CHARACTERISATION OF INTERMITTENT FAULTS IN LOW-VOLTAGE UNDERGROUND CABLE SYSTEMS

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ABSTRACT

Condition monitoring of high and medium voltage cable systems is well established. At present interest shifts to investigate condition assessment of Low Voltage (LV) network as well. Experience shows that external damage and water ingress play a major role in LV systems. To build an understanding of degradation mechanisms associated with LV cable failure, artificially damaged cable sections have been tested in laboratory. Water ingress shows to cause a slow process starting with partial discharge like activity. This eventually leads to a short circuit which recovers at the zero crossing of the voltage. Simulations show that the amplitude of the short circuit current can exceed the rated current. However, its duration is insufficient to cause breaking of the fuse and degradation continues unnoticed. These results add to better understanding of the underlying mechanism needed for further development of condition assessment techniques.

INTRODUCTION

Underground power cables provide electricity to customer connections. These cables are a valuable asset to the grid operator and condition is therefore monitored. Since its economic value scales with the amount of power transported by a connection, so far most effort was put into the condition assessment of high and medium voltage cable connections. Several methods are currently available to monitor the insulation condition at these voltage levels.

A disturbance in the Low Voltage (LV) grid has low impact on a grid operator's total customer-minutes-lost since only a few connections will be affected. However, because of lack of redundancy on the LV level and complexity of the meshed LV grid, the costs to repair involved with a LV disturbance is higher compared to high and medium voltage disturbances. Due to the absence of suitable measurements, the LV grid condition cannot be assessed and replacement often only takes place after repeated disturbances. With higher penetration of de-central generation, an increasing (but unknown) load-flow can be expected. Therefore, increased awareness of the LV grid condition is desired.

High field stress degradation mechanisms such as treeing and partial discharges in the insulation material are not expected in LV insulation. Intrinsic degradation of the cable system is therefore expected to be low and lifetime expectancies are high. Statistics show that LV disturbances are most often caused by external damages. With the low voltage, field stress is not an issue and a damage in cables and accessories may not lead to an outage directly when conductors are not significantly affected. LV cables often suffer from so-called intermittent faults, causing occasionally a fuse to break, seemingly without further damage. The fuse may be replaced many times with unpredictable intervals before the fault becomes permanent. This is a costly aspect for the operator and causes repeated outage time to the customer. A correlation with rainfall is often indicated, suggesting that water ingress could play a role in the development of a fault.

Oil-impregnated paper insulated cables have previously been investigated in reference [1]. The results suggest a slow degradation process that can take weeks or months until damage leads to a fault. Currently, plastic insulated cables are applied in new connections and are also used to replace old cables. In a previous investigation into the effects of water ingress in case of Poly-Vinyl Chloride (PVC) insulation [2], a slow degradation process was identified with a simplified representation of a cable. To investigate the development of damages towards a fault in a full cable section upon water ingress, artificially damaged cable sections have been tested in the laboratory. This study aims for a better understanding of LV faults and possibly provides a step towards the development of condition assessment techniques.

The paper first describes the test setup. Next, fault development is explained based on visual observation, voltage and current characteristics. Results are used for analyzing actual situations using simulations. Finally, conclusions are drawn.

TEST SETUP

A typical LV cable used in the Netherlands contains four conductors and an earth screen. In general, PVC insulation and aluminum conductors are used for the main cable, supplying power to several tens of households. One of the four conductors is used as Protective Earth and Neutral (PEN). A cable with 95mm^2 conductor cross-section was selected for the tests. The cross-section of the cable is shown in figure 1. An artificial damage was created by drilling a hole into the cable. This type of damage was preferred as it is more

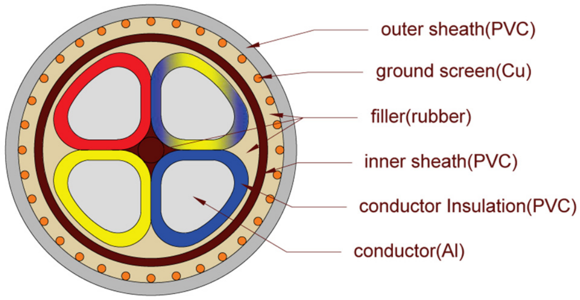

Figure 1: Cross-section of the cable under test.

reproducible and controlled compared to scraping or cutting. The depth was chosen such to reach the aluminum conductors. By choosing a proper drilling spot, either a phase-to-phase, phase-to-neutral or phase-to-ground fault could be created as is represented in figure 2. A hole in between two conductors can cause a phase to phase or phase to neutral fault, depending on whether the PEN conductor is affected.

Cable samples have been placed in a protective environment and supplied at their nominal voltage. Due to laboratory limitations, the rated current of the connection was 50 A. A current limiting impedance is placed to study the effects of the fault without breaking protective fuses. Its value (0.9 Ω) is such to allow an instantaneous current of 225 A with a phase to phase short circuit. This is within the short time limit of the circuit breaker. Water is added to the fault spot in drops of 60 µl every 60-90 seconds. The water conductivity was adjusted such to equal an average ground water conductivity (0.7 mS/cm), measured by a conductivity tester. A camera is used to record the process visually. Voltage measurements are taken using a differential probe and both high (1Hz - 20 MHz) and low (100 kHz - 500 MHz) frequency current measurements are taken using current probes. A schematic representation of the test setup is given in figure 3.

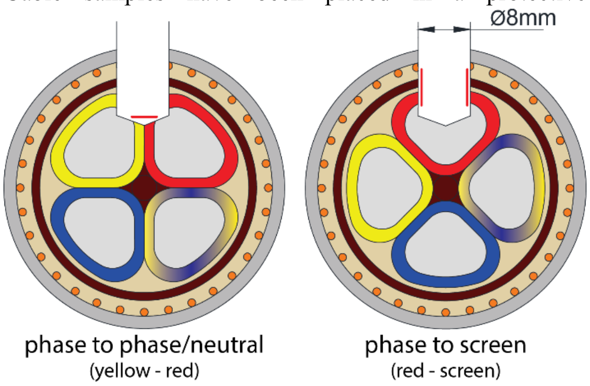

Figure 2: Artificial damage types (degradation is expected at the locations indicated by a red line).

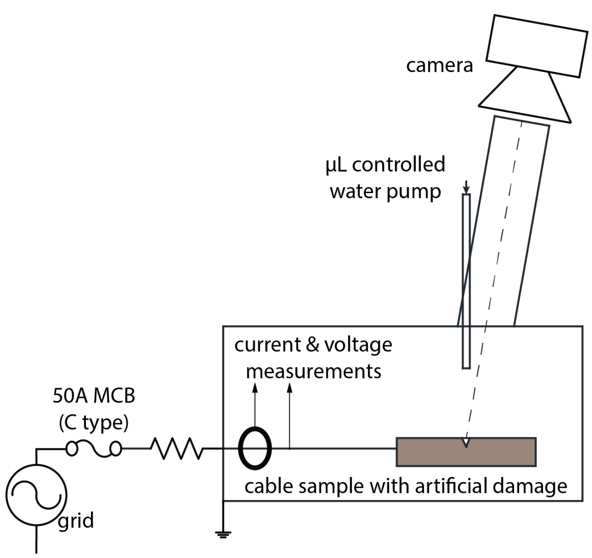

Figure 3: Schematic representation of the test setup.

FAULT DEVELOPMENT

The development of a fault from a damage upon water ingress can be described in the following stages:

- Water evaporation
- Partial discharges (PDs)
- Full discharges
- Recovery
- Escalation of damage.

Due to the water conductivity, the water will evaporate as it connects two conductors with a voltage difference. Once the water has evaporated, discharges can be observed both visually and by high frequency current measurements. Small parts show orange colored discharges over the surface between the two conductors, however not crossing the full length. In the beginning stage, black traces can be observed at the locations where these discharges occurred. This is shown in figure 4.

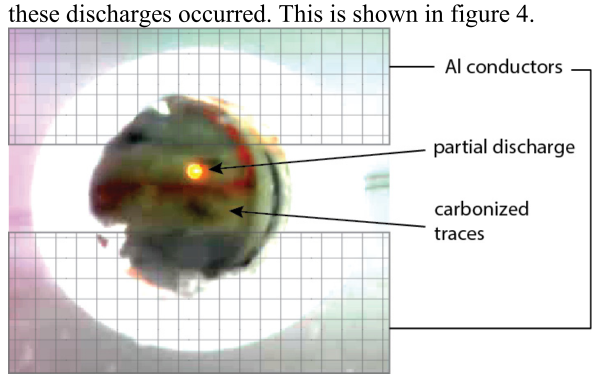

Figure 4: Image showing early PD and carbonized traces over the insulation surface between aluminum conductors.

These discharges appear to occur randomly at different locations. After some time the complete observable insulation surface is covered by a black carbonized layer. Current measurements show spiked current with amplitude in the order of several tens of milli-amperes with the maximum intensity around the peak of the voltage. Example waveforms are given in figures 5 and 6

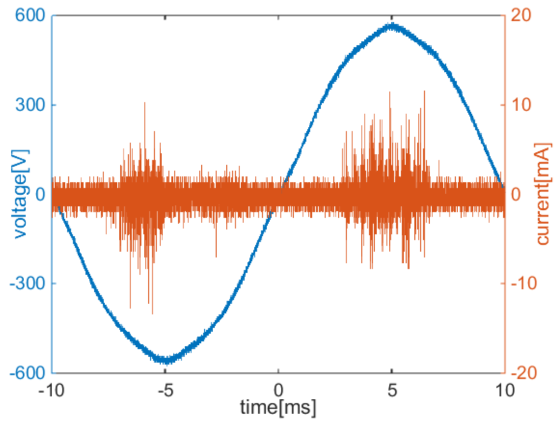

Figure 5: Measured high frequency current for a phase to phase fault.

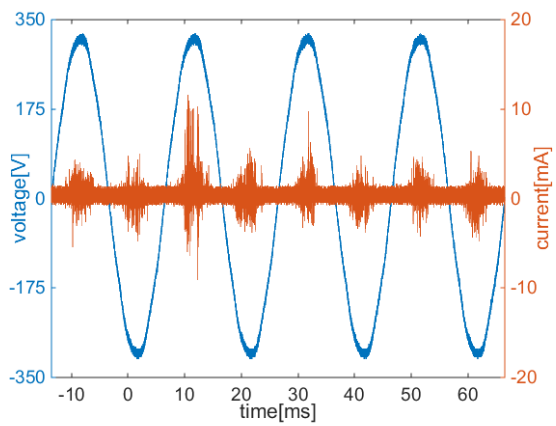

Figure 6: Measured high frequency current in a phase to screen fault.

for phase to phase and phase to screen faults respectively. On high time-resolution measurements, rise-times as short as several nanoseconds can be observed. Based on these observations these discharges can be classified as partial discharges.

From the first water ingress, the intensity of PDs increases with the development of the fault until reaching a constant level. This is dependent on water ingress. PD intensity reaches maximum levels after water evaporation and then decays. A low intensity appears to remain without further water ingress. PDs occur both with a phase-to-phase, phase-to-neutral and phase-to-screen faults. However, the intensity is generally lower with phase to neutral or screen voltage. To this point no method was found to accurately quantify the intensity. PDs occur simultaneously across the surface and often form an array which moves randomly over the surface. An example of intense PD activity is given in figure 7. Based on the dependency of water it is most likely that PDs are caused by microscopic water droplets remaining after evaporation of the bulk water presence.

PD's leave carbonized traces over the insulation surface

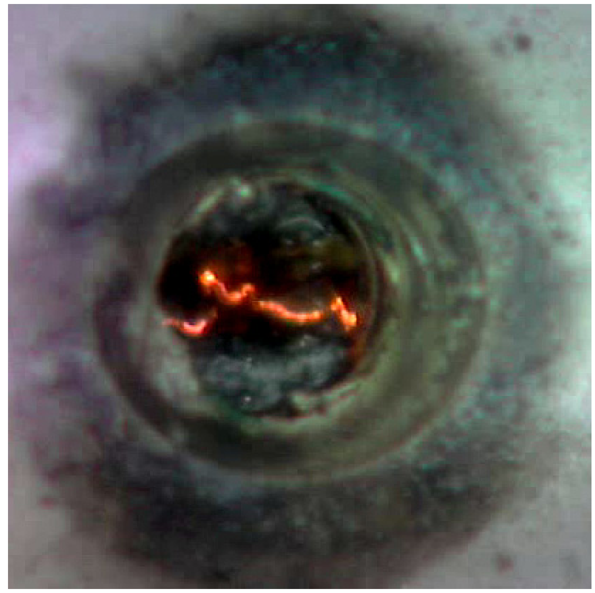

Figure 7: Image showing line of PD activity over surface between conductors.

between the conductors. This is caused by the high temperature of the discharge arc. With a phase-to-phase fault, sufficient time (several hours) of PD activity leads to a full discharge. In the case of a phase-to-screen fault this was not reached within testing time of approximately 20 hrs. Aluminum suffers from accelerated corrosion in the presence of water and a voltage difference. This is expected to limit this form of degradation under the phase-to-neutral voltage. The duration and intensity of the process may vary greatly under less controlled conditions as in an actual situation for cables in service.

A full discharge causes a high current, depending on the short circuit power of the grid behind the fault. It initiates around the peak of the voltage. The arc is interrupted at the voltage zero crossing and does not initiate again until further PD activity has occurred. In the laboratory setup, the short circuit current is limited to 225 A for the phase-to-phase case. An example is given in figure 8. A full discharge dissipates heat at the fault location, which

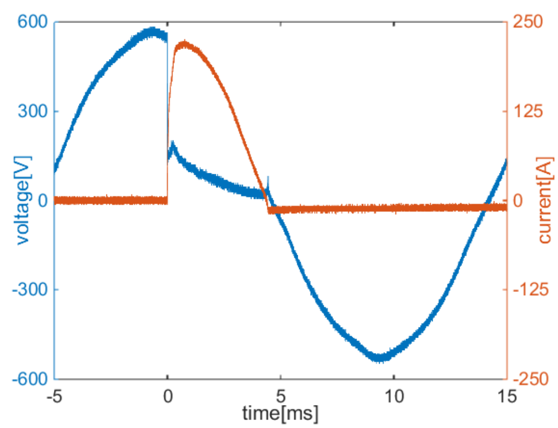

Figure 8: Measured phase-to-phase short circuit.

causes a recovery of the fault. PD activity is decreased significantly. With the heat, further degradation of the insulation material will take place and part of the aluminum conductor will melt. The resulting degradation of a phase-to-phase test of approximately 20 hours is illustrated in figure 9.

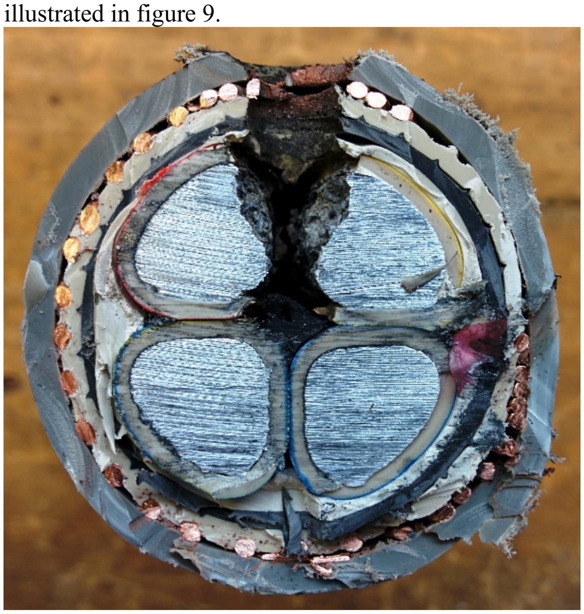

Figure 9: Cross section of tested cable section after degradation.

In this case the damage has not yet developed sufficiently to cause the fuse to break. Under higher short circuit current, degradation of the cable may be different as more energy is dissipated at the fault location. Damage at the fault spot will eventually escalate and lead to such level to cause a disturbance to the operation of the grid in either a sustained short or open circuit. In the shorting case the fuse interrupts the current and reconnection may be possible afterwards without direct break again, as further heat dissipation may change the fault.

FAULT CURRENT AND PROTECTION

Given the observations as described in the previous section, a fault causes current transients associated with PDs and with full discharges. In [3], a high frequency model was established based on the cable under test described above. From this model, it can be concluded that PD signals will be practically impossible to measure at the substation due to the attenuation of high frequency signals in the cable.
Full discharges give a large current for approximately 5 ms which should in principle be measurable. A model of the grid impedance is used to estimate the amplitude of these transients. For this, a basic case entailing a 400 kVA transformer with a 300 meter long cable is explored. Initial simulations showed that household connections and their branched cables from the main cable have negligible effects on the amplitude of these transients.

A typical 400 kVA transformer has a resistance of 5.1 mΩ and reactance of 56 µH per phase [4]. In this study, the effects of the bus bars and parallel cables are neglected. Furthermore, the impedance of the supply network to the transformer is considered small compared to the LV side and is also neglected. Based on these assumptions the system is represented as in figure 10.

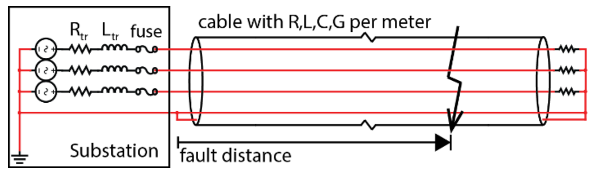

Figure 10: Schematic representation of a short circuit situation.

The model includes the transformer parameters in the substation for the basic case as described above. The cable is modeled according to [3] with measured per unit length resistance, inductance, capacitance and conductance with mutual coupling. The fault is modeled as a perfect switch with a fixed impedance when closed. The fault is assumed to behave as in the laboratory tests. In figure 11, the measured fault impedance from the test is given. From this measurement the minimum impedance was taken for simulation at 0.3 Ω.

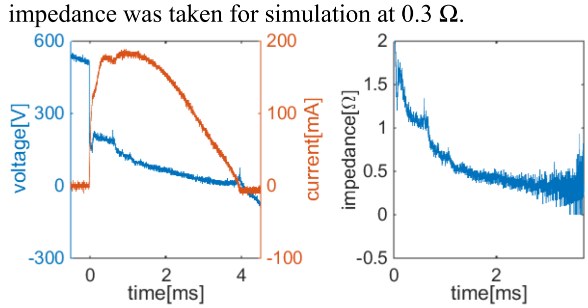

Figure 11: Measurement of the fault impedance.

This system with the described parameters was simulated to obtain current transients as can be expected in a LV grid. The currents are those passing the fuse in the substation. Several simulated current transients for different distances are given in figure 12 and 13 for a phase-to-neutral and phases-to-phase short circuit respectively. These results can be used for the development sensors to be employed in the substation.
Furthermore, the information can be used to estimate if such signals would break the fuse and possibly cause a disturbance. The cable is specified for a maximum current of 200 A, and generally fused at this level using a standard gL type fuse [5]. The fuse breaks on this current based on overheating of the fusing element. Given a 5 ms time of overcurrent, heat conductivity in the fuse can barely take place to the fuse body. The breaking characteristic is purely dependent on heating of the fusing element only [6]. In [5] the breaking characteristic is given with the I^2t product for this short time period. This represents the joule product and is representable for heat

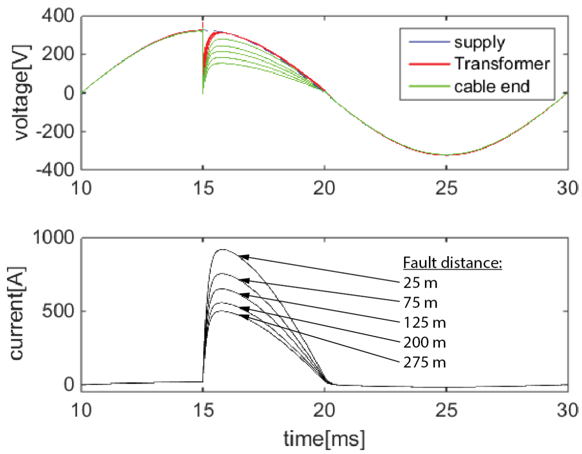

Figure 12: Simulation of phase to neutral short circuit current for various fault distances.

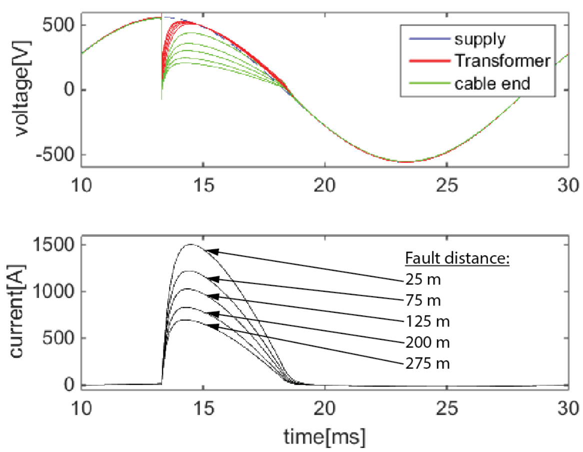

Figure 13: Simulation of phase to phase short circuit current for various fault distances.

dissipation in the fusing element, with respect to a 1 Ω impedance. From the simulated short circuit current, this value can be calculated and compared to the fuse value in order to predict if the fuse will melt. In table 1, the I^2t product for the currents given in figures 12 and 13 are given.

Fault distance [m]	*I^2t [A^2s] (phase-neutral)*	*I^2t [A^2s] (phase-phase)*
25	*2177*	*6111*
75	*1463*	*4003*
125	*1089*	*2827*
200	*794*	*1844*
275	*643*	*1300*

Table 1: I^2t values for fault distances in standard situation.

For a 200 A fuse, the value is in the range of 140,000-400,000 A^2s [5]. This shows that the short circuits taking place in these circumstances will not melt the fuse and can take place without causing a disturbance. For such faults to break the fuse, the fuse rated current should be considerably lower and would often impair the power capacity of the connection.

CONCLUSIONS

Artificially damaged LV cable sections have been tested on water ingress with laboratory experiments. The tests show a slow degradation process which is dependent on water ingress and the fault configuration. The process shows partial discharges occurring over the surface of the cable insulation in a damage spot. Partial discharges cause carbonization of the insulation and eventually lead to short circuits for short time. The fault partly recovers after water ingress stops or a discharge occurs. The fault development is thus rather dependent on the conditions of the cable.

Using simulations, the short circuit current is calculated for a configuration that can actually occur in practice. Current transients exceeding the rated current are observed, however being far below the breaking characteristic of a standard fuse. These results show that this process will often go undetected in LV grids until damage has escalated.

Obtained results add to a better understanding of the underlying degradation mechanism. Based on this understanding, a step towards condition monitoring in LV grids has been made which can be used in developments towards improved asset management.

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REFERENCES

[1] S. M. Rowland and M. Wang, 2008, "Fault Development in Wet, Low Voltage, Oil-Impregnated Paper Insulated Cables.", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 2, 484-491.

[2] B. Kruizinga, P.A.A.F. Wouters and E.F. Steennis, 2014, “PVC degradation and discharges due to water ingress in LV underground power cables.”, *Int. Conf. on Condition Monitoring and Diagnostics,* Jeju, S. Korea, 70-73.

[3] B. Kruizinga, P.A.A.F. Wouters and E.F. Steennis, High Frequency Modeling of a Shielded four-core Low Voltage Underground Power cable, *IEEE Trans. Dielectr. Electr. Insul., in-press*

[4] L. Mischler, 2015, *Electrical Installation Guide*, Schneider Electric, Rueil-Malmaison, France, G25.

[5] *IEC 60269-1*, 2006, International Electrotechnical Commission, Geneva, Switzerland.

[6] A. Wright and P.G. Newbery, 2004, *Electric Fuses, 3rd. ed.,*Institution of Electrical Engineers, London, United Kingdom, 17-40.