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Corrosion in Low-Voltage Distribution Networks and Perspectives for Online Condition Monitoring

Armand van Deursen, Graduate Student Member, IEEE, Peter Wouters and Fred Steennis

Abstract—The low-voltage distribution grid is an essential link for the integration of distributed renewable sources. It is expected to experience stronger loading and load variation in the near future. At the same time, part of the low-voltage network is an aging infrastructure. Distribution system operators are therefore becoming increasingly interested in being able to diagnose their low-voltage assets. This paper describes corrosion phenomena that are observed in aluminum conductors after a damage is inflicted to a cable section. Such a damage is suspected to initiate long-term degradation. Short-duration intermittent current peaks are observed in laboratory experiments and similar peaks are now also recorded in the field. The perspectives for online monitoring, by registering these events, are investigated by having a large number of measurement devices installed on connections in service. The research is directed to gain a better understanding of the relation between the current peaks and cable circuit failures as well as the underlying degradation mechanisms.

Index Terms—Aluminum, corrosion, dry-band arcing, electric breakdown, fault currents, power cable insulation, power system monitoring.

I. INTRODUCTION

MODERN components connected to the electrical distribution network include photovoltaic cells, heat pumps and battery-powered electric cars. These components are typically connected to the low-voltage (LV) distribution grid, and an outage in this part of the grid will have a larger impact now than it would have had in the past. Although the LV grid is considered an increasingly vital asset, the development of condition monitoring lags the status for the medium-voltage (MV) and high-voltage (HV) grids. This can be understood in terms of the number of customers involved in an outage at LV level versus MV and HV. On the other hand, from an economic perspective, maintenance of the low-voltage grid is relatively expensive. Data over 2015 from a Dutch grid operator (2.7 million connections) show that repair costs for the LV grid exceed those for the MV grid by almost a factor 3, see Table I [1]. This is mainly related to the number of failures per year occurring at the different voltage levels.

Without the presence of local storage, future load profiles are expected to put increased stress on the LV distribution network. The high and strongly variable currents may cause thermo-mechanical stress on the LV components. Dutch Distribution System Operators (DSOs) fear this increased stress will accelerate degradation of the cable system. In addition to concerns related to future load profiles, much existing cable infrastructure has aged and a proper assessment of its condition could prioritize maintenance and replacement. For these reasons, DSOs are interested in finding ways to assess the quality of their LV networks.

Table I: Repair costs and customer minutes lost (CML) for the LV and MV network of a single grid operator over 2015

<table>
<thead>
<tr>
<th>Grid voltage levels</th>
<th>MV</th>
<th>LV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated cost per outage$^1$</td>
<td>€7,000 ($7,471)</td>
<td>€2,300 ($2,455)</td>
</tr>
<tr>
<td>Number of outages per year</td>
<td>627</td>
<td>5,500</td>
</tr>
<tr>
<td>Average CML per outage</td>
<td>38,000 min (633 hr)</td>
<td>2,500 min (42 hr)</td>
</tr>
<tr>
<td>Total costs per year</td>
<td>M€ 4.4 (M$ 4.7)</td>
<td>M€ 12.7 (M$ 13.6)</td>
</tr>
</tbody>
</table>

$^1$ Costs in USD are calculated using the yearly average exchange rate of 2015 [2].

Degradation mechanisms can depend on regional ground properties and therefore the presented study is oriented to the Dutch situation. Also, applied grid components and practices may differ strongly between different countries. Section II describes the Dutch situation and experience from earlier research on LV degradation. Section III will focus on one of the identified degradation mechanisms, namely corrosion of aluminum conductors. Online monitoring will be discussed in Section IV and results on registration of high-amplitude, short-duration currents that eventually lead to failure of the connection are presented in Section V. Conclusions are drawn in Section VI.

II. CONDITION ASSESSMENT OF THE LV GRID

The Dutch LV distribution network consists of nearly 100% underground power cables. Of these cables, 67% are constructed with aluminum conductors [3]. The nominal phase-to-neutral voltage is 230 V, at a frequency of 50 Hz. The LV cables are typically direct-buried at a depth of 60 cm. As 26% of The Netherlands lies below sea level [4], one does not often have to dig deep to encounter groundwater. Many cables will therefore be situated in a wet environment.

Three distinct paths of research are pursued to assess the perspectives for an economically viable approach to monitor the LV grid:

1) Data analytics: Based on data collected on outages, a DSO’s asset database and environmental data, the DSOs aim to determine whether characteristics can be identified that give the LV connection a high failure probability. Some of these characteristics are age, type of component and soil type. Also, a data-driven approach for valuating the LV grid is investigated parallel to the presented study [5]–[7].

2) Degradation mechanisms: Mechanisms that degrade LV cable assets and eventually lead to failure of the connection are identified and investigated. Statistics on the reliability of the Dutch electricity grid [3], which are collected annually,
show that failures in the LV grid typically originate from an external factor, such as digging. Two mechanisms that may occur after such a damage has been inflicted (without an immediate outage as a result) have been identified, being corrosion of aluminum conductors [1], [8] and dry-band arcing resulting in intermittent current peaks [9]–[12]. The former may occur when a damaged component of the LV grid is submerged for a longer period of time and the latter may occur when small amounts of water can penetrate the component or in case the water is periodically present in the cable.

3) **Online monitoring:** With the knowledge of the mechanisms causing degradation, online measurement techniques for monitoring the LV network and possibly predict upcoming failures are being developed. Since the currents resulting from the corrosion process were found too small to be observed in a secondary substation, the focus is currently on detecting the intermittent current peaks mentioned earlier. It is important to note that, to be economically feasible, each monitoring solution should be cheap and should preferably aggregate many customers per device. This is essentially different from monitoring e.g. HV circuits and poses constraints on monitoring options.

### III. CORROSION

Copper and aluminum are widely used conductor materials for power cables. Aluminum is the most applied material for LV cables in the Netherlands. It is preferred because of its relatively low cost, while still being sufficiently electrically conductive.

In general, aluminum is able to withstand corrosion, even when placed in an aqueous environment [13]. The aluminum surface is passivated by a layer of aluminum oxide, after which the corrosion process stops [14]. However, stray currents, either DC or AC, are known to enable corrosion of aluminum. The corrosion process requires a minimum current density, but the process is not fundamentally understood [13].

Upon repair of failed cable systems, a white powder is sometimes encountered together with a reduced conductor cross section. This powder is believed to be a combination of aluminum corrosion products. Although the exact composition is not known, it is expected to be a combination of aluminum oxide and bayerite, boehmite or corundum, depending on the process temperature [14]. An example of a cable section with corroded aluminum conductors is shown in Fig. 1. The scale of this phenomenon is currently unknown.

![Fig. 1. Example of a corroded piece of LV cable with aluminum conductors. The conductors experienced complete loss of connection. The white powder has been removed for clarity. The corroded area continues under the remains of the sheath.](image)

Literature on AC induced corrosion is mostly written in the context of steel structures and investigates voltages in a range between millivolts and tens of volts [15] rather than several hundred volts from exposed LV conductors.

This study investigates the influence of two highly relevant parameters for AC induced corrosion in the context of aluminum as a conductor material for LV underground power cables. For submerged conductors, these parameters are conductivity of water, which acts as an electrolyte, and its temperature. The results will provide input to data-driven research for valuation and risk estimation.

**A. Experimental setup and procedure**

An experimental setup was designed to study the corrosion of aluminum under the influence of AC in a controlled, aqueous environment. A schematic representation of the setup is depicted in Fig. 2.

An aluminum sample is placed in a water filled container by means of cable glands. The water temperature is controlled within a margin of 0.3 °C by means of a heating element in the container and a heat exchanger connected to an external cooling circuit.

For every experiment, a new electrode of 99.5% pure aluminum is used as sample under test. This class of aluminum is also applied for power cables. The samples are cut to a length of 30 cm and have a circular cross section with a diameter of 2 mm. The aluminum is covered in heat shrink tubing with an interruption over a distance of 5 mm at the center of the electrode, see Fig. 4a. A stainless steel plate is used as a ground electrode.

Experiments were performed at temperatures of 13 °C and 20 °C. These two temperatures were chosen because they represent the range of the ground temperature around the LV...
power cables in the area of interest [16]. The experiments were carried out with tap water, which has a conductivity of 0.35 mS/cm in this case, as electrolyte. A higher conductivity was realized by adding sodium chloride and verified by using a conductivity meter with a resolution of 0.01 mS/cm and an accuracy of 2%. The applied conductivity range is representative of the ground water conductivity in the area of interest [17].

For all experiments, the applied voltage was 230 V at 50 Hz between the electrodes. This voltage represents the phase-to-neutral voltage level in the Netherlands and was provided by an AC voltage source. The path for the corrosion current can be disabled by a switch, so the resistance of the aluminum electrode can be calculated from the differential voltage measurement and the current delivered by the voltage source.

The following quantities are recorded by a 12-bit oscilloscope, with 20 MHz filter on all its input channels:

- The voltage across the sample under test, using a custom-made differential amplifier;
- The current delivered by the voltage source, using a 2 MHz current probe;
- The current that returns through the ground electrode, using an active current probe with 15 MHz bandwidth.

The experiment ends when the sample under test breaks. This moment can be clearly identified from a sudden, large voltage increase at the input of the differential voltage amplifier.

### B. Results

The duration of every experiment is the period between the moment of voltage application and the mechanical breaking of the aluminum conductor. Experiments at different temperatures are indicated with different colors and symbols and plotted as a log-log graph in Fig. 3. The data show a linear dependency, except for the lowest conductivity values, in particular at 20 °C.

The condition of a sample at the start of the experiment is shown in Fig. 4a. A snapshot taken after the experiment is displayed in Fig. 4b, which shows that on the surface of the aluminum, an oxide layer has accumulated that remains. Fig. 4c shows a limited amount of accumulated corrosion product near the edges of the aluminum section exposed to the electrolyte. Visual inspection during the experiments at higher conductivity showed that the corrosion product was created and immediately removed from the surface. This phenomenon may explain the exceptionally long duration of the experiment at 20 °C and 0.35 mS/cm. The largest effect was a reduction by 6%, observed at a conductivity of 0.35 mS/cm.

A straight line can be fitted in this plot for each temperature according to the relationship in Equation 1. In this equation, $t$ is the duration of the experiment, $\sigma$ is the conductivity of the electrolyte at the beginning of the experiment and $\sigma_0$ is the conductivity of the used tap water. Parameters $p_1$ and $p_2$ are specific to this experiment and depend on temperature, see Table II. The resulting fit is displayed in Fig. 5 (some longer duration data are outside the displayed range).

The relationship between the results from the laboratory experiments and the corrosion that is encountered in the grid is difficult to determine:

- Depending on the damage that is inflicted to the cable, different amounts of water may penetrate the cable;
- The flow of water around the cable will have an influence on the rate of corrosion product removal from the surface, which in turn will have an effect on the corrosion rate.

The corrosion current is relatively small and its potential for being monitored in a remote substation is considered to be low.

![Fig. 3. Overview of experiment duration. The figure is plotted on a log-log scale.](image)

$$t(\sigma) = p_2 \left( \frac{\sigma}{\sigma_0} \right)^{p_1}$$ (1)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$p_1$</th>
<th>$p_2$ (min)</th>
<th>RMSE(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>-1.7</td>
<td>527</td>
<td>62.3</td>
</tr>
<tr>
<td>20</td>
<td>-2.1</td>
<td>897.8</td>
<td>651.4</td>
</tr>
</tbody>
</table>

| Root-mean-square error |

### IV. CONDITION MONITORING

While for HV connections any damage to the insulation will cause immediate failure of the connection, this is not necessarily true for MV connections [18] and therefore certainly not for LV connections. The electric field strength in LV cables is low and the insulation between two conductors can even be replaced by air without necessarily causing any problems. For MV cables, recovery from breakdown is sometimes observed and the circuit only fails after repeated current peaks [19].

#### A. Observable phenomena in LV connections

After direct faults upon digging, intermittent faults (with unknown background) constitute the second largest cause of outages in the Dutch LV grid. These causes account for 28%
Laboratory research has shown that when small amounts of (conducting) moisture penetrate down to the conductors, a process called dry-band arcing can occur [11], a process which is extensively described in the context of outdoor HV insulators [20]. Dry-band arcing is a phenomenon involving an electrolyte which partly evaporates, leaving a narrow band behind with a local high electric field strength. The arcing creates local spots of high temperature, burning the insulation material between the conductors and polluting its surface with conductive material. When sufficient pollution has formed on the surface of the insulator, a breakdown occurs. The currents involved in the dry-band arcing process itself are relatively low, especially in the context of low-voltage cables (< 1 A), and are expected to be hard to distinguish from load currents. Detection is further complicated because of the meshed topology of LV grids, making travelling wave based measurements of discharges, as applied to MV and HV cables, unpractical for LV cable networks. However, the breakdown produces a current of several hundreds of amperes, or beyond, that can be easily observed in a secondary substation. An example of current and voltage waveforms during such a breakdown, produced with a laboratory setup, can be seen in Fig. 6. The duration of the breakdown is usually a quarter of a cycle; too short to trip the fuse protecting the circuit. However, repeated breakdowns are expected to cause enough pollution so that eventually a breakdown will sustain long enough to trip the fuse. Typically the discharge ignites around a voltage peak (when the electric field strength is highest) and extinguishes at the next zero crossing, giving the current peak a duration of about 5 ms. At the same time of the current peak, a drop in voltage is observed. Similar waveforms are also reported in [9], [10].

The intermittent faults are possibly the result from the final discharge after a series of smaller discharges that have gone unnoticed. The idea is to design a monitoring technique based on the intermittent current peaks. From registering these events, we may be able to predict an upcoming failure. To this purpose, the research was moved from the laboratory to the grids in operation.

B. Monitoring equipment and procedure

Two different types of measurement systems were available for measuring voltage and load current, while also detecting intermittent current peaks. They are distributed over the grids of the three largest DSOs of the Netherlands. The systems are powered from the same rails as they are measuring and are connected to the LV rails in the secondary substation by means of fused clamps. The clamps are installed between the MV/LV transformer and the connection fuse, so no measurements are lost in case a fuse is tripped. Currents are measured by means of current transformers, which are installed behind the connection's fuse. The systems are configured to record and store the current and voltage waveforms when a trigger level is exceeded. The key parameters of both systems, shown in Fig. 7, are listed in Table III.

System 1: The first system [21], was originally designed for monitoring MV connections and has been adapted for LV. The software was modified to meet the needs for monitoring the intermittent current peaks in the LV grid. The trigger level for
Fig. 6. Current (top) and phase-to-phase voltage (bottom) waveforms of a discharge in a cable section which is energized from a three-phase wall outlet (only two phases are used). Measurements are recorded in a laboratory with an oscilloscope.

Fig. 7. Measurement system 1 (a) and measurement system 2 (b).

Table III: Specifications of Measurement Systems

<table>
<thead>
<tr>
<th></th>
<th>System 1</th>
<th>System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency</td>
<td>4 kHz</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Recorded voltages</td>
<td>$3 \times$ phase-to-neutral</td>
<td>$3 \times$ phase-to-neutral</td>
</tr>
<tr>
<td>Recorded currents</td>
<td>3 phases</td>
<td>3 phases and neutral</td>
</tr>
<tr>
<td>Current transformers</td>
<td>Eleq TQ30 (250/1 A)</td>
<td>Eleq TQ30 (250/1 A)</td>
</tr>
<tr>
<td>Connectivity</td>
<td>Teltonika 4G router</td>
<td>Westermo 3G router</td>
</tr>
</tbody>
</table>

Current peaks can be set for each phase individually. Twelve systems with this device are currently installed in the grid and another ten will be installed in the near future.

System 2: The second system [22] is based on a commercially available device. It has a common trigger level for the three phases. Nine systems with this device are currently installed in the grid and eighteen more will be installed in the near future.

The field measurements are aimed to determine whether intermittent current peaks occur in the grid and whether they will eventually lead to failure. To increase the likelihood of registering a failure, high-risk cable sections are chosen to be monitored. They are selected by utility technicians with knowledge of the past performance of the connection. For every recording device, trigger levels need to be set. They are set to about 80% higher than the highest recorded root-mean-square (rms) current in the first two week after installation. This value is considered to be a good setting for registering intermittent current peaks, while avoiding registering too many other incidental high currents such as inrush currents. In case no intermittent current peaks are observed in a period of a few months, the connection is considered ‘clean’, or at least not attractive enough for these experiments, and the measurement device will be relocated to a different LV connection. Measurement data is collected daily from the measurement devices through the wireless telephone network by an automated process on a server from where they are available for further analysis.

C. False triggers

The intermittent current peaks similar to Fig. 6 are not the only signals to trigger the recording devices. Inrush currents (as shown in Fig. 8), may also cause a high-amplitude short-duration current. These can easily be distinguished from intermittent current peaks:

- Intermittent current peaks typically start at a voltage peak, while inrush currents may start at any phase angle;
- Intermittent and inrush currents both start off with a steep current increase, but inrush currents typically last longer (several periods) and reduce in amplitude much slower;
- The rms current before and after an intermittent current peak will typically be identical, while the rms current after an inrush current will be higher than before.

V. RESULTS OF ONLINE MONITORING

The recorded waveforms are discussed below, after which an overview of all measurement results is presented.
Fig. 8. Triggered current measurement that is classified as an inrush current. The trigger level for phase L3 was set to 100 A.

Fig. 9. Current (top) and phase-to-phase voltage (bottom) waveforms of a typical phase-to-phase intermittent current peak. The fault ignites around the peak of the voltage between the two phases involved.

Also, tripping of a fuse is sometimes recorded. An example during a phase-to-phase fault is shown in Fig. 11. The fuse protecting phase L2 eventually tripped after the fault remained for two periods, as can be concluded by not returning of the load current after the two power frequency cycles. After replacing the tripped fuse, operation continued as before, with intermittent current peaks still taking place. If the same fault reoccurs, either the same fuse or the one in the other involved phase may trip.

Fig. 12 shows the registration over a period of nine months for a single connection. The current peaks in different phases are indicated with different colors and symbols. It is noticed that all phases are involved and both phase-to-phase and phase-to-neutral breakdowns occur. Maximum amplitudes of the current peaks exceeding 1000 A were registered without tripping the fuse, while the fuse rating was 160 A for this specific connection.

High peak currents occur throughout the period of measurement with maybe a higher rate near the months June and July. The lack of a clear behavior points to the need of a large number of long time observations to be conclusive on the perspective of recording these events as basis for predictive maintenance.

B. Long-term monitoring

An overview of the results from all measurement locations is presented in Table IV with the duration of monitoring. From only a few circuits no peak currents were recorded. This is related to their selection, which is based on past occurrence of
<table>
<thead>
<tr>
<th>System</th>
<th>Location</th>
<th>Months measured</th>
<th>Number of peaks</th>
<th>Range of peaks (A)</th>
<th>Fuse(s) tripped</th>
<th>Repairs</th>
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<td>1</td>
<td>Torenstraat, Zegge</td>
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<td>65</td>
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<td>34</td>
<td>182 – 1273</td>
<td>Yes, 1 phase</td>
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<tr>
<td>1</td>
<td>De Pinas, Dintelloord</td>
<td>6³</td>
<td>3</td>
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<td>206 – 620</td>
<td>Yes, 3 phases</td>
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<td>Grotiusplantsoen, Rijen</td>
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<tr>
<td>2</td>
<td>Verbindingsweg, Apeldoorn</td>
<td>10</td>
<td>71</td>
<td>231 – 1644</td>
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<td>No</td>
</tr>
</tbody>
</table>

¹ This location is not being monitored any longer because no or very few intermittent current peaks were being measured.
² Although this location produced promising measurements, the measurement device had to be removed due to reconstructions of the secondary substation.
³ The connection failed before the measurement device was properly configured.

Outages in these circuits. It indicates that high current peaks are common events in suspicious circuits. The ranges of current peaks are indicated and they may reach values exceeding the measurement range of the recording devices. In only two cases they have led to a tripped fuse. In one of these events a repair action has been taken place, since all three phases had become bonded together in a damaged cable section. It has been decided that for future events, if not urgently required, no repair will be undertaken except for replacing the fuse. In this way, a better assessment of the development of a fault is aimed for.
VI. CONCLUSION

Corrosion of aluminum was studied in the context of underground LV power cables. Aluminum samples were energized with a 230 V AC voltage and a current path to a ground electrode was provided through tap water as electrolyte, with controlled conductivity and temperature. The dependency with conductivity can be described with a power law, giving rise to a fast increase of the corrosion rate with higher conductivity. It was found that the AC induced corrosion process is only slightly depending on the temperature for the range typical for ground water (13-20 °C). A higher temperature resulted in a faster corrosion process for experiments with conductivity over 0.4 mS/cm. At low conductivity, in particular for measurements at 20 °C, the corrosion rate seems to drop faster.

Intermittent current peaks as observed in a laboratory environment are now also measured in the operational LV grid. This leads to the expectation that these current peaks may indeed be a good indication for upcoming failure. The present data set of failed connections is small however, and the size of the field study will be extended to increase the number of registered outages. The measurement results that have been collected until now were obtained while using a trigger level set to 80% higher than the highest recorded rms current as mentioned in subsection IV-B. This means that on connections with high loading, a relatively small current peak may not be recorded. A next generation measurement system could benefit from additional functionality such as:

1) Dynamic trigger levels: Setting the trigger levels too low will result in excessive data, much of which will not be useful. It will also be costly in case no flat-fee rate is agreed upon with the mobile telephone network operator. Too high a trigger level will cause missed signals from the grid that failure may be imminent. Dynamic per-phase trigger levels based on the rms currents will detect incidental current peaks, while avoiding the risk of false triggering by an increased regular load. Also the ‘learning period’ that is currently in place can be avoided.

2) Local waveform interpretation: Another solution to these problems could be local waveform interpretation by the measurement device. When the device is programmed to detect current peaks with the characteristics as indicated in this work, false triggers due to e.g. inrush currents can be filtered out. Trigger levels may not even be necessary in this situation.

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