SMART CABLE GUARD – A TOOL FOR ON-LINE MONITORING AND LOCATION OF PD'S AND FAULTS IN MV CABLES – ITS APPLICATION AND BUSINESS CASE

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ABSTRACT

Smart Cable Guard is already for a few years a known instrument to monitor MV underground power cable systems, while the cable is in service (on-line). Its ability to locate weak spots and to create an on-line PD map has resulted in many interesting cases of avoided faults, showing its ability to reduce the SAIDI and SAIFI. Recently, a new feature was added to SCG, being an on-line fault locator. Immediately after a fault occurs, the SCG fault locator detects and locates this fault, even in networks where traditional protection equipment does not detect the fault because of the network's grounding. These features let the Dutch DNO's Enexis and Alliander conclude that SCG is a valuable tool to reduce their SAIDI and SAIFI and large scale application is now under preparation.

INTRODUCTION

For several years Smart Cable Guard (SCG) has proven to be an effective monitoring instrument for on-line diagnosis of MV underground power cables by locating defects while the cable is in service. These defects are weak spots that generate partial discharges (PD's), but have not failed yet. This feature is called in this paper the SCG Defect Locator (SCG-DL).

In 2014, a new feature was added to SCG, being an accurate on-line fault locator, called in this paper the SCG Fault Locator (SCG-FL).

A fault is defined as a failure or breakdown, where the full cable system insulation is bridged by a short circuit. Such a short circuit does not always result in a detectable short circuit current. It will depend on the network grounding whether a short circuit current will become large enough to be detected by traditional protection equipment.

This paper will discuss both SCG features:

1. SCG-DL: In case of a weak spot with PD's detected and located with SCG, the DNO can replace this weak spot before a fault happens. The principles of SCG-DL were extensively discussed in many papers in the past [1, 2, 3] and only a short summary will be given in this paper. Based on many years of experience with SCG-DL, this paper shows the relation between the PD activity from the weak spot and the probability of a fault within a certain time interval, both for PILC and XLPE insulated cables. As far as it is known by the authors, this is unique information.
2. SCG-FL: In case of a fault, with SCG-FL the DNO immediately knows the exact fault location, speeding up the repair time. How SCG-FL can locate faults accurately will be explained in detail in this paper. Also the result of a field test on a live cable will be treated. Based on its principles SCG-FL performs perfectly well in any network, even in a network with an isolated neutral.

Both features (SCG-DL and SCG-FL) help network operators to reduce the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI).

The above mentioned location or pinpointing of weak spots and faults has an accuracy of 1% of the cable length, both for SCG-DL and SCG-FL.

In this paper, first SCG will be treated in general, with a focus on its basic functions and operating conditions. Then, the features SCG-DL and SCG-FL will be introduced in separate chapters. This will be followed by a discussion of the business case of SCG, as seen by two different network operators.

SCG IN GENERAL

For on-line PD monitoring, traditional PD detection devices use only one inductive sensor. Using only one sensor has the disadvantage that it is difficult or often even impossible to locate PD's and to distinguish PD's from noise.

SCG comes with two inductive sensors (for a general set-up, see Figure 1) that can be placed for instance around the earth lead(s) at each cable end of the cable system being guarded (see Figure 2 for an example of a sensor places at one cable end).

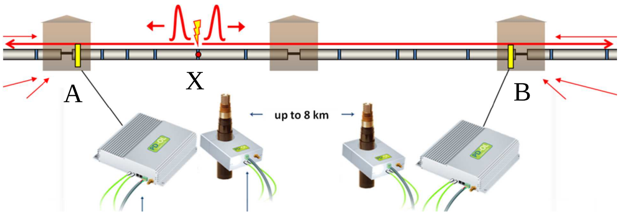

Fig. 1: Typical SCG set-up with left (location A) and right (location B) a sensor and a dedicated industrial computer with wireless or LAN internet connection.

In Figure 1, the two inductive sensors are placed (for instance) around the earth leads (see Figure 2) in the substations A and B. These positions can be several kilometers (km) away from each other, up to 12 km (depending on whether the focus is on SCG-DL, SCG-FL, or both). For safe installation the inductive sensors have a split core that allow for clamping around the earth lead(s) without the need for disconnecting the earth leads.

From a weak spot or fault at position X (in Figure 1), electromagnetic waves travel along the cable in two directions, away from the spot X. Each of the two inductive sensors detects the travelling wave passing. The travelling wave amplitude, together with the time of arrival, is stored. The difference in arrival time tells where the source of the travelling wave (PD or fault) is located.

Both inductive sensors measure the currents passing by from the travelling waves, whether it is from PD's (mA range) or from faults (Ampere range).

In order to locate the PD's and faults the internal clocks of the two inductive sensors must be time synchronized with an accuracy of 100 ns or better. SCG's time synchronization is based on patented pulse injection technology, being

- economical (it is using the inductive sensors for regular pulse injection as well),
- practical (SCG's pulse injection doesn't use GPS, thus, there is no GPS module needed nor a GPS antenna on the roof of a building) and
- reliable (if an SCG sensor can inject on regular moments time sync pulses, being correctly measured at the other cable end, then this sensor can also measure PD pulses correctly).

Fig. 2: Typical set-up of a SCG sensor placed around the earth leads of a three phase XLPE MV power cable in a substation.

At both locations A and B, once per hour (for PD's) or immediately (for faults) the stored data is sent via internet to a server. Here all data is combined. Only travelling wave data is accepted of which the difference in arrival time corresponds to a source (defect or fault) located inside the cable length under test. The rest of the data is considered to be noise. This feature is SCG's robust noise suppressing feature. The red thin arrows at the locations A and B in Figure 1 represent such external noise, correctly discarded by SCG.

SCG AS DEFECT LOCATOR (SCG-DL)

SCG-DL: PD maps

The SCG-DL functionality is fully based on PD detection and localization. The SCG function for PD's is being used by many network operators to trace weak spots successfully. Numerous papers were written on this issue. An example of a PD map is shown in Figure 3. This PD map was measured in a network of one of the network operators using SCG. The weak spot was replaced before the cable failed. Investigation of the replaced component showed heavy degradation and the network operator clearly stated that an important outage in a city was avoided [3].

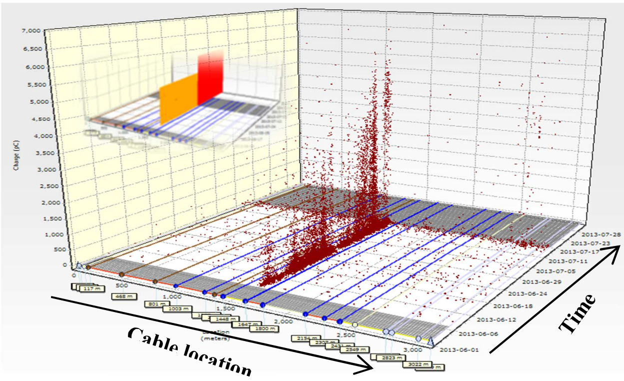

Fig. 3: PD map as a function of time (z-axis) for the whole cable (x-axis). The PD intensity is plotted on the vertical axis. The insert shows the SCG colored warnings levels given as a function of time [3].

SCG-DL: time between the start of PD activity and a fault (if the weak spot is not replaced)

Sometimes, network operators don't replace a weak spot identified by SCG. Although often this results in a fault, a network operator can have reasons to do so. This gives the SCG development team the unique opportunity to check how much time there is between a) the start of PD activity, b) an SCG warning about a critical weakness (warning level 1) and c) the actual fault moment for MV cables in service. Weibull statistics were used to make a correct interpretation of all the data. Considered as a fault was all data where indeed a fault happened after a certain period of PD activity. Also data was included from cases where a weak spot showed such severe degradation that the network operators indicated that the weak spot would have resulted in a fault in the near future and moreover that they were happy the defect was replaced.

In this way, in total 29 cases could be used for the Weibull calculations (in addition to censored data). Another paper (to be published at Jicable 2015) will treat all information in detail. Although it is impossible to predict accurately the time until a fault occurs, one can estimate the chance on having a fault within a certain time period. In Table 1 this period is identified for a 50 % change on having a fault. For example: after seeing for the first time PD activity in an XLPE cable system with SCG it will take on average 2 months to have a chance of 50 % on a cable fault (row 3; column 2). After an SCG warning of the highest level 1 the period is reduced to only 10 days (row 3; column 3).

Table 1: Time until 50 % chance on having a fault (failure or breakdown) from

- **the start of PD activity (column 2)**
- **an SCG warning level 1 (column 3)**

	start PD until fault	SCG warning level 1 until fault
PILC cable systems	16 years	3 years
XLPE cable systems	2 months	10 days

These results show several interesting things:

- it takes many years (on average) before weak spots in PILC cable systems result in a fault;
- it takes only a couple of days to months (on average) before weak spots in XLPE cable systems result in a fault;
- SCG's warning based on the interpretation of the PD activity is indeed able to come much closer to the actual fault moment than without such interpretation, taking into account the following:
  - for XLPE cable systems the SCG's warning moment is considered to be adequate
  - For PILC cable systems it is still difficult to come with an SCG warning only a few days before a reasonable chance on a fault.

So far, the above mentioned results were obtained for complete systems (PILC or XLPE based) and not yet for their individual components because the number of cases is still too limited. It is the intention of the SCG development team to come in the future with similar accurate warnings for these individual components such as cable, joints and terminations. Further refinements concerning voltage level and types of components are also a challenge. The expected large scale application of SCG will for sure help to come to such refinements.

SCG AS FAULT LOCATOR (SCG-FL)

SCG-FL: application range

Traditional protection equipment and short circuit indicators are based on measuring the 50 Hz short circuit currents. Not all networks with a fault come with a short circuit current large enough to be detected by this equipment. Especially, faults in high impedance grounded networks can stay undetected or at least un-interrupted for a long time. As a further result, a cross-country fault can occur, leaving the network now with two faults to be found and repaired. This can happen especially in cable networks or networks with a mix of lines and cables.

SCG's feature SCG-FL doesn't detect the 50 Hz short circuit currents in case of a fault, but it detects the travelling wave that comes from a fault. Such a travelling wave is the start of the fault current and it is always present, independent of the network grounding. Like a PD, the travelling waves from a fault travel in two directions away from the fault through the cable with almost the speed of light, passing SCG's sensors. The sensors detect these waves, including their arrival times. Whether such travelling waves develop into a full and large 50 Hz short circuit current or not doesn't matter for SCG, the traveling waves have been detected already. The arrival time of the first slope is a very accurate indicator for the fault position. The arrival times are immediately communicated to a server. And within minutes after the fault, the network operator gets a message (sms, email) with the fault's exact time and precise location.

Due to the detection of these traveling waves, SCG-FL can be used successfully any situation, for instance in the following situations:

- in a network with low or high grounding impedance to find and locate any fault (because for SCG it doesn't matter whether a fault is switched off or not by the protection equipment);
- in a network where certain faults recover (self-restoring faults), only to appear again after a few days, weeks or months; these faults are difficult to locate for network operators because of their temporary recovery (because SCG can also detect such faults, also the first one);
- faults with the unwanted characteristic to become high-ohmic after the fault is switched-off (because SCG is not influenced by the ohmic nature of the fault afterwards).

Any of such faults are found immediately and with a location accuracy of 1 % of the length between the two SCG sensors [4].

SCG-FL: example of a fault located

It is not so easy to test this SCG-FL feature, since luckily faults don't happen too often. Nevertheless, it was possible to prove SCG's ability to detect and locate faults, as will be elaborated below.

In the past some laboratory test and field test with switching actions (representing travelling waves resulting from a fault) already showed that SCG-FL must be able to detect and locate faults indeed.

In December 2014 a field test was done on a 10 kV power cable in the network of the Dutch DNO Alliander, where a real fault was made intentionally, while the cable was in service. Because it was a cable in a network with an isolated neutral, the fault didn't result in an outage. Nevertheless, as explained above, SCG was able to detect and locate the fault correctly.

The circuit under test is shown in Figure 4. It is a 12.4 km long circuit with 3 single-core XLPE cables running between the Dutch substations Harderwijk and Uddelermeer. In both substations an SCG system was installed on the cable. On December 6th, at 9:13 am, one of the three cable phases was cut, 6.9 km away from substation Harderwijk. As expected, the fault was correctly detected and located.

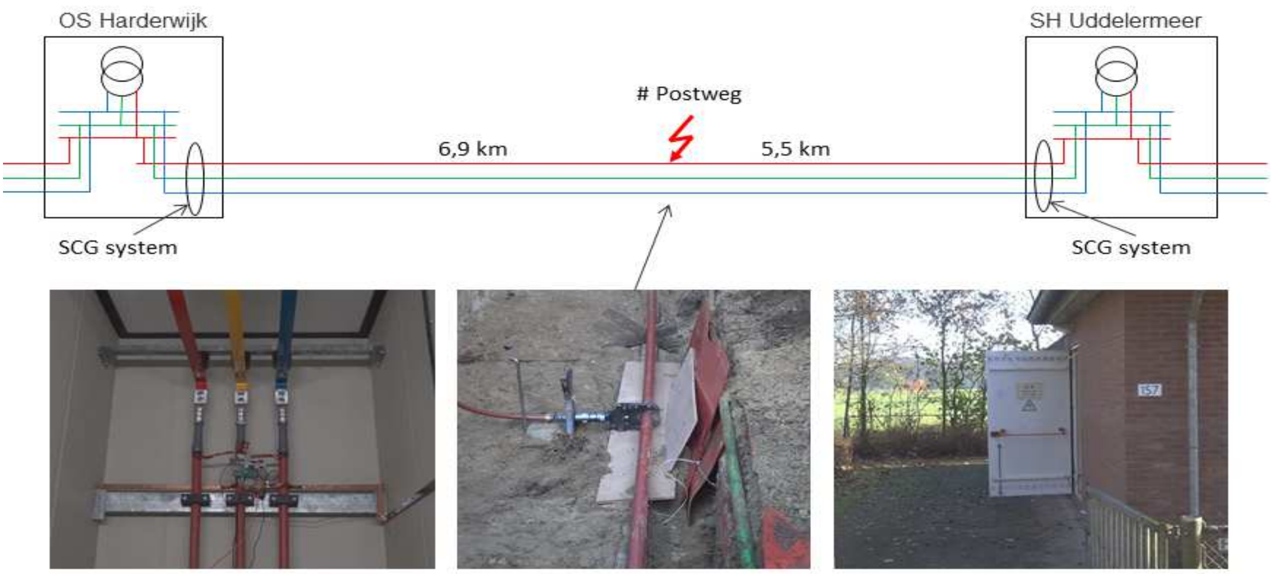

Fig. 4: 10 kV XLPE cable circuit with a length of 12.4 km, where an intentional fault was made at 6.9 km from the substation Harderwijk (OS Harderwijk). The left photo shows the SCG sensor in substation Harderwijk, the right photo shows the substation Uddelermeer and the middle photo shows the knife ready to cut one of the three phases of the power cable.

The automatically generated message by the SCG system was received by the network operator within minutes after the creation of the fault.

The recorded signals as captured by SCG are shown in Figure 5.

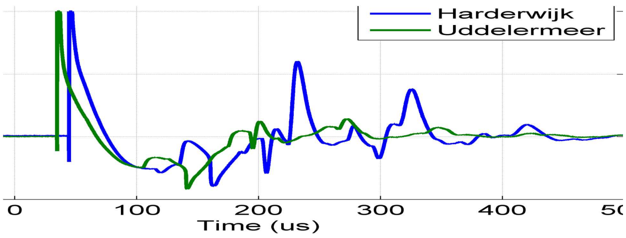

Fig. 5: real time SCG recording of the travelling wave signals from a fault, with recording locations substation Harderwijk (blue) and Uddelermeer (green).

The message with the fault information that was sent by the SCG server appeared a few minutes after the fault, as is shown in Figure 6.

Fig. 6: Message that appeared in the inbox of the network operator a few minutes after the fault, showing the exact location of the fault.

This test shows SCG-FL's ability to detect and locate a fault in a network, even in a network with an isolated neutral.

SCG BUSINESS CASE

The Dutch distribution network operators Enexis and Alliander did evaluate the potentials of SCG from a business case point of view.

In order to obtain this result, detailed information was needed about

- the network (how many faults, related outages and present SAIDI and SIAFI, types of cables and its components, background of the present faults, network grounding, etc.…), per region or city;
- the effectiveness of SCG to reduce the SAIDI and SIAFI, also in relation to the cable component types and the network grounding.

An important starting point for the business case calculation was the assumption that SCG was able to:

- detect and locate weak spots from internal defects with an efficiency of 65 % in PILC cables up to 4 km and XLPE cables up to 8km. These are weak spots with PD's detectable by SCG-DL and that would eventually result in a fault (if not replaced). The efficiency mentioned here is based on long term experience with SCG-DL
- detect and locate faults (those that can't be avoided) in cables up to at least 8 km with an efficiency of at least 90 %. Such faults might result from weak spots that don't generate PD's detectable by SCG-DL (35 % of the weak spots related to internal defects) and all other faults that are the result of external defects like those from digging activities.

It would require a full paper to discuss all further starting points and show all calculation results. But in summary the conclusions of Enexis and Alliander are as follows:

- The application of SCG is a cost effective way to reduce the SAIDI and SAIFI:
  - o SCG-DL is mainly of interest in areas which have a high density of customers and where many failures happen;
  - o SCG-FL is mainly of interest in networks where, because of the type of grounding, first failures don't result in a switching action, making such faults difficult to locate with traditional equipment;
- SCG is considered to be THE monitoring system to prevent MV cable and accessory failures.

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