ACCURATE ON-LINE FAULT LOCATION AND PD ACTIVITY LOCATION RESULTS OBTAINED WITH SCG – A LONG TERM UTILITY EXPERIENCE

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ABSTRACT

In recent years, Alliander (one of the largest network owners in the Netherlands with almost 40 000 km of MV cable (PILC and XLPE) installed a number of Smart Cable Guard (SCG) systems to verify its effectiveness in preventing failures or, if there is a breakdown, to reduce the repair time (outage time). Alliander concluded that SCG is indeed a very effective tool for on-line detection and location of (intermittent) faults and PD's in MV power cables. These phenomena are located with an inaccuracy better than 1%, based on travelling waves. On average, each SCG system could have prevented about 6150 customer minutes lost per year. Preventive repair also allows to see the cause of degradation, helping to develop counter measures. SCG can be used in all types of MV cable networks and replaces Fault Passage Indicators as well. Based on this, Alliander will implement more SCG systems in the upcoming years.

INTRODUCTION

MV power cable systems suffer from outages. DNO's can profit a lot in case such outages can be precisely located immediately when they occur. It would even be better if such outages can be avoided.

For the first situation (locating faults) one of the largest DNO's in the Netherlands, Alliander, decided to apply an on-line fault locator that can locate any fault in their cable with an accuracy of 1 % of the monitored cable length. For the second situation (avoiding outages), the same equipment is used by Alliander to measure on-line partial discharges (PD's). When such PD activity is measured and located on-line, Alliander can go into the field and replace the defective asset, often a cable joint, before it leads to a breakdown and outage.

Alliander as a network owner has a power cable network of approximately 87 000 km (of which 37 500 km MV cable), over 3 000 000 customers and a SAIDI of approximately 21 minutes.

The equipment applied is called Smart Cable Guard (SCG). For several years publications treat its basics and first field experiences. Some more recent publications reflecting this are [1]. [2], [3], [4], [5], [6] (of which [1] and [2] are papers published at CIRED in 2013 and 2015). Many more fundamental publications related to SCG can be found in for instance [7], [8], [9], [10]. The paper at hand is the first publication where one of the utilities applying SCG is reporting its long term field experiences, with a focus on the on-line fault locator part of SCG. This paper will not inform further about how SCG works (since the above mentioned publications treat this extensively).

Before elaborating some interesting results, it is good to emphasize here that SCG is NOT measuring 50 Hz short circuit currents in order to measure and locate a fault. Instead it is measuring the travelling waves that occur in the first microseconds after a fault. This is done with high-frequency (100 kHz – 10 MHz) current sensors at both cable circuit ends, which are accurately time synchronized. Especially publication [4] is dealing with this issue. Based on this approach, various advantages can be achieved which will be explained below.

The fault locator can detect and locate normal faults followed by switching actions, but also can detect and locate faults which are not seen by the protection equipment. For instance:

1. Faults which take place in a network with an isolated neutral where the fault current is far below the detection level of the protection equipment.
2. Faults with very short durations (a few milliseconds), after which they disappear (so called intermittent faults). It is surprising to learn that such faults indeed happen, sometimes many months before a fault occurs to which the protection equipment responds. The fault locator is thus able to identify and locate weak spots long before the power is switched off, making it possible to perform a repair activity. Such faults happen typically in cable networks with an isolated neutral or impedance grounding, both in paper and polymer insulated power cables.

The fact that any fault is located with an accuracy of 1 % of the cable length between the sensors is very helpful. In case of a normal fault it helps to restore the network quickly. In case of a fault to which the protection system is not responding, the fault location is often accurate enough to identify the defective component.

As a result, Alliander can now use the fault locator to increase the reliability of its network, much welcomed in cable network areas where an outage has considerable consequences.

This paper will also treat PD location results, especially to show that surprisingly PD levels from a defect are often in a range of 10 000 to 100 000 pC in the weeks or days prior to a failure. Such a PD level is far beyond the traditional focus on 10 to 100 pC, showing that on-line PD detection is a different "world".

FAULT LOCATION EXPERIENCES

The following table 1 shows a summary of faults that have been detected with SCG in Alliander's network during the period between February 2015 and November 2016. Details are given in table 3 in the end of the paper.

The number of SCG systems installed on average over this 22 month time period was 64 (status December 2015), and the average cable circuit length guarded with each SCG system was 3.7 km (often covering more than one cable section with ring main units in between).

In this period there were 19 (intermittent) faults in total in the network guarded by SCG, of which 15 were indeed correctly detected by SCG (cases 1 to 14 and case 16). The cause for the 4 missed detections has been identified and has been incorporated in the knowledge rules to prevent reoccurrence. In 1 case (case 15), SCG has been installed because of an assumed potential weakness based on an intermittent fault detected with other equipment (SASensor), which couldn't locate the intermittent fault. When after 250 days of monitoring there were still no detections, nor cable failures, the SCG system was removed again to be used elsewhere.

Table 1 Summary of detected faults with SCG in Alliander's 10 and 20 kV MV cable network (see for details table 3).

case	date of repair or breakdown	cable type, length	failing component	fault cate-gory	loca-tion in-accu-racy
1	2015-02-26	PILC, 4.5 km	mastic joint	c	0.1 %
2	2015-07-14	PILC, 4.1 km	stone into cable	d	0.1 %
3	2015-09-29	PILC, 2.5 km	mastic joint	d	0.6 %
4	2015-10-23	XLPE, 12.5 km	heat-shrink joint	a	0.1 %
5	2015-11-14	XLPE, 12.5 km	heat shrink joint	a	0.7 %
6	2015-12-22	XLPE, 13.0 km	heat shrink joint	b	0.0 %
7	2015-11-24	XLPE, 13.3 km	heat shrink joint	d	0.1 %
8	2016-03-22	PILC, 1.9 km	digging into cable	b	0.1 %
9	2016-05-25	PILC, 2.8 km	resin joint,	b	0.3 %
10	2016-06-06	PILC, 1.3 km	heat shrink joint	b	1.3 %
11	2016-07-03	PILC, 0.5 km	oil-filled joint	b	5.5 %
12	2016-07-25	PILC, 1.4 km	resin joint	a	0.5 %
13	2016-07-26	XLPE, 1.8 km	unknown cable issue	b	1.1 %
14	2016-11-29	XLPE, 12.5 km	heat shrink joint	a	0.9 %
15	n.a.	PILC, 3.4 km	n.a.	e	n.a.
16	2016-08-19	XLPE, 1.8 km	termination	b	0.1 %

In table 1, fault categories are mentioned. The categories are a, b, c, d and e and will be explained below (graphically illustrated in figure 1 as well):

a) Just a breakdown with automatic switching off
b) A breakdown with automatic switching off. This was preceded by some intermittent faults from the same spot, too short in time (< few hours) before the breakdown, such that a preventive repair action was not possible
c) A breakdown with automatic switching off. This was preceded by some intermittent faults from the same spot, long enough in time (> few hours) before the breakdown, such that a preventive repair action could have been done, but wasn't done
d) One or more intermittent faults followed by a preventive repair action of the weak spot
e) One or more intermittent faults, but not (yet) followed by a preventive repair action of the weak spot nor by a breakdown and automatic switching off.

For each of the fault categories, the application of SCG has advantages, as listed below in table 2.

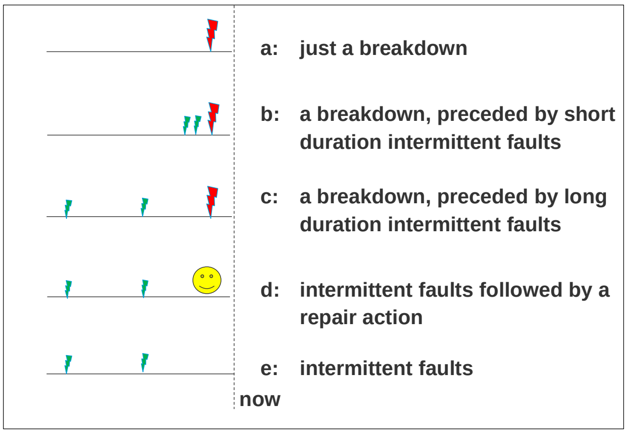

Figure 2 Faults, intermittent faults, repair and / or breakdowns (with switching action), categorized.

Alliander concluded that applying SCG to quickly locate a breakdown, combined with the possibility to avoid a breakdown in case it is preceded by intermittent faults (also located), is highly attractive to reduce the outage time and outage frequency (reducing SAIDI and SAIFI).

The following cases will be treated in more detail, just to illustrate how a network owner can respond to a (intermittent) fault, as detected and located on-line by SCG. These cases will be shown in the following Section.

Table 2 Advantage applying SCG per fault category

Fault category and description		Advantage applying SCG
a	Just one breakdown, the automated switch switches off (potentially an outage)	Immediate location of the breakdown spot with 1 % accuracy
b	One or more intermittent faults, immediately followed by a breakdown and the automated switch is switching off (potentially an outage)	
c	One or more intermittent faults, after a long time followed by a breakdown and the automated switch is switching off (potentially an outage)	
d	One or more intermittent faults, followed by a repair of the weak spot	Avoiding an outage
e	One or more intermittent faults, not followed yet by a repair of the weak spot nor a breakdown	Possibility to avoid an outage

Examples of (intermittent) faults detected by SCG

Two examples will be given below. Both are dealing with PILC. But it is emphasized that also XLPE cables have been guarded with SCG for fault location, where the maximum cable length on which SCG for this purpose was installed was 13.3 km long, see table 1 and table 3.

Example 1 – PILC cable of 4.1 km length

This example is reflecting the case 2 in table 1 and table 3 (fault category is c). The cable is a 4.1 km long PILC cable.

Only 11 days after installing SCG, 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 centre, informing about the fact that there has been an (intermittent) fault. This messaging was repeated a few times, because there were several intermittent faults. According to the difference in arrival time of the travelling waves recorded by SCG, the location of all the intermittent faults was 2872 m.

Before the cable could break down (completely) and had an automatic switch off, Alliander switched the cable section off manually, isolating it from the rest of the network. After that the cable was subjected to a 18 kV DC withstand test (suitable for PILC). During this testing, the cable broke down at the position 2869 m. It was concluded that the SCG information correctly found a weak spot and a full breakdown with an outage was prevented. The amount of outage minutes prevented was estimated by Alliander to be 21010 minutes.

The difference between the identified and actual fault position was 3 m, being a location error of 0.07 % (rounded to 0.1 % in table 1). At the fault location, Alliander found the PILC had a small stone that had penetrated the lead sheath. The faulty location is shown in figure 2.

Figure 2 Weak spot in the PILC. A small stone was found inside the cable, probably it had penetrated the cable over time.

Example 2 – PILC cable of 2.8 km length

This example is reflecting case 9 in table 1 and table 3 (fault category d). The cable is a 2.8 km long PILC cable. More than 5 months after the installation of SCG, a breakdown was detected and located at 2684 m. There were also 18 intermittent faults preceding the breakdown, but these happened in the minutes / few hours before the breakdown only. As such Alliander didn't have enough time to proactively switch off the cable section manually before the actual breakdown occurred.

The breakdown took place in a resin joint. The joint location was at 2693 m. The difference between the identified and actual fault position was 9 m, being a location error of 0.32 % (rounded to 0.3 % in table 1).

Alliander did the corrective actions in their traditional way (using GSM fault indicators and then going along various ring main units and identifying the direction of the breakdown based on local indicators in these ring main units; finally the cable section is isolated by manual switching and the main switch is closed again). The total number of customer minutes lost for this outage was equal to 55 902. Alliander made an estimation of the customer minutes lost, would the fault location as identified by SCG directly have been used to guide the corrective actions. The total number of customer minutes lost for that case were estimated at approximately 41 000. A reduction of more than 25% with respect to the traditional corrective procedures in this case.. Alliander concluded that applying the fault location identified by SCG also in case of a full breakdown, can have a significant positive impact on the outage duration.

PARTIAL DISCHARGE LOCATION

As has been shown in many publications already, SCG is also able to detect and locate on-line partial discharge activity in power cables. Just one example will be shown here as the focus of this paper is on fault location. This example is given to illustrate that SCG can do more than just detect and locate (intermittent) faults.

The example is a 12.9 km long XLPE cable running from a substation to a windfarm. Consequently, one can expect a high current load occasionally. As there had been problems with the reliability of joints, SCG was installed to guard the cable circuit on the 20th of February 2015. On the 8th of May 2015, intense PD activity was found in one of the joints, 4 km away from the left substation in figure 3. Peculiarly, the PD level went in just a few days from undetectable (< 5000 pC for this long cable circuit) to about 100 000 pC (100 nC!). It shows that, different from the focus of PD testing during a type test or factory acceptance test, in field applications the focus can be on larger partial discharge levels (> 100 pC), being very effective (as was shown in many other cases).

Alliander decided to replace the joint, after which the circuit became free of discharges (apart from wide spread noise randomly distributed along the cable, as is also visible in figure 3). The joint was dismantled and it became clear that the PD activity was the result from an overheated conductor connector, after which the XLPE cable insulation was cracked as shown in figure 4.

Alliander concluded, that SCG is well able to detect weak spots producing PD activity in power cable systems. This helps to prevent outages, reducing the SAIDI and SAIFI.

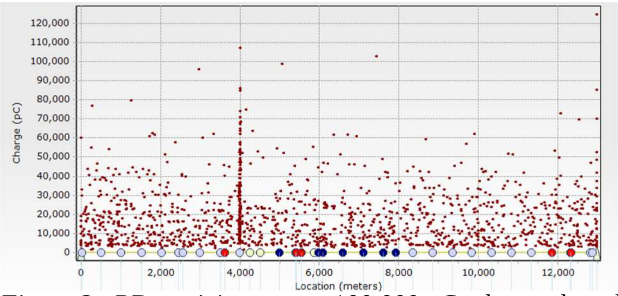

Figure 3 PD activity up to 100 000 pC, detected and located with SCG, coming from a joint at 4 km from the left substation, found in a 12.9 km long XLPE cable circuit.

Alliander experienced that applying SCG in the above mentioned period prevented 9 PD based outages, with an estimated total amount of 420 000 customer minutes lost avoided.

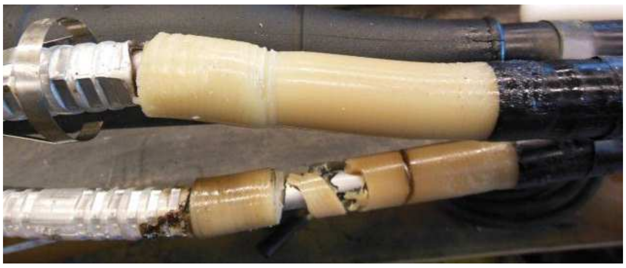

Figure 4 Joint from figure 3, after dismantling. Due to an overheated conductor connector, the XLPE cable insulation was cracked. NB: this joint was replaced before it failed!.

ANALYSIS

In total, there were 20 faults, of which 4 were not well interpreted by SCG. It is assumed that such cases will become less over time because of better knowledge rules and better equipment (a next generation SCG was introduced recently to implement this).

Taking into account the remaining 16 cases (100 %), then in total 11 cases (69 %) came with an immediate breakdown or one preceded by intermittent faults in the few hours or minutes just before the breakdown, such that Alliander couldn't prevent the breakdown. For these cases, SCG can help to support the network restoration based on the accurate fault location information. This potentially saves about 25 % of the customer minutes lost. This would be in the range of 100 000 to 200 000 customer minutes lost avoided. In the remaining 5 cases (31 %), a breakdown could be avoided and was indeed done in three cases (case 2, 3 and 7 in table 1 and table 3), with an estimated reduction of the customer minutes lost of 80 740. Would this be translated into 5 cases, then this would come in the range of 100 000 to 200 000 customer minutes lost avoided as well. Case 7 had zero customer minutes lost because of the back-up situation (parallel cable), but with a breakdown that back-up would be lost. This could trigger a breakdown in the (higher loaded) parallel cable as well, which would then result in a significant number of customer minutes lost, a realistic high-risk scenario. As a result, the total potential of reducing the customers minutes lost is in the range of 200 000 to 400 000 (just based on SCG's fault location feature).

Because of SCG's other feature, being locating PD from weak spots, Alliander could identify 9 of such spots which were replaced, preventing a failure. This came with an estimated reduction in customers minutes lost in the range of 420 000.

Consequently, applying SCG opens the door to reduce the customers minutes lost ranging from 620 000 to 820 000. And most of this was realized indeed, being 570 000. With 64 SCG systems, guarding 240 km of cable circuits, used in a period of 22 months, on average, each SCG system could prevent by approximation 5300 to 7000 (mean value: 6150) customer minutes lost per year. The average location error for SCG's fault locator has shown to be better than 1 %. A similar value is known to be applicable for SCG's PD locator.

Based on this experience, Alliander concluded that SCG is a reliable and valuable tool to help reducing the SAIDI and SAIFI in an economical way. Both preventing failures by acting on PD activity and intermittent faults as well as finding a breakdown spot quickly are very useful.

In case of PD related and intermittent fault related replacements, the fact that the component has not yet destructively failed, makes a network owner quite able to determine the exact root cause. This is very helpful in instructing technicians to install in a better way, or to instruct manufacturers to come with better solutions in the (mainly joint) design.

Alliander also concluded that SCG can replace Fault Passage Indicators (FPI). That is because FPI's only identify the area of a breakdown, whereas SCG directly determines the fault location PLUS that SCG is responsive to intermittent faults (not detected by FPI's) and PD activity (not detected by FPI's either). Also SCG can be used in any network, independent of the network grounding (like direct grounding, impedance grounding or isolated neutral). It means for instance that SCG is working perfectly well in a network with an isolated neutral where FPI normally isn't activated because of the reduced fault current level.

In this way, Alliander considers SCG as a very useful tool that is serving many different goals at the same time and it is a future proof concept. Based on this, Alliander decided to extend the number of SCG systems from 42 in 2015, to 142 in 2016 and to 400 in 2017, and with the object to grow further towards 3000 in further years.

CONCLUSIONS

Alliander concluded that Smart Cable Guard (SCG) is a very effective tool for on-line detection and location of (intermittent) faults and PD's in MV power cables. These phenomena are located with an inaccuracy better than 1% in respect to the total cable length in almost all cases. On average, each SCG system could have prevented about 6150 customer minutes lost per year. Preventive repair also allows to see the cause of degradation, helping to develop counter measures. SCG can be used in all types of MV cable networks and replaces even Fault Passage Indicators as well. Based on this, Alliander will implement more SCG systems in the upcoming years.

REFERENCES

[1] Fred Steennis et all., 2015, "Smart Cable Guard – A tool for on-line monitoring and location of PD's and faults in MV cables – its application and business case", *CIRED conference Lyon, France, 2015. Paper 1044.*

[2] Hugo Miguel Pereira, 2013, "Partial discharge on-line monitoring in MV underground power cables as part of condition based maintenance strategy", *CIRED conference Stockholm, 2013. Paper 0604*

.[3] BC. Van Maanen, et all., 2016, "Learning from on-line monitoring of medium voltage power cables – with PD and fault location", *Cigré conference, Paris, France, 2016. Paper B1-205*.

[4] Accurate on-line fault location (full breakdowns) for MV cables with Smart Cable Guard", *Jicable conference, Versailles, France, 2015, C4.2*.

[5] Ravish P.Y. Mehairjan, et all., 2014, "Experiences with the Introduction of Online Condition Monitoring in Asseet Management for Distribution Networks", *CMD Conference 2014, Jeju, Korea*.

[6] Fred Steennis, et all., 2014, "Smart Cable Guard for PD-online monitoring of MV underground power cables in Stedin's network", *CMD Conference 2014, Jeju, Korea.*

[7] Yizhou Qian, et all., 2015, "Risk on failure, based on PD measurements in actual MV PILC and XLPE power cables", *Jicable conference, Versailles, France, 2015, C1.2*.

[8] Yan Li, et all., 2016, "Effect of ground return path on partial discharge signal propagation along single-core and three-core power cables", *International Transactions on Electrical Energy Systems, 2016, DOI: 10.1002/etep.2179.*

[9] Li, Y., 2015, "Extended functionality of on-line partial discharge monitoring equipment for medium-voltage power cables", *PhD thesis TU/e, 2015, ISBN: 978-90-386-3811-9.*

[10] Paul Wagenaars et all, 2011, "Influence of Ring Main Units and Substations on Online Partial-Discharge Detection and Location in Medium-Voltage Cable Networks", *IEEE Transactions on power Delivery, Vol. 26, No. 2, April 2011, pp: 1064 – 1071*.

Table 3 Overview of detected faults with SCG in Alliander's MV cable network (network voltage 10 kV and 20 kV). The location inaccuracy of the fault location is based on a percentage of the total cable length.

case	Date SCG installed	Date first intermittent fault detected by SCG	Number of intermittent faults	Date Breakdown with switch operated	Date Repair to avoid breakdown	Cable length [m]	Fault location from SCG [m]	Actual fault location [m]	% error fault location	Outage minutes prevented	Failed component	Cable type	Fault category	Remark
1	2014-12-30	2015-02-25	124	2015-02-26		4522	2615	2620	0.11 %	n.a (if prevented: 10 168)	Mastic filled joint	PILC 10 kV	c	10 h of intermittent faults before the cable broke down
2	2015-07-03	2015-07-14	14		2015-07-14	4125	2872	2869	0.07 %	21010	Cable	PILC 10 kV	d	Stone piercing lead sheath cable
3	2015-03-17	2015-09-15	6		2015-09-29	2527	1212	1196	0.63 %	59730	Mastic filled joint	PILC 10 kV	d	
4	2015-03-06	2015-10-23	0	2015-10-23		12477	4734	4750	0.13%	0	Heat shrink joint	XLPE 10 kV	a	back-up circuit, outage minutes prevented = 0
5	2013-12-02	2015-11-14	0	2015-11-14		12477	10670	10580	0.72 %	0	Heat shrink joint	XLPE 10 kV	a	back-up circuit, outage minutes prevented = 0
6	2015-02-20	2015-12-22	6	2015-12-22		12982	11332	11332	0 %	n.a.	Heat shrink joint	XLPE 10 kV	b	
7	2015-11-20	2015-11-23	2		2015-11-24	13266	4480	4466	0.11 %	0	Heat shrink joint	XLPE 20 kV	d	back-up circuit, outage minutes prevented = 0
8	2015-11-18	2016-03-22	13	2016-03-22		1872	1662	1660	0.11 %	n.a.	Cable	PILC 10 kV	b	Breakdown cable because of digging activities; 13 intermittent faults just prior to the failure
9	2015-12-03	2016-05-25	18	2016-05-25		2803	2684	2693	0.32 %	n.a.	Resin joint	PIILC 10 kV	b	
10	2016-06-03	2016-06-06	11	2016-06-06		1254	335	319	1.28 %	n.a.	Heat shrink joint	PILC 10 kV	b	
11	2016-06-29	2016-07-03	8	2016-07-03		513	8	36	5.46 %	n.a.	Oil filled joint	PILC 10 kV	b	Intermittent faults were detected 7 min. before breakdown.
12	2015-12-03	2016-07-25	0	2016-07-25		1439	1202	1209	0.49 %	n.a.	Resin joint	PILC 10 kV	a	
13	2016-03-03	2016-07-26	15	2016-07-26		1848	1308	1287	1.14 %	n.a.	Cable	XLPE 10 kV	b	
14	2013-12-02	2016-11-29	0	2016-11-29		12477	3134	3245	0.89 %	0	Heat shrink joint	XLPE 10 kV	a	back-up circuit, outage minutes prevented = 0
15	2014-09-03	n.a.	0	n.a.		3396	n.a.	n.a.	n.a.	n.a.	n.a.	PILC 10 kV	e	After detection of an intermittent fault with another system (SASensor), SCG was installed. After 250 days without significant activity the system was removed again.
16	2016-06-07	2016-08-19	3	2016-08-19		1751	1472	1471	0.06 %	n.a.	Termination	XLPE 10 kV	b	