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Enhanced Resiliency, Reliability, and Less Congestion with 24/7 Monitoring Platform for Aged Underground Distribution Networks

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SUMMARY

The existing electrical distribution grid is approaching the end of its technical life while load will grow faster than ever: improved resiliency and congestion management is required. Utilities are challenged to keep their aging grids up under long pre-existing conditions with not only rapidly increasing loads, but also erratic and changing load profiles. To cope with this, grid modernization is a prerequisite, and its primary goal is to sustain or improve the existing grid's Key Performance Indicators and at the same time facilitate the load growth. Utility's modern asset management should at least be condition based: requiring insights in actual asset health and environmental risks as well as collection and systematical analyses of history. Using modern asset management, utilities can "sweat" their assets as much as possible without running to failure.

Most failures in MV cables are preceded by Partial Discharges (PDs), which can be detected and located to pinpoint specific defects. Whereas periodic testing of cables is very common, it requires taking critical assets offline and stressing the cables by testing at higher than rated voltage levels.

Smart Cable Guard (SCG) is an online continuous monitoring system based on two sensors, which has been in practical operation for over 10 years and is currently monitoring over 7.500 kilometers of cable worldwide. The SCG platform detects and locates PDs generated by weak spots as well as permanent and intermittent faults, issuing a warning within 5 minutes of occurrence.

Continuous (24/7) monitoring has the benefit of actual condition data. Any weak spot detected based on PDs can be monitored over time. This allows to assess risk based on the development of PD activity and potentially relate this to loading and/or seasonal effects. This provides more insight in comparison to a single measurement, where thresholds (i.e., based on discharge level) need to be relied on for risk estimation and future predictions. Unexpected outages are prevented by real-time operational warnings from the SCG online monitoring platform for 70% or more of the cases. Outage duration is reduced by immediate and highly accurate localization, in some grids up to 50%.

By using continuous monitoring, uncertainties are greatly reduced. By replacing average lifetime statistics with de-averaged live digital monitoring, fact-based decisions can be made. This leads to more flexibility in planning upgrades, saving capital and expenses, and reducing the use of resources and environmental footprint. Risk is accurately quantified and allows timely replacement before failure; and up-to-date knowledge of the condition of cables add substantially to the resilience of the network.

This insight, and temperature indication, make Smart Cable Guard an ideal platform for optimizing asset usage and maximizing load: serving congestion management. Or from an asset management

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perspective: investing in a monitoring system reduces the overall CAPEX and OPEX. Now it is possible to continue using compromised cables for which the moment of failure can be better predicted.

KEYWORDS

Fault location – monitoring – partial discharges – weak spots – power cable insulation - congestion

1. Resiliency and congestion management

The need for electric power grows all over the world. There are new users, vastly growing user categories (e.g., data hotels), and new user categories due to electrification (e.g., EV charging). The infrastructure to deliver electrical power from its source to a user needs to follow this growth. On top of that, developments like distributed generation make load-flow in the grid more complex and the performance requirements even bigger, at the distribution level in particular.

Services must be delivered by an existing (often older) grid, consisting of underground cables where power density is the highest. Clients' businesses are growing and their dependency on electric power even more. This combined with government regulation leads to legal entitlements; contracts for power delivery will be strict, and often include penalties.

It is impossible for utilities to expand their networks in the pace of the growing demand for both technical and financial reasons. Each permanent or temporary opportunity to carry a larger load over existing cables must be pursued. To make it even more challenging: the existing grid is approaching the end of its technical life and therefore the existing grids need improved resiliency and congestion management.

2. Challenges for Distribution System Operators

Utilities in general and Distribution Systems Operators (DSOs) in particular are challenged to keep aging grids up and perform in long pre-existing conditions with, since recently, rapidly increasing loads and changing load profiles. The Medium Voltage (MV) network is challenged the most, as redundancy is limited whereas loading is high. As far as capacity expansion is possible, it takes a lot of time, capital, labor and cannot compromise daily operations. Vulnerability to feeder outages is bigger than ever. Specific user's needs must be met, often leading to bigger load-flow or load patterns of unusual dynamic character. Performance downtown in larger cities is extra complicated due to its exposure to large or prestigious clients. Existing inner city grid set-up complicates matters further, for instance with manholes and their safety challenges. Reconstruction work must be done under aggravating circumstances, while, e.g., obtaining permits, can cause delays. Pro-active congestion management will be of great value but requires a drastic change in utilities' operational methods and procedures. Therefore, rather than (slow) capacity expansion, priority should be given to modernization of the existing grid.

The primary goal of grid modernization is to sustain or even better improve the existing grid's Key Performance Indicators (KPIs) and at the same time facilitate the growth in overall load and its new flow profile. Most utilities work with KPIs for their failure statistics such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency (SAIFI) and Customer Average Interruption Duration Index (CAIDI). As grid utilities are regulated by the local Public Service Commission that's the party with whom the KPI's are often communicated and agreed with.

Utility's modern asset management is risk based or at least condition based. This requires insights in actual and local specific asset health, environmental risks as well as collection and systematical analyses of history. Using modern asset management, utilities want to "sweat" their assets as much as possible but not run them to failure. Most failures in MV cables are preceded by Partial Discharges (PDs), which can be detected and located to pinpoint specific defects. Periodic testing of cables is very common and can be done with e.g., Very Low Frequency (VLF) or Oscillating Wave Test System (OWTS) test methods. However, this requires taking critical assets offline and expensive and labor-intensive test equipment, while it stresses the cables because testing is done at higher than rated voltage levels. This type of testing can introduce new risks, but it also measures only at one distinct point in time, see Figure 1, potentially missing essential developments.

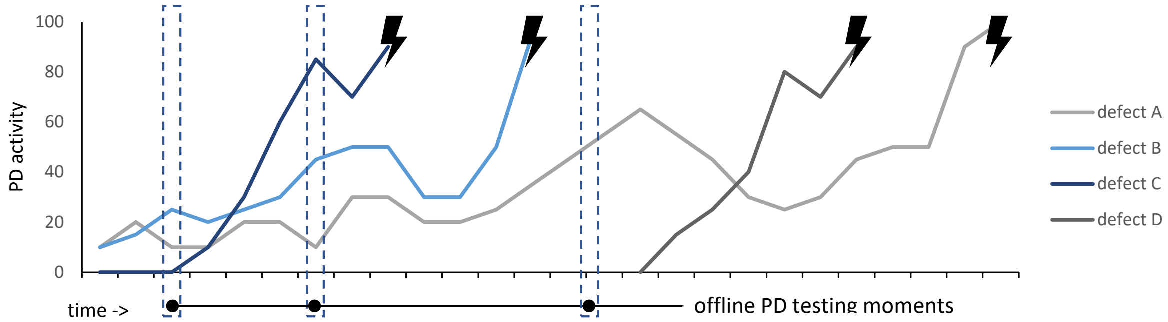

Figure 1: PD activity for various defects developing over time - with indication of potential offline testing moments.

Online PD monitoring, at the contrary, can be performed continuously, while dynamics in weak-spot behavior can be considered. Continuous monitoring allows for more accurate risk assessment and can be done at the operational voltage level and without taking a cable offline. Online monitoring can also provide immediate pinpointing of (intermittent) faults and measurement of cable temperature dynamics. Therefore, it is a valuable tool in getting control over aging assets under complex and dynamic loading.

3. Monitoring distribution cables

Figure 2: antenna, control unit and sensor of Smart Cable Guard

DNV has developed Smart Cable Guard (SCG), an online continuous monitoring system based on two sensors, which has been in practical operation for over 10 years and is currently monitoring over 7.500 kilometers of cable worldwide [1]. The SCG platform detects and locates Partial Discharges (PD) generated by weak spots. It also detects and locates permanent and intermittent faults, issuing a warning within 5 minutes of occurrence. The use of two sensors (see figure 2) to monitor a cable section allows for easy installation in existing cable systems.

To monitor a section of a cable, a sensor is placed at the start and at the end of this section. Data is collected at a datacenter using a control unit at each sensor location. The sensors are accurately time-synchronized using a system of signal injection, where the sensors inject a PD-like signal into the cable network which is picked up by the other sensor. This allows to synchronize the sensors up to nanosecond accuracy and continuously check the measurement performance. An overview is given in Figure 3.

Any PD source or fault event within the cable circuit under monitoring will excite a pulse into both directions away from the source. By comparing the arrival time of the two pulses arriving at the sensors, the location of origin of the pulse, i.e., defect, can be determined. This is an effective method to exclude signals (noise, disturbance) from outside the monitored cable section and to be able to pinpoint upcoming defects in the cable system.

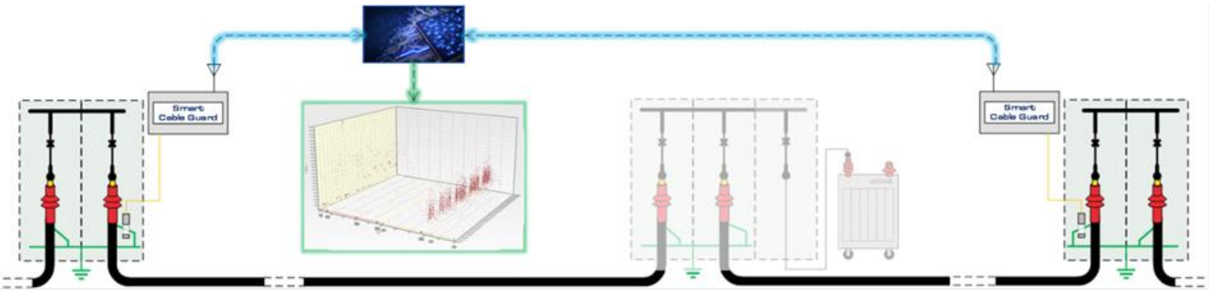

Figure 3: Schematic overview of Smart Cable Guard online monitoring system in power network.

Since online monitoring with this approach does not need disconnection (isolation) of a single cable, monitoring does not need to be limited to a single, isolated, section of cable between stations, manholes or ring-main-units (RMUs). PD pulses normally can travel ‘through’ stations and therefore can be picked up further away. Experience shows that several intermediate RMUs can be covered, and effective monitoring be performed [2]. The synchronization system between sensors ensures that signals can travel between the two sensors (and therefore PD and faults can be detected).

Two examples of failure prevention are given below:

The first example is as described in [3] for a PILC cable of 4.1 km length operated by Dutch DSO Alliander and categorized as “one or more intermittent faults followed by a preventive repair action of the weak spot”.

Only 11 days after installing SCG in this cable, 14 intermittent faults were detected within a couple of hours. Within a few minutes after each intermittent fault, Alliander received an automated message from the SCG control center, informing them about the occurrence and location of the fault. This messaging was repeated a few times because there were several intermittent faults. Before the fault could cause a (complete) breakdown with automatic switch off Alliander switched the cable section off manually, isolating it from the rest of the network. It was concluded that the SCG information had correctly identified a weak spot and prevented full breakdown with outage. The cumulative amount of outage minutes prevented was estimated by Alliander to be 21.010 customer minutes. The difference between the identified and actual fault position was 3 m, being a location error of 0.07 %. At the fault location, Alliander found the PILC suffered a small stone that had penetrated the lead sheath. The faulty location is shown in figure 4.

Figure 4: Weak spot in the PILC cable caused by small stone.

The second example is of a 1.4 km long 22 kV XLPE cable. SCG detected PD activity at 1,111m, near to a joint that was located at 1,090m from the left station. As the weak spot grew but was consistently present at the same location, SCG Level 2 warning was issued (figure 5). The DSO decided to take the circuit offline and performed verification testing (OWTS) which pinpointed the PD activity (cluster) at 1,100m (figure 6). The cable was retrieved and dissected: investigation revealed local degradation in the insulation layers of a heat-shrink joint due to a workmanship issue.

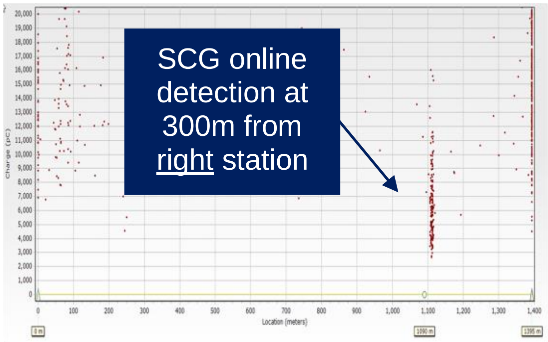

Figure 5: SCG graph depicting cable location, time, and PD level.

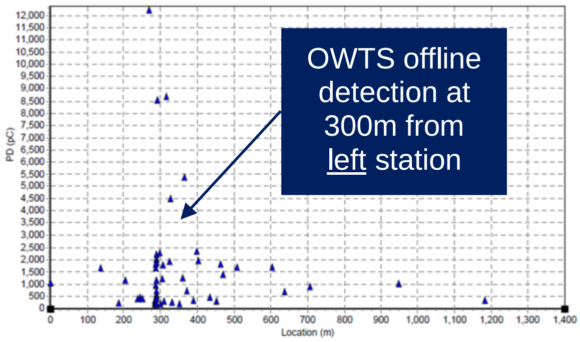

Figure 6: OWTS graph depicting cable location and PD level.

Smart Cable Guard is real-time, round-the-clock monitoring of cables using its digital twin. It applies advanced predictive data analytics based on more than 20 parameters to make informed decisions. Under common (noise) conditions, up to 8-mile XLPE or 3-mile PILC cable can be monitored with a single system. SCG can monitor through switchgear stations and branch (T) splices. It communicates via a web interface and can be connected via an API to SCADA, DMS or other utility systems.

4. Reliability and Resiliency improvements with 24/7 cable monitoring

Continuous (24/7) monitoring has the benefit of actual data. Any weak spot detected based on PD measurement can be monitored over time. This allows to assess risk based on the development of PD activity and potentially relate this to loading and/or seasonal effects. This provides more insight in comparison to a single measurement, where thresholds (i.e., based on discharge level) need to be relied on for risk estimation. Secondly, any unexpected failure (e.g., due to digging activities or without preceding PD activity) can be pinpointed immediately, significantly reducing outage time. The latter is especially effective when feeders consisting of several manholes or RMUs are being monitored at once: it removes the need to check many locations for fault passage indicators.

The effectiveness of monitoring systems applied in practice has been shown in recent years. General statistics show that approximately 70% of failures can be prevented using online PD measurement. A 2017 study performed by a grid operator showed that each SCG system can prevent about 6,150 customer-minutes-lost yearly [3]. This study also concluded location accuracy at less than 1% of the cable length. A joint study in Germany [4] between DSO Rheinische NETZGesellschaft (RNG) and DNV shows that Smart Cable Guard can reduce grid outage time by 55%.

Of course, the effects are present per feeder under monitoring as such; overall grid reliability can be increased with increasing number of feeders being monitored. Figure 7 shows a trend of failure statistics as function of the number of cable circuits under monitoring based on modelled data numbers from several DSOs: performance increases with the number of circuits under monitoring.

Active monitoring is most beneficial when cable sections associated with the highest risk and impact are monitored. Good insights into general failure statistics of the network can therefore support prioritizing installation locations for monitoring equipment. Highest reliability can be achieved by monitoring *all* circuits; however, an optimum will be found when trading off cost against benefits: monitoring should be applied at locations where outage consequence cost is at par with or higher than the monitoring expense. Model based approach has shown that users of SCG tend to decide investing in systems if their pay-back time is shorter than two to five years. With a certain penetration of monitored cables prioritized based on consequential cost, benefits decrease.

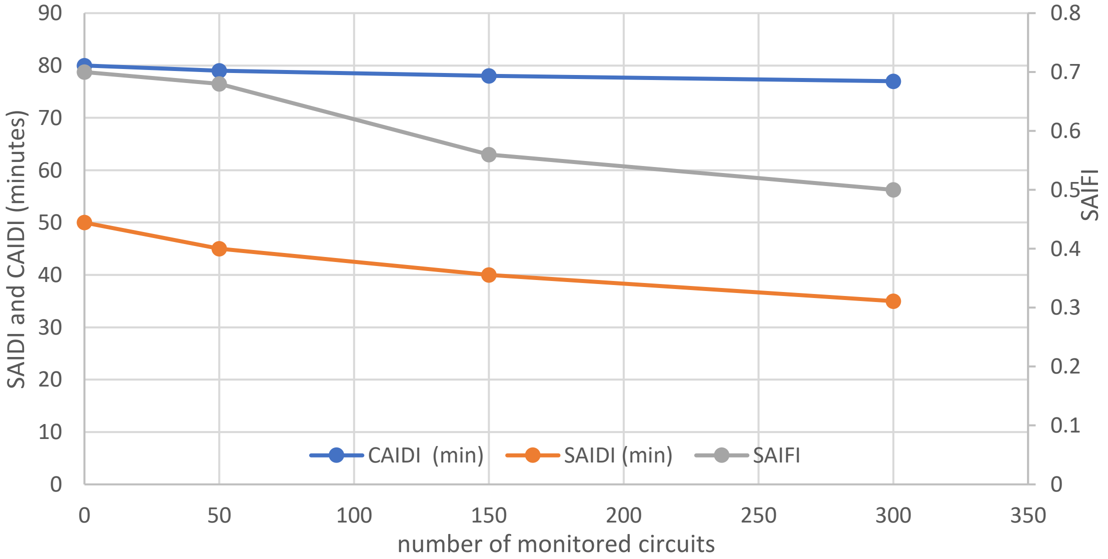

Figure 7: CAIDI, SAIDI and SAIFI as function of number of circuits under monitoring.

5. Futureproof data-driven cable maintenance

Continuous monitoring allows to have continuous insight in the condition of each feeder cable under monitoring. This will evolve corrective maintenance practices (repairing after failure) into preventative maintenance practices.

Preventative maintenance practices can be based on various levels of information availability. Firstly, maintenance (or replacement) can be performed based on statistics of component risks and history. This generally gives relatively high uncertainty due to averaged statistics, specific circumstances, and unknowns. This can be improved by adding occasional singular condition measurement (offline) or spot checks. However, this approach still contains uncertainties given that time-based dynamics are not considered, and measurement intervals are typically long (at least one but often up to and over four years). Therefore, grid operators should be conservative using this method as it could call for replacement of cables which are statistically at risk, though may in-fact still be in good condition.

Using continuous monitoring, uncertainties as described above are greatly reduced. By replacing average lifetime statistics with de-averaged live digital monitoring, fact-based decisions can be made. This leads to more flexibility in planning upgrades, saving money, and reducing the use of resources and the environmental footprint. Risk is accurately quantified and allows timely replacement before failure. This removes ad-hoc repairs and unexpected outages. It also allows to gain control over assets that would otherwise be 'too uncertain' to rely on, and therefore be replaced earlier. This can stretch a grid's operation and keep capacity available, i.e., optimally use the scarce resources. Relatively old PILC cables, for instance, can sustain for a very long time, though the age by itself may warrant replacement if no further information is available.

Since failure probability is qualified per specific component, it can be weighed against the consequence of an outage in that particular feeder, therefore, managing risk in a controlled manner. Where increasing capacity of a specific feeder may otherwise be of too high a risk, continuous monitoring of the feeder can alleviate this.

What monitoring does, is giving a grid operator the opportunity to change their asset management philosophy: there can be acted before something happens, where there was no such possibility in the past. As a result, grid operators change their way of operations, from reactive repair crews to pro-active asset managers, less 'fire extinguishing' more prevention.

In addition, outages are shortened as localization is immediate and very accurate. The emphasis of the operator's tasks and duties change from search and fault localization testing to insight and control based on crisp and readily available supporting information. Also, safety is served with monitoring. Less unexpected failures and accurate localization leads to less and shorter field trips, being better prepared when digging and dissecting, specifically less risk in and around manholes and less rush repairs.

From a longer-term perspective: having accurate and actual cable information enables asset planning with well-founded decisions how to best spend investment capital for new cables that optimally serve resiliency. Longer-term but still proactive replacement plans can be made.

6. Congestion management making use of monitored cables

As mentioned before, worldwide utilities look for increasing grid transport capacity. Loading existing cables to a higher level than in the past for that purpose, if possible, is much faster and requires less capital than building new connections. This can, however, not be done without careful study of the conditions and management of elevated risks. With continuous monitoring, 24/7 insights create an understanding of the current capability of existing feeders and allow to increase the load above basic limits in a safe and controlled manner. For instance, utilities who use a radially operated open ring system consider closing the rings, only if monitoring can limit the probability and consequence of failure.

Thanks to continuous monitoring, more users can be connected and (temporarily) higher load applied because their risks are controlled by more intelligence and mitigated by better and faster asset protection. From an asset management perspective: investing into a monitoring system reduces the total CAPEX and optimizes the use of cables: while in the past for reliability reasons you had to select cables for replacement, now it is possible to use even compromised cables because the moment of failure can be much better predicted, enabling a much more subtle process of taking assets offline and replacing total circuits or only specific pinpointed weak spots at the right time. Obviously, this has consequences for operations and control: this new insight creates flexibility and new options, but new work methods and procedures have to be introduced to manage this real-time.

In the meantime, new potential has been discovered: the actual temperature of a feeder can be determined using the propagation time variations of continuous monitoring technology. This temperature data can be integrated into the analytics platform and used for better weak spot prediction and more dynamic loading. [5,6]

7. Conclusions

Online continuous monitoring enables a utility to invest efficiently in terms of cost and time to determine the weak spots in its grids with highest risks for an outage as well as the severest impact. The insight resulting from the monitoring directs a utility where to deploy its limited resources; and provides an important component for congestion management and rapid demand expansion. This digitalization ensures that more data can be retrieved from the network and helps utilities at short and longer term to better design and use its networks.

24/7 insights in the condition of cable systems can be gained by monitoring their PDs and (intermittent) faults. Indications for upcoming failures are higher PD levels, steady or intermittent PD increase, clustering of PD activity etc. The failure prediction increases in effectiveness when it is based on analyzing a larger number of parameters and tying these to a database with all earlier experiences and events. Unexpected outages are prevented by real-time operational warnings from online monitoring for 70% or more of the cases. Outage duration is reduced by immediate and highly accurate localization, in some grids up to 50%.

Continuous monitoring is most rewarding when applied on cable sections associated with the highest risk and impact. Highest reliability can be achieved by monitoring all circuits, however, with identifying the most critical cables, returns can be optimized. Model based approach show that users tend to decide to invest into systems if pay-back time is lower than 2-5 years. SAIDI, SAIFI and CAIDI performance statistics can be considerably improved (up to 55%) if the worst 25% of all critical cables of a grid are brought under monitoring.

The early warning for outages and up-to-date knowledge of the condition of cables add substantially to the resilience of the network. From a longer-term perspective: having accurate and actual cable information enables asset planning with well-founded decisions how to best spend investment capital for new cables that will best serve resilience. A monitoring platform enables proactive maintenance, investment, and resource planning, as well as capitalizes operational costs.

The insight, real-time feedback of condition, and temperature indication, make Smart Cable Guard an ideal tool to optimize asset usage and maximize loading of cables which is looked after for congestion management. Seen from asset management point of view: investing into a monitoring system reduces the total CAPEX. And it optimizes the use of cables: now it is possible to use even compromised cables for which the moment of failure can be better predicted. A much more subtle process of switching assets is enabled. Obviously, this has consequences for operations and control: the new insights create flexibility and options, but new work methods and procedures have to be introduced to be manage this real-time. Cable monitoring enables congestion management of underground distribution networks.

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