FIELD STUDY OF INTERMITTENT FAULTS IN LOW-VOLTAGE UNDERGROUND CABLE SYSTEMS

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ABSTRACT

With both energy production and consumption becoming more electrified, the low-voltage distribution grid will play an increasingly important role in the future. Dutch DSOs also expect that the dynamics of future load cycles will accelerate degradation of their low-voltage cable systems. For these reasons, they are exploring ways to measure the quality of their low-voltage networks. An identified method based on measuring intermittent current peaks was transferred from laboratory tests to live grid monitoring. Promising and interesting results from these measurements are presented in this paper.

INTRODUCTION

The adverse effects of using fossil fuels as an energy source are widely recognised. One of these effects, global warming, recently resulted in the Paris Agreement, signed by 195 countries. These countries are committed to keep the global rise of temperature below 2 degrees Celsius [1]. At the same time, global energy demand is rising. In order to create a more sustainable society, the search for alternative, renewable, energy sources and related technology is ongoing. Wind and solar energy are popular alternatives: Off-shore wind parks are rapidly being developed [2] and photovoltaic panels are now a common sight on rooftops. Also, from the perspective of energy consumption, new options emerge and they are becoming more common every day, e.g. battery-powered electric cars for transportation and heat pumps or infrared panels for heating.

What many of these modern technologies have in common is that they produce or consume energy in the form of electricity. In order to connect these technologies, the electricity grid will become increasingly important. This holds in particular for the low-voltage (LV) grid, since this is where most of these appliances will connect to. Also because the LV grid is not implemented with redundancy, a failure in the future will have a larger impact than it would have had in the past.

The development of condition monitoring for the LV grid, however, lags the maturity of that for the medium-voltage (MV) and high-voltage (HV) grids. This can be understood by noting the limited number of customers involved in an outage in the LV grid versus those affected by an outage in the MV or HV grids. However, from an economical perspective, maintenance of the LV grid is relatively expensive. Data from a single network operator (with 2.7 million connections) show that the costs to maintain their LV grid exceeds the cost to maintain their MV grid by a factor of nearly three, see Table I [3].

In a situation where local storage is only installed to a limited extent, the dynamics within load cycles in the near future are expected to be more severe, which is associated with high and variable currents. Dutch Distribution System Operators (DSOs) expect that thermo-mechanical stress resulting from these currents may accelerate degradation of the cable system.

For these reasons, the DSOs are looking for ways to assess the quality of their networks, in order to get a better grip on their grid and monitor its state. The equipment would need to monitor a large number of connections simultaneously in order to keep the costs per customer to an acceptable level.

Earlier research identified that many faults in the LV grid result from damage inflicted to the cable system, which did not cause an outage immediately. In a wet environment, which is particularly the case in the Netherlands, water may penetrate the damaged connection. This situation was simulated in a laboratory environment and it was found that intermittent current peaks occurred in the connection that resulted from a short circuit path between two conductors [4]. This path is created by a process called dry-band arcing. An example of current and voltage waveforms recorded during such an intermittent current peak is shown in Fig. 1 [5]. Due to the heat development of the short circuit, the conductive path is burnt away and the process restarts.

The research has moved from the laboratory stage to the live grids of the three largest DSOs in the Netherlands. The idea is that monitoring these faults until the fuse eventually trips will provide the DSO information about the development to upcoming failures. This knowledge is useful for judging the state of other monitored connections.

Table I - Repair costs and Customer Minutes Lost (CML) for the LV and MV network of a single grid operator over 2015

Grid voltage levels	MV	LV
Estimated cost per outage (€)	7,000	2,300
Number of outages per year	627	5,500
Average CML per outage (minutes)	38,000	2,500
Total costs per year (M€)	**4.4**	**12.7**

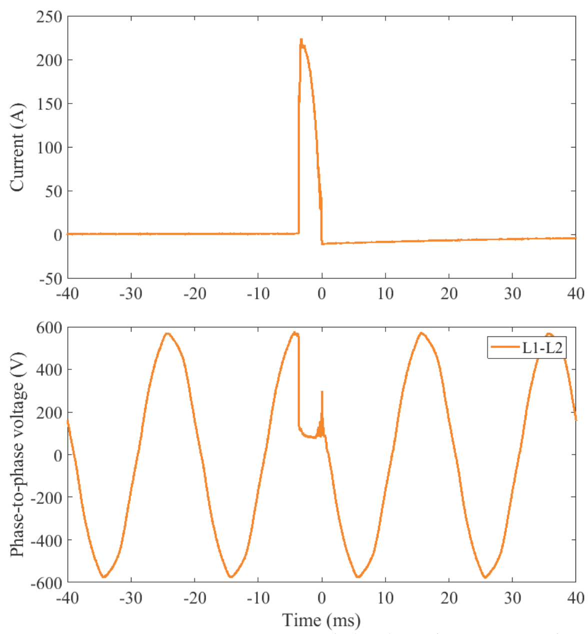


Fig. 1 – Intermittent current peak (top) and corresponding voltage drop (bottom) in laboratory experiment.

In the following sections, the two different measurement systems are introduced, after which a number of recorded cases are discussed. Subsequently, recommendations are proposed for a next-generation measurement system and conclusions are drawn.

MEASUREMENT SYSTEMS

For monitoring LV connections, two different measurement systems were assembled from available components. These measurement systems were placed in the secondary substations of the involved DSOs. Every DSO only used one of the two available systems, so the technicians responsible for placing the devices did not have to get familiar with multiple devices. In total, fifty devices were available. The following subsections will discuss the properties of the current peaks that are aimed for to be measured and the two different measurement systems that are used to this purpose. Some practical issues regarding setting a trigger level, choosing a measurement location and data management are discussed.

Current peak characteristics

The observed intermittent current peaks typically show the following characteristics:

- Initiates near the voltage peak, where the electric field strength is highest;
- Extinguishes at the current's next zero crossing, which gives it a duration of around 5 ms;
- Occasionally a longer duration is observed.

The duration of these currents will be too short to trip the connection's fuse. This means the event can occur many times before an outage will occur.

System 1

The first system was assembled around a commercially available Janitza UMG 605 originally meant for power quality measurements. The currents through both the three phase conductors and the neutral conductor are measured by means of 250/1 A current transformers. The system is equipped with a 3G modem by which the measurement data can be obtained remotely and the device parameters, such as trigger level, can be set.
This device is used to monitor rms voltage and current and records their waveforms at full bandwidth in case a trigger value is exceeded. For this system, a single trigger value was set for all monitored currents.

Fig. 2 – Measurement system built around a Janitza UMG 605 Power quality analyser.

System 2

The second system was assembled around a Locamation iAIM 251 with custom software. The currents through the three phase conductors are measured by means of 250/1 A current transformers. This system is equipped with a 4G modem. A different trigger value can be set for each phase.

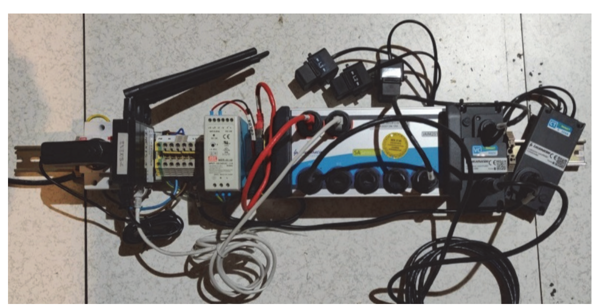


Fig. 3 – Measurement system built around a Locamation iAIM 251.

Trigger level

The measurement devices were configured to record voltage and current waveforms when a predetermined current threshold was exceeded: the trigger level. This level needs to be low enough, not to miss current peaks. It also needs to be high enough, preventing to trigger on temporary high load current. As a compromise, the trigger

level was set to about 80% above the largest recorded rms load current over a period of two weeks.
Occasionally, triggering occurred without an initiating single current peak. An example of such an event is shown in Fig. 4. The trigger level of 200 amperes was exceeded, but from the waveform it was concluded that an inrush current triggered the measurement.

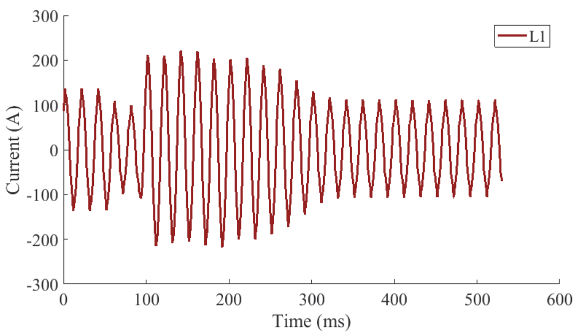


Fig 4 – Recorded current waveform, classified as an inrush current. The other phases have similar characteristics and are omitted in the figure.

Inrush currents can be distinguished from intermittent current peaks:

- Intermittent current peaks typically start around the peak of the voltage, while inrush current may start at any phase angle;
- Both inrush currents and intermittent currents begin with a large increase of current, but inrush current typically have a longer duration and their amplitude reduces much slower;
- The rms current following an inrush current will be higher than before, while the rms current after a current peak will be identical.

Circuit selection

The measurements in the grid aim to determine if intermittent current peaks occur in the grid and whether they will eventually lead to failure of the connection. Because it may take a long time for an arbitrary connection to fail, high-risk connections are selected by utility technicians with knowledge of historical performance of the different connections. In the case that no current peaks are recorded in a period of a few months, the monitored connection is considered 'clean' and the measurement device is relocated to another connection.

Transfer of measurement data

All measurement data are collected on a daily basis by a server. From this server, the data is available for further analysis. In the case that the measurement system temporarily cannot connect to the mobile phone network, the server will retry the next day. In order to keep track of the measurements, all filenames have timestamps and a unique number which relates to the specific measurement system.

FIELD RESULTS

Current and voltage waveforms with the same properties as the waveforms that were previously recorded in the laboratory are now being measured in the grid. Three different interesting cases will be discussed.

Case 1: Tripping of fuse

This monitored connection showed different intermittent current peaks. Fig. 5 shows a phase-to-phase intermittent current peak. Note that the voltage drop is much less severe than in Fig. 1. This can be explained by the position of the voltage measurement. In the case of the laboratory measurement, the voltage was measured about 15 cm away from the short circuit, while the fault location in the field measurement was at a distance tens to hundreds of meters away from the secondary substation. Fig. 6 shows a single phase-to-neutral current peak. Whether the current peak ignites in the positive or negative half cycle appears to be arbitrary.
Eventually, the fuse of this connection tripped, as is indicated in Fig. 7. While the fault current existed in both phases L1 and L2, only the fuse protecting L2 tripped. The next time, a similar event could also trip the fuse of the other phase. Registration of the occurrences of intermittent current peaks through time results in Fig. 8. Peak bursts, in particular with high magnitude in the June-July period, are observed. After replacement of the fuse, the current peaks remain to occur and are expected to again cause tripping of a fuse in the future.

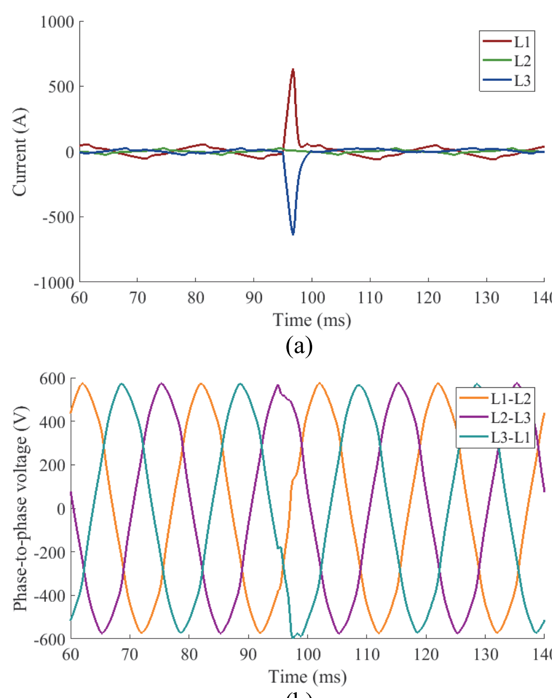
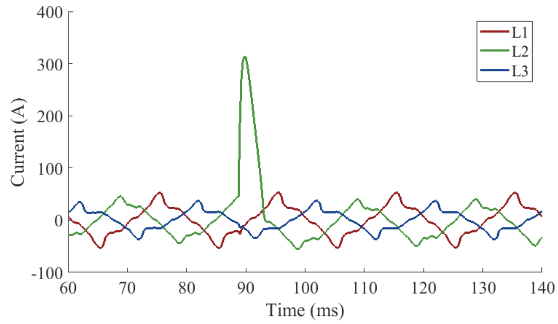


Fig. 5 – Phase-to-phase intermittent current peak (a) with corresponding voltage dips (b).



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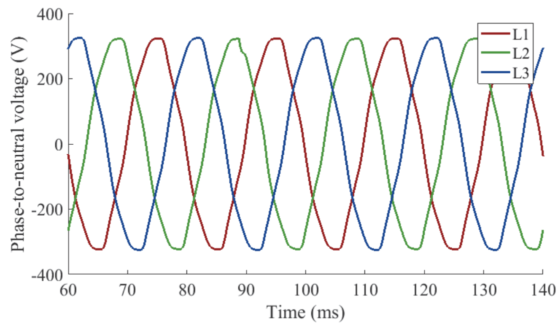


(b)

Fig. 6 – Phase-to-neutral intermittent current peak (a) and corresponding voltage dip (b).

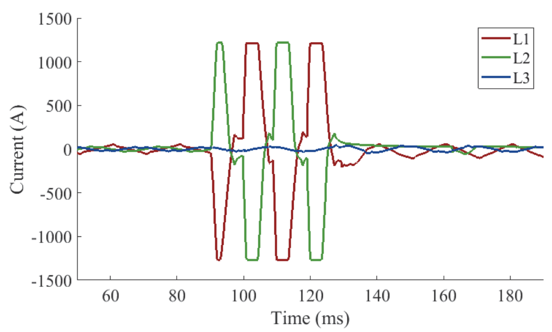


Fig. 7 – Phase-to-phase short circuit that eventually trips the fuse protecting L2. The flat tops in these current waveforms result from 'clipping' of the ADC.

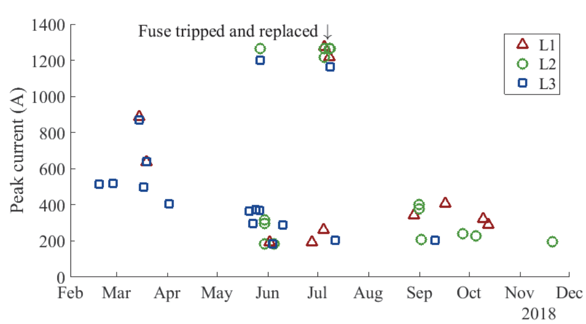


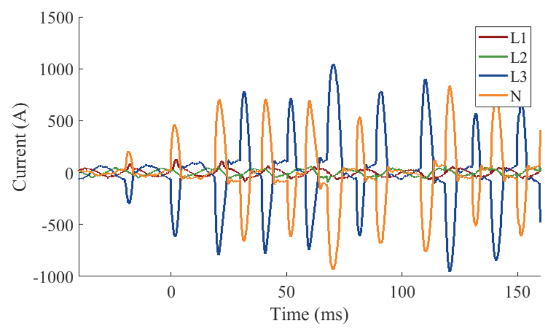
Fig. 8 – Occurrences of intermittent current peaks represented through time leading to tripping of the connections fuse.

Case 2: Voltage complaints

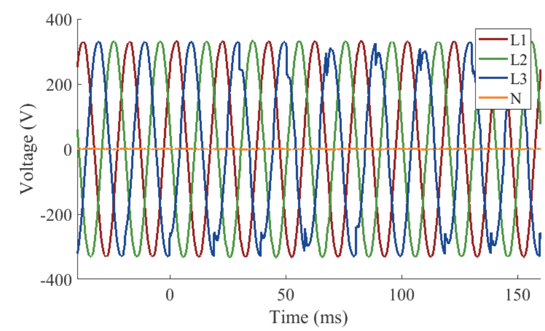
In this case, the measurement system was installed at the connection after voltage complaints from customers. In a period of eleven days, intermittent current peaks occurred on three occasions. Two of these occasions stand out due to the low interval between the intermittent current peaks, see Fig. 9.

During a period of 800 ms, the short circuit ignites and extinguishes nearly every half cycle. The corresponding voltage dips are already significant at the bus bar of the secondary substation. Therefore it is not surprising that connected customers suffered from poor voltage continuity.

The decision was made to perform a fault-localisation procedure, after which two joints were replaced. After replacement, no intermittent current peaks were recorded during a period of over a month.



(a)



(b)

Fig. 9 – Repeated intermittent phase-to-neutral intermittent current peaks (a) and corresponding voltage dips in phase L3 (b).

Case 3: Current peaks below trigger level

This case is presented in order to point out the limits of the currently implemented trigger method. During the 'learning period', both the measurements from Fig. 10 and Fig. 11 were recorded at the same connection, two hours apart from each other. This example shows that intermittent current peaks can occur with a lower amplitude than other incidental high currents. In this situation it would be impossible to set a trigger level that would register all and only intermittent current peaks.

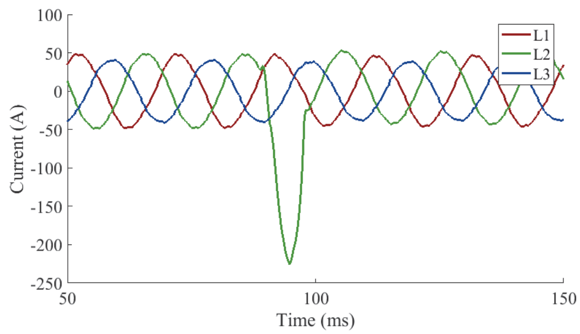


Fig. 10 – Intermittent current peak with a maximum amplitude of 226 A.

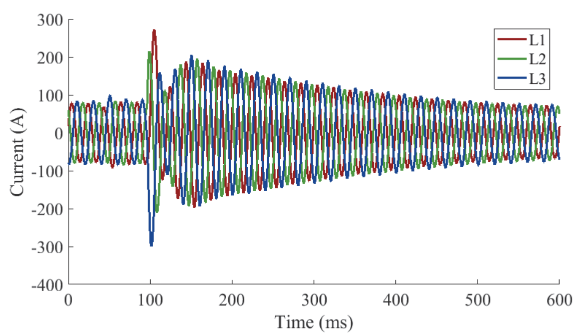


Fig. 11 – Inrush current with a maximum amplitude of 301 A.

RECOMMENDATIONS

A next-generation measurement device would benefit from one of the two following recommendations, both regarding triggering:

- Dynamic trigger levels: In case a trigger level would automatically be set based on the (changing) rms current value, both the quantity of missed current peaks and the quantity of false positives would be reduced. Also, the 'learning period' of two weeks can be avoided.
- Local waveform interpretation: When the measurement device would be programmed to identify current peaks based on the characteristics as presented in this paper, no trigger would be necessary. Additionally, the event can be recorded with only amplitude, duration, a timestamp and phase number, significantly reducing the amount of generated data that needs to be transferred.

CONCLUSION

Laboratory experiments showed that current peaks with certain characteristics result from damaged cable sections into which water can penetrate. Current peaks with the same characteristics have now also been recorded in the low-voltage grids of three DSOs. In a number of cases, the connections that produced intermittent current peaks experienced an outage or reparations were made. After the reparations, the current peaks were no longer registered. Therefore, the current peaks are believed to indicate that the connection is at risk of failing. However, the present dataset of failed connections is too small to predict when the connection will fail. For these reasons, the experiments are continued in the future.

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