, while with the OIP cable sample it took about 4 hours. Figure 3 shows the arc admittance for 100 accumulated breakdowns for both the OIP and PVC samples. A large variability is observed: over ±20% with respect to the average value. Whereas the arc often extinguishes close to the voltage zero crossing in case of the OIP cable sample, in many cases the arc extinguishes earlier for the PVC cable sample. The minimum arc voltage is lower for the OIP cable sample. This is likely related to the shorter conductor distance, which may also be the cause of earlier extinction. With both sample types, the arc admittance scales nearly proportional to the arc current. Linear approximations are given in Figure 3 with slopes of 14 mS/A for OIP and 8 mS/A for PVC. There is a small difference between the positive and negative current cycles. Roughly similar characteristics are also observed in [7]. If the arc admittance is modelled as a linear relation with the current, the coefficient represents the reciprocal arc voltage, i.e. the near constant arc voltage observed in Figure 2. The admittance coefficients β of 14 mS/A and 8 mS/A correspond to arc voltages 71 V and 125 V for OIP and PVC respectively.

2.3. Discussion

A short circuit may also occur within the household connection, due to a faulty equipment or accidents in households. Such faults are cleared by the fuses or circuit breakers at the residential distribution panel. Faults from the LV grid should be distinguished from those occurring within households. Fuses is substation need very high currents (e.g. around 10 kA for a break within 5 ms for a 200 A fuse) to cause an immediate break. In households the rating is much lower (typically 16-40 A) giving rise to distinct interruption characteristics. To quantify these characteristics, an estimate of behaviour for fault current due to cable faults in the grid is made.

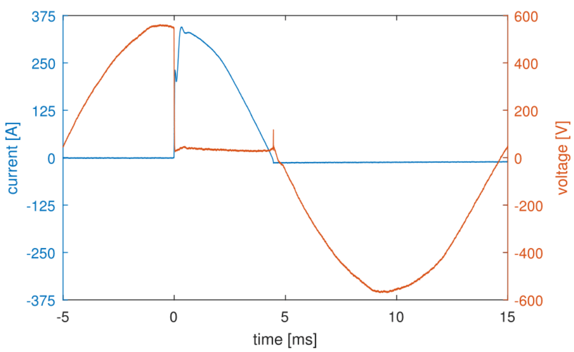


Fig. 2 - Typical voltage and current waveform during a breakdown.

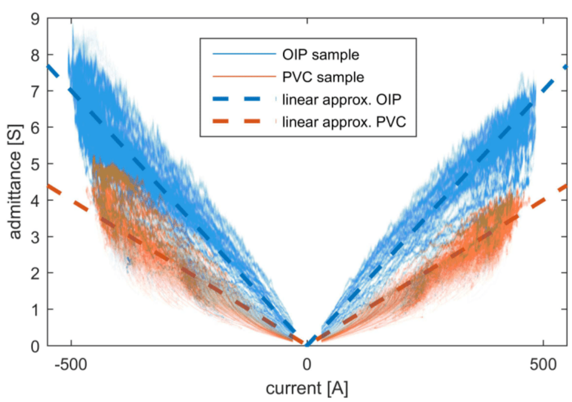


Fig. 3 - Simultaneous plots of the arc admittance vs. current for OIP and PVC samples.

Assuming a linear relation between the arc admittance and current, the peak current I_{peak} can be expressed as

$$I_{peak} = \frac{\sqrt{2}\,V - \frac{1}{\beta}}{|Z_{tr} + Z_{cbl}|}$$

In the LV grid, the short circuit impedance is mainly determined by the transformer in the substation (Z_{tr}) and the cable impedance (Z_{cbl}) [8]. The expected peak current for a phase-to-phase fault ($V = 400$ V) can be determined. Impedance values for cables typically applied in the LV grid are used and the β coefficients are taken from the experiments in Section 2.2. These arc admittances are associated with the shortest arc length possible for the respective cable type as the experimental samples were damaged accordingly. In practice the damage may be such that the arc length is longer, thus lower currents may be expected. The expected peak current versus the cable length is given in Figure 4.

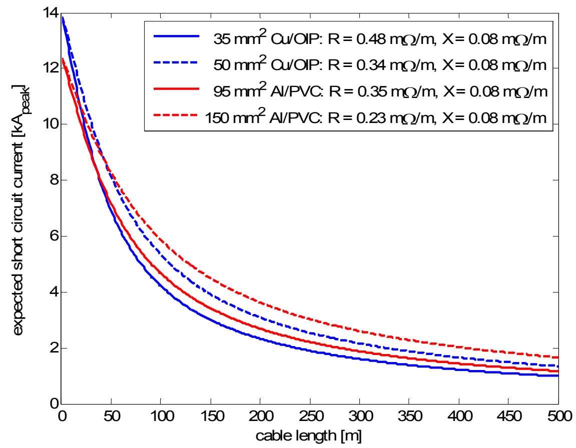


Fig. 4 - Expected peak current versus cable length with a 400 kVA transformer ($R = 5.1$ mΩ, $X = 16.9$ mΩ for each LV phase) for different cable types given a phase-to-phase fault (per unit length resistance and reactance are provided). The Cu cables were OIP and the Al cables PVC insulated.

For households, in most cases, Miniature Circuit Breakers (MCBs) are used [9]. Even if the circuit breaker operates, a short circuit current arises until the connection is interrupted. The time needed to disconnect depends on the short circuit current and the MCB rating. If the current is much higher compared to the rating of the MCB, the breaking time can be within the order of arcing time observed in Section 2.2. In this case, transients as are observed with cable failure could originate from residential short circuits. The standards for MCBs do not provide clear specifications of operation within this time range. The instantaneous tripping current is generally determined at breaking times of 10 or 100 ms and longer. Therefore, the behaviour of a commonly applied circuit breaker type (Schneider iC60H, C type) was determined in an experiment described in [3]. Assuming that the result of this specific breaker type can be generalized, the conclusion is, that similarity of a household fault and a main grid fault exists only if the main cable fault occurs at a distance of more than 500 m. At shorter distance the current amplitude from a main grid fault is high and interruption by the MCB results in a different current profile. Furthermore, a short circuit in a household is less likely to repeat and the start of the current transient probably can occur randomly with respect to the phase angle. A transient originating from a cable damage is expected to start around the voltage peak value. These differences could be exploited to distinguish the origin of the signals.

3. LV grid study

The feasibility of detection of temporary short-circuit transients in a real grid as a method to identify damaged cables is explored. Within the short arc duration as observed in Section 2.2 fuses applied in substations need a high current for an immediate break (e.g. 7.5 to 12 kA for a 200 A fuse within a 5 ms duration [10]). Depending on the fault admittance and the distance to the fault location, transients occur without breaking the fuse.

A number of commercially available measurement modules (SASensor [11]) were adapted for a pilot study in 2016, Figure 5. The system was configured with four voltage sensors and three current sensors. It records the average RMS voltages and currents over every 5 minutes to obtain a load profile. A transient recorder operates at 4 kHz sampling frequency, and saves 4.1 s of data when a threshold is exceeded for any of the current sensors. Most feeders in the investigated grid are protected with fuses below or equal to 200 A. The monitored cables were selected based on problems in the past; usually a fuse being replaced multiple times but without repairing the connection. In total 23 cable connections have been monitored in the pilot, of which in 5 cases an outage occurred. Three of these cases are discussed below.

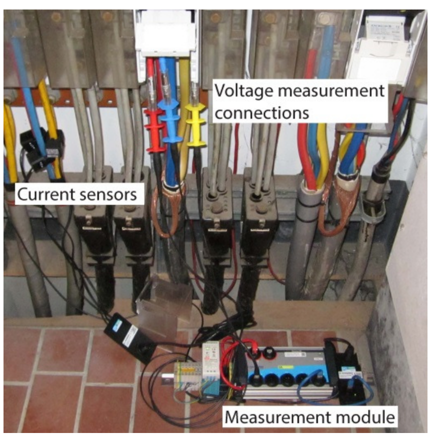


Fig. 5 - Measurement module installed in a LV substation.

3.1. Case study 1: failing joint

An OIP insulated cable with four 50 mm^2 copper conductors and in addition four 6 mm^2 copper conductors for the public lighting system. The cable has been monitored at the main conductors for 8 months until an outage occurred. An overview of the measurements is shown in Figure 6. During the measurement up to the outage 26 events have been recorded. An example of such event is shown in Figure 7. From the current profiles the 50 Hz base load current is subtracted in order to highlight the transient current. The amplitude is 270 A after compensation for the baseline load with a duration of 4 ms. The arc initiated around the peak of the voltage. Over the course of measurement, several events have been recorded with comparable characteristics, mostly for phase 3 (blue), but also for the other two phases. A few days before the outage, a transient with duration of over a power cycle was recorded, Figure 8. Its duration was 30 ms and with amplitude of 270 A on phase 2 (yellow). The fault was found in a mass filled branch joint, at 225 m from the substation.

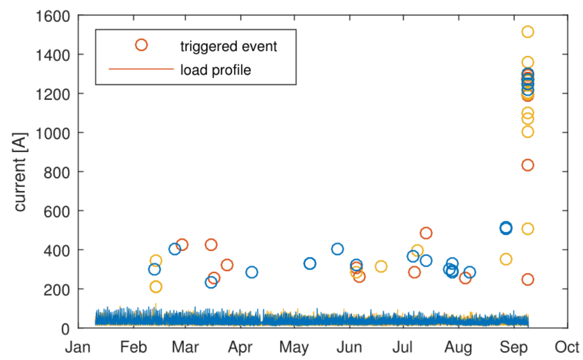


Fig. 6 - Overview of the measurements associated with case study 1. Daily averages are shown as line graph at the bottom, the circles indicate peak current from triggered events. Colours indicate different phases.

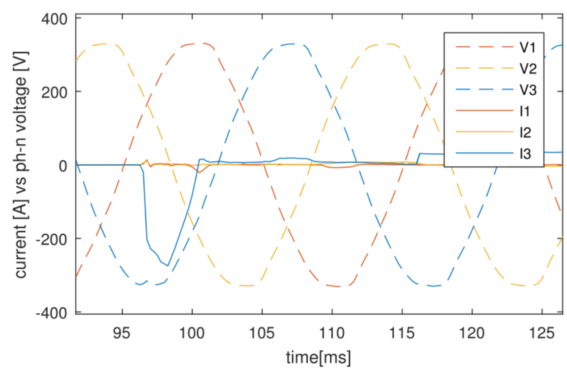


Fig. 7 - Triggered event on blue phase recorded at 10-05-2016, with subtracted base load.

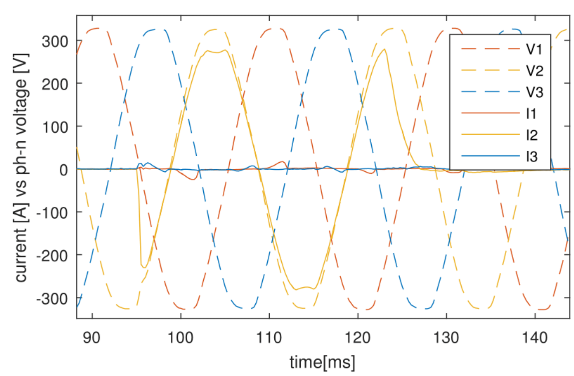


Fig. 8 - Triggered event on yellow phase recorded at 28-08-2016, with subtracted base load (12 days before the outage).

3.2. Case study 2: fault 160 m from substation

The measured cable has PVC insulation and 50 mm^2 aluminium conductors. The period of measurement was from 14 September till 17 October. An outage had occurred on 18 August, after which an automatic fuse was installed. No events have been triggered by the sensor until 14 October. Afterwards, 12 events have been triggered until an outage occurred at phase 2 later that day (spread over 19 hours). An overview of the last three days is shown in Figure 9. Further events are triggered (16 times, including 5 on which the installed automatic fuse interrupted) for about 9 hours, until the connection was taken out of service by the grid operator. Events are triggered upon transients at the other phases as well. The transient for the first event is shown in Figure 10. This pattern has typical breakdown characteristics with a short circuit between two phases. Most of the later events have similar patterns. All three phases are involved.

Upon investigation, a faulty component was found at 160 m distance from the substation. The actual failing component is not known. Because all three phases are involved, most likely a joint has failed. The automatic fuse recorded short circuit currents up to 2 kA.

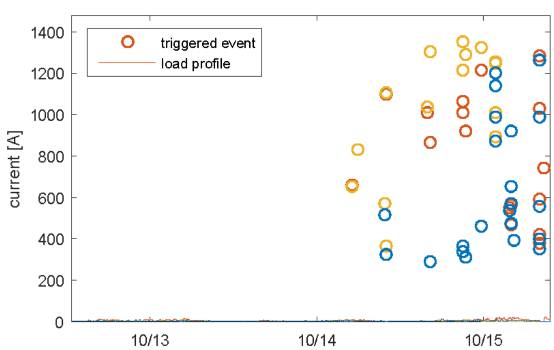


Fig. 9 - Overview of the last five days of measurements associated with case study 2. Daily averages are shown as line graph at the bottom, the circles indicate peak current from triggered events. Colours indicate different phases.

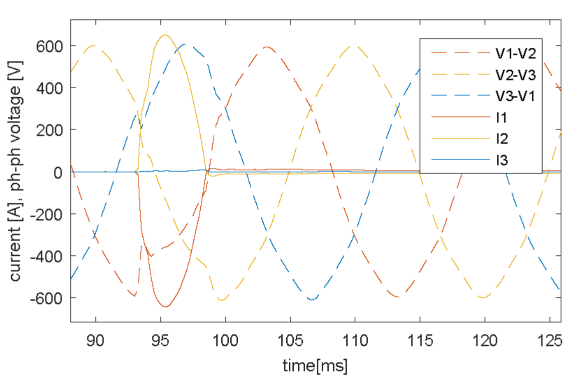


Fig. 10 - Triggered event on red and yellow phase recorded at 14-10-2016 (19 hours before the outage and 45 minutes before the next event).

3.3. Case study 3: service cable failure

The measurement unit was installed in addition to an automatic fuse. During the measurement time of three weeks, several issues emerged. First, an illegal tap was found. Second, the cable was overloaded at regular time instances: the cable is rated for 160 A, while currents exceeded 250 A for about a minute every evening. This did not cause a fuse break. During the measurement time, one transient with the characteristics of a cable fault was detected. This transient is shown in Figure 11. Several transients with full cycle duration similar as the one shown in Figure 12 occurred. The pattern does not match typical characteristics expected from a breakdown, as the current starts near the voltage zero crossing. This is expected to be a switching transient.

Power issues were repeatedly reported by connected customers. The connection was therefore tested. A cable damage was found in the service cable connected to this customer block at approximately 60 m from the substation, see Figure 13. A recently (less than four years earlier) installed gas pipeline is present underneath the cable, suggesting that the cable could have been damaged during its installation.

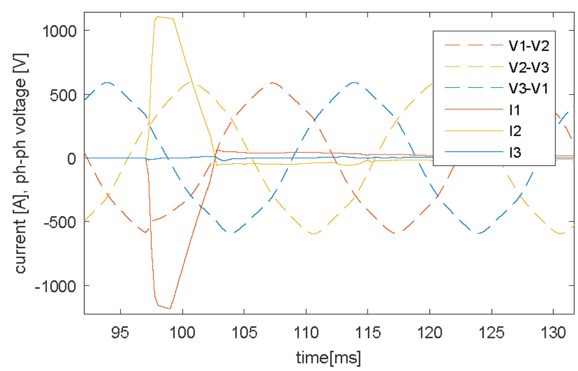


Fig. 11 - Triggered event for case study 3 on red and yellow phase recorded at 18-11-2016 with subtracted base load. Clipping occurred, the actual amplitude including base load was 2200 A, measured with the automatic fuse.

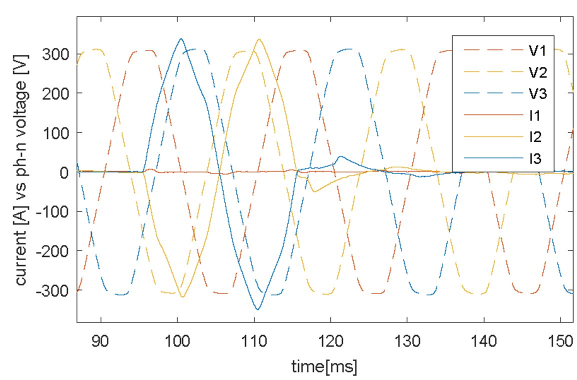


Fig. 12 - Triggered event on yellow and blue phase recorded at 17-11-2016 with subtracted base load.

Fig. 13 - Photograph of the damage cable found in the connection monitored in case study 3.

4. Conclusions

Breakdown arcing has been investigated both in the laboratory and in the grid. A comparison is made.

In laboratory tests, a clear intermittent behaviour is observed. Typical breakdown signals show a current transient igniting around the voltage peak and its extinction is close to the voltage zero crossing. Only in a few cases the arc extinguished over one millisecond before the zero crossing. Early extinction is observed more often with a longer arc length (i.e. conductor distance). Comparison of two cable types also shows higher arc conductance with decreasing arc length. The arc conductance scales nearly linearly with the arc current with its slope representing the reciprocal arc voltage.

The behaviour of MCBs was investigated to compare the effect of a household short circuit to cable breakdown current patterns. Under specific conditions the patterns are comparable. However, the expected peak currents are likely to be lower than occurring during cable faults. Possible overlapping is only expected from cable faults over 500 m away from the substation.

Measurement in the grid has shown similar signals as obtained in the laboratory tests. In five cases, an outage was observed. Usually, typical cable fault related transients were observed beforehand. This indicates a correlation of such transients and the likelihood of an outage. A large variation of the time to an outage was observed ranging from several hours to several months. Furthermore, clear trends in e.g. breakdown current or rate of events towards an outage have not been observed so far. In some cases, typical short circuit transients have been observed while a failure did not occur within the monitoring time.

This research will be continued in collaboration with three main Dutch utilities. It will aim both for further understanding of the underlying ageing mechanisms and for finding feasible options to monitor the LV grid. Besides the technical aspects, it also includes a study of the economic perspectives of condition monitoring in the LV grid.

5. Acknowledgement

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