Optical System for Underground Cable Maintenance, Mixed Lines Fault Discrimination and Underground Cable Fault Location

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ABSTRACT

The use of optical current transformers for measuring currents connected with conventional communications fibers opens up unconventional possibilities for the operation of underground cables. A system on a 115kV cable with distances of 12km has been developed and implemented. The cable's nominal currents together with the screen currents at the grounding points have been measured, and this represents a paradigm shift in the management of buried cables, providing maintenance, discrimination and fault location.

KEYWORDS

OCT Optical Current Transformer.

SM Single Mode fiber optic.

INTRODUCTION

The underground cable installations are a reality that for various reasons begins to impose.

The strong social rejection of the overhead installations, the weather non-dependence of the underground facilities, their own security and their capacity to reach the urban centers, make these facilities an element of greater interest within the transport network of any TSO.

The presence of electric mobility in the cities is going to suppose a strong increase in the mesh needs and as result, a strong increase of this type of facilities is expected.

Despite their clear advantages, they have certain drawbacks. They tend to be unassisted systems or with very precarious maintenance, precisely because of their buried condition. They also present problems in lines of a mixed nature, for the discrimination of where the fault lies, due to the disparity of the characteristic impedance of both lines (aerial and underground). Finally, in case of fault, it is difficult to discern the point of failure, and consequently the times of replacement of the installation.

Currently, alternatives are still being searched to monitor and operate this type of facility in a safe manner. So Cigre has several working groups [1], in which the remote sensing is a constant.

As an alternative we suggest improving the information available about the installation with both: the nominal currents of the cable and the currents of the screens. Conventional current measurement systems require power supply systems and, of course, are not considered passive and therefore maintenance-free.

Optical current transformers, developed with optical fiber, do allow this type of measurement, module and phase, (remote and passive) and the deployed system shows that this approach is feasible. Also, with the contribution of these magnitudes has been resolved in a complete and compact way all the needs of this type of facilities, which would be the Maintenance of the facility and the Discrimination and the Location of the fault.

OPTICAL CURRENT TRANSFORMER (OCT).

The use of fiber optic systems have dramatically increased in the last ten years. Deployment of fiber optics within the field of communication have allowed for features, that until now were considered exclusively academic level.

Optical fibers allow direct measurements of magnitudes relevant to underground power cables, such as current (Faraday effect), temperature and strain measurements (Rayleigh, Raman or Brillouin scattering).

Development of the parts making up a guided optical system, including light sources, amplifiers, polarizers, mirrors, and passive parts, has greatly improved, especially when working within the usual communications window of 1310 nm and 1550 nm.

Some existing fiber optic current measurement solutions based on initial patents, do not allow for the connection of optical transformers and interrogators using standard single-mode fibers of type G652 or G657, as they require polarization-maintaining (PM) fibers for the connection. However, at this time, measurement schemes that do not require the PM method, have been developed, such that the connection link can be deployed using standard single-mode fibers for the communication [2,3].

In this way, it is possible to connect interrogators located in a substation with OCTs, using the single-mode optical communication fibers already installed alongside cables. The passive OCTs do not require any power supply, and they are free from maintenance.

The distance between interrogator and OCT is not the limiting factor, which instead is defined by the following conditions:

- Number of OCTs used per fiber, normally 3, 6 or more.
- Structure of the OCT measurement scheme (Faraday, Sagnac or other effects)
- Emission power; it is feasible to work with

10-24 dBm of light power, especially when working in the 1550 nm band.

- Sensitivity of the used receivers, where it is possible to work with -34 dBm.

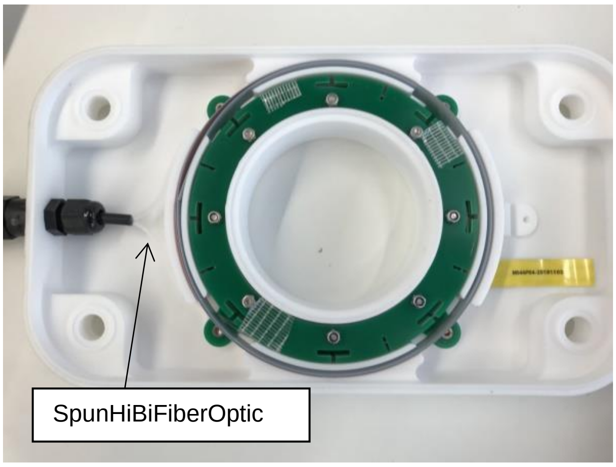

Figure 1 OCT for manhole. With two windings, one oriented to maintenance with 50 meters of fiber and another oriented to protection currents with 4 meters of fiber.

MAINTENANCE.

In underground cables, the maintenance process is very limited.

The main reason for this reality is that cross bonding and grounding boxes are normally buried and the access, in general, is not easy. The currents that flow through the earthing system (screens and ground) are, undoubtfully, clear indicators of the health of the whole cable system and the current's amplitude and phase, gives a complete picture of the status of cable system and of the surrounding environment where it is located, and allows the engineer to make useful comparison with what is expected according to the initial design.

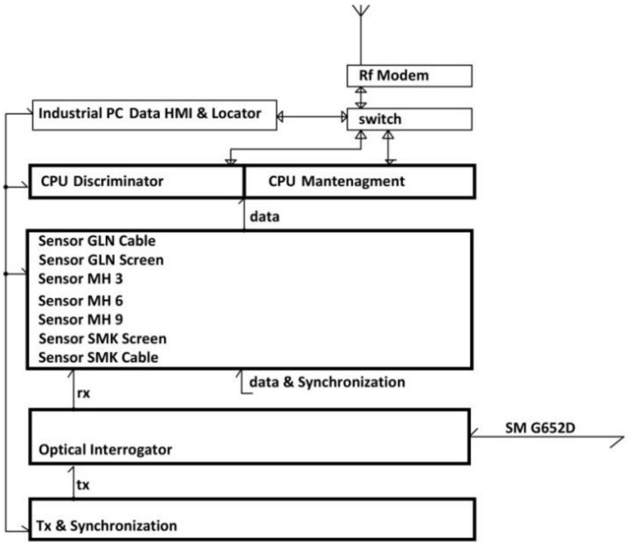

Figure 2 General scheme of the Optical-Electronic system that is located in substation

Therefore, in order to have an improved maintenance of the cable, a model of that cable is needed, developed with EMTP software models or equivalent, and on this model (normally of concentrated parameters) we can feed it with real magnitudes, such as the voltage of operation and the nominal currents.

As a consequence of all this, we will have screen currents with a certain magnitude and phase.

Since these currents in the CMOS system are measured, it is possible to establish deviations of the installation in real time, or by working on their historic data, and thereby improve the health estimators of the installation.

There are very clear situations of maintenance, such as:

- Loss of grounding. In case of loss of grounding, current measurements will be zero. The CMOS system is able to discern signals as low as 2 amps in module and phase.
- Surge arrester short circuit. In that case we would have an unexpected grounding in a transposition. In the initial tests a strong phase change has been detected in the grounding signals.
- Tan Delta. Since the CMOS system is provided with measurement of both the line voltage and the screen currents, both header and ground in module and phase, it is feasible to define a delta tangent.

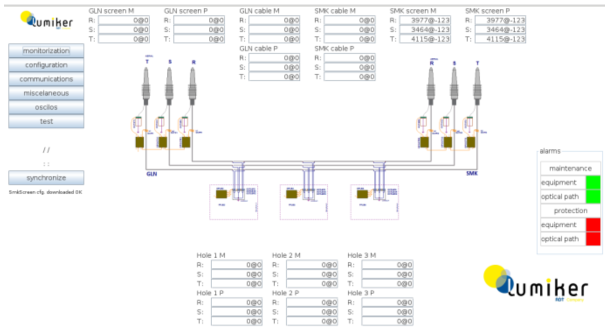

Figure 3 System maintenance screen

The maintenance measures, which in the current installed system would be 26 currents in module and phase, are obtained every 10 seconds. Their dynamic range is from 2 amps up to 400 Amps for screen currents and up to 4000 Amps for the currents flowing through the cable.

The measurement process is as follows:

- In a synchronized way, 26 current buffer and 3 voltage buffer of 25 cycles are filled for each of the magnitudes used in the CMOS system.
- The frequency of the network is determined.
- Cycles are added, interpolating the samples to adjust the frequency of the network with the sampling frequency. This allows reducing the noise but keeping the information related to network harmonics.
- This cycle is available every 10 seconds.

This process is absolutely necessary if the aim is to reduce background noise to calculate homopolar currents.

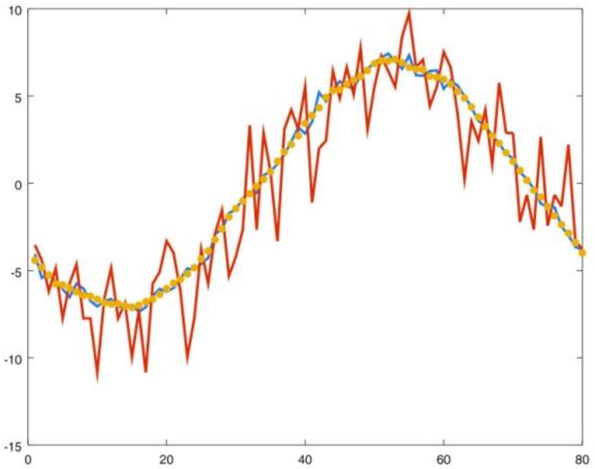

Figure 4 Measurement of five amps primary current. In red the direct measurement, in yellow the result of the synchronized averaging of the signal.

From these measurements it is feasible to determine the following:

- Magnitude and phase of the nominal cable currents (6 currents).
- Magnitude and phase of the screen currents (24 currents).
- Magnitude and phase of the currents that flow to earth, in each of the grounding points (5 currents).
- Estimation of the voltage profile on the screen.
- Estimation of the earth resistance.

All these results are collected, via PC, and are presented continuously on an HMI. They are also sent to a remote server via a radio modem, so that it is not required to interact with the communication systems of the electric company. The files are in ASCII format to facilitate the developing of data processing programs.

DISCRIMINATOR.

In the rather frequent cases of mixed lines (overhead lines and underground cables), the availability of the line as a whole is severely affected by its mixed nature, since the possibility of reclosure after an internal fault is conditioned to the fault being located inside or outside the underground part, including the transition substation's terminations. This discrimination process, which must be very precise, is impossible with the usual protection equipment based on distance relays. Attempts to achieve a sufficient resolution have been made via travelling waves theory [4], as well as by acoustical methods in optical fibers mediated distributed systems type DAS [5].

Another possibility, very clear and much more precise is to develop a differential line protection by taking the current of the line in the cable headers. For the determination of the presence of fault in the cable termination, it is enough to consider the earthing of the cable, knowing that the termination bottle is always supported on a support structure isolated from the ground.

To develop such protection, the only limitation is the measurement of current at both ends of the line and this is entirely feasible with the presence of passive OCTs at that ends.

The protection schemes are absolutely standard, with the definition of through current and differential current, the definition of a trip half-plane plus the contribution of the directionality of the currents.

LOCATION.

Given the amount of information the CMOS system can gather, fault location is also a possibility worth considering since the design of the system, with OCTs at all grounding points, gives a thorough overview of all currents in the earthing system.

The locator algorithm is fed by the information coming from the protection. Specifically, there is an oscillography of 25 cycles (3 of pre-fault and 22 of post-fault), with 80 samples per cycle. The oscillo contains 26 protection current channels, and 3 voltage channels.

This information is collected by the PC when the locator is activated every time a fault is detected.

The location algorithm presents the following blocks:

Discrimination of fault.

It is the result of the fault discriminator process previously described. It is based on conventional line differential protection theory, which aims at determining whether the fault occurred within or outside ofthe cable. Moreover, the discriminator is able to indicate the faulty phase (it is assumed that the fault is always single phase to ground).

Major Section Discriminator (MS) in fault.

In principle, short circuit currents returning on cable screen sum up at the end of each major section (MS), where the three screens are short circuited and solidly bonded. So in an intuitive way a very simple way to know if an MS is faulty or not, would be to apply differential protection theory to the screen currents. If the screen differential current of an MS marks zero, that section would not be in fault.

Normally, nowadays cross bonded systems employ coaxial bonding leads for the grounding of screens at joint locations.This also means that, at joint locations, only the sum of the currents in the two conductors of the bonding leads can be measured.The only points where the screen currents are available segregated are the two cable terminations. This also means that, at joint locations, only the sum of the currents in the two conductors of the bonding leads can be measured.

Taking these three currents individually, we can calculate the positive and homopolar sequences of these currents. If the three currents are very identical, especially in phase, which is what happens if the short-circuit current flows through the screen, but is not a MS in fault, the equivalent homopolar sequence will be very high, and the positive sequence low. Otherwise, we can say that this MS is in fault.

So if we go from left to right (MS 1, 2, 3, 4), we determine if this MS is in fault or not. If it is not, the current of that section is subtracted from the current measured in the coaxial of the next earthing. The current obtained would be the current segregated from the screens of the next MS.

This can be done from right to left as well as from left to right. Both algorithms must match.

Determination of the minorpart in fault.

This is very straight forward by knowing the currents in the screens at the ends of the major section MS. It is enough to apply differential protections theory on the screen currents and, giving the transpositions of screens, together with the information of the phase in fault coming from the phase differential protections, it is determined without possibility of error, which of the 9 minor part of the MS is faulty.

Discrimination of the point of failure.

The algorithm, at this point already knows both the major section MS, with its segregated grounding current, as well as the minor part in fault. Short-circuit currents at their ends are also known.

Without loss of generality, suppose that the fault is in phase B and MS 2 according to the scheme of figure 6.

In this situation, we know the six currents of the cable, since they coincide with those of the terminals, since the capacitive currents are not considered, as they are much lower than the short circuit ones. We also know the six screen currents that exist at the ends of the MS. We do not know the earth resistance and the possible resistance of fault, that although it has low value, since it is a fault in cable, we do not know its value.

If we consider a reasonable model for this short-circuit situation, the only parameters of interest would be the cable and screen resistances, the cable and screen inductances and the mutual inductances between cable-cable, screen-screen and cable-screen.

With these assumptions one can see what the screen circuit would look like, for this short circuit situation.

Since the screen circuits are connected in the final parts of the MS, two meshes are formed, in which the currents are known by direct measurement, and the concentrated parameters of the cable are those obtained from the cable model, and the sum of the voltage of both net must be zero.

This happens regardless of the value that the fault resistance or the earth resistance values may have. It is true that there is some variation in the values of inductance and mutual inductance as a function of the resistivity of the ground, but in the tests carried out with PSCAD, working with values from 100 Ohms / meter to 5 Ohms / meter, we have not found great variations. The behavior is quite stable and we understand that the reason for this is that the resistivity of the terrain is a factor that modifies these values in the same way. If we develop the algorithm in a complete way, the value x is resolved as a result of a division, and this variability affects in the same way the numerator as the denominator, and its effect is canceled.

CABLE MANAGEMENT OPTICAL SYSTEM (CMOS).

As a result, a pilot installation is being developed in Denmark with the following characteristics.

As in all cable systems, there is a parallel installation of single-mode fiber optic layout. This layout is understood as an auxiliary service of the installation, thought primarily for issues related to communications, and therefore it is normal to work with single-mode fibers. Thus it is feasible to place OCTs both in the cable headers and in the earthing of the cable.

Due to the optical structure of the OCT used, it is possible to work with one or with two OCTs, that is, a double winding, without incurring in power losses, and so it has been decided to completely separate the maintenance management of the cable and the discrimination-location, assigning different OCTs for each case.

The TSO (Figure 5) is installing in a 115kV cable that connects GLN substation with SMK substation. The full length of the cable is about 12km and is composed of four Major Sections (MS), with two grounding at the cable header and three grounding at the manholes 3,6 and 9. The rest of the manholes are used to make the necessary transpositions of the screens. This gives a set of 36 minor parts.

The main numbers of this installation are:

- 6 OCT of nominal current measurement (from 10 A - 4000 A) in cable, 3 located in the GLN substation and 3 located in the SMK substation, located 12 km far.
- 6 OCT of measurement of short circuit current measurement in the cable, with a capacity of 60kA (kiloamperes) of measurement, 3 located in GLN and 3 located in SMK.
- 3 OCT maintenance and 3 OCT protection in Main Hole 3, 6 and 9.
- 3 OCT maintenance and 3 OCT protection in screen of the cable header in the GLN substation.
- 3 OCT maintenance and 3 OCT protection in screen of the cable header in the SMK substation.

This gives an amount of 42 OCTs of different type, on a semi-distributed installation of 12 km.

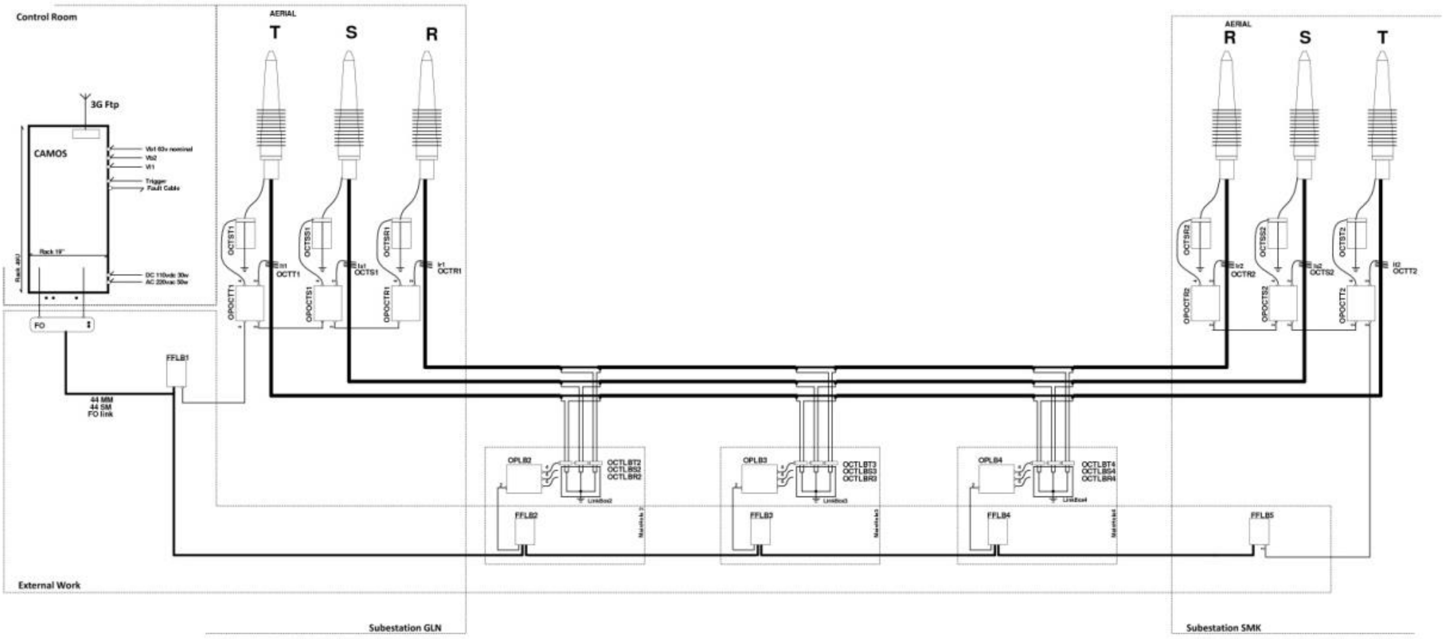

Figure 5. CMOS squeme

CONCLUSIONS

The quick development of optical communications on single mode optical fibers, is opening applications for the use of such fibers, as sensors of magnitudes of great relevance for the electricity sector.

In the case of the current, this magnitude is fundamental for developing new applications, either because new information is provided that until now was very complex to obtain, such as predictive maintenance on cable or the location of the point of failure, either because improves the possibilities over existing ones, in this case, differential protections that provide security of use to the installation.

The deployment of the CMOS system on an TSO cable is demonstrating this new approach. They are deploying 42 OCT (Optical Current Transformer), over distances of 12 kilometers. They are considered very low measures, completely oriented to maintenance, where the precision of the measure and the ability to extract precise information for them, working in the Cloud, to obtain useful information for the network operator. Short circuit situations have also been considered, where the discrimination of the fault, and the quick and truthful location of the point of the fault is the key to increase the service time of the installation.

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[5] Jensen, Christian Flytkjær “Online Location of Faults on AC Cables in Underground Transmission Systems”

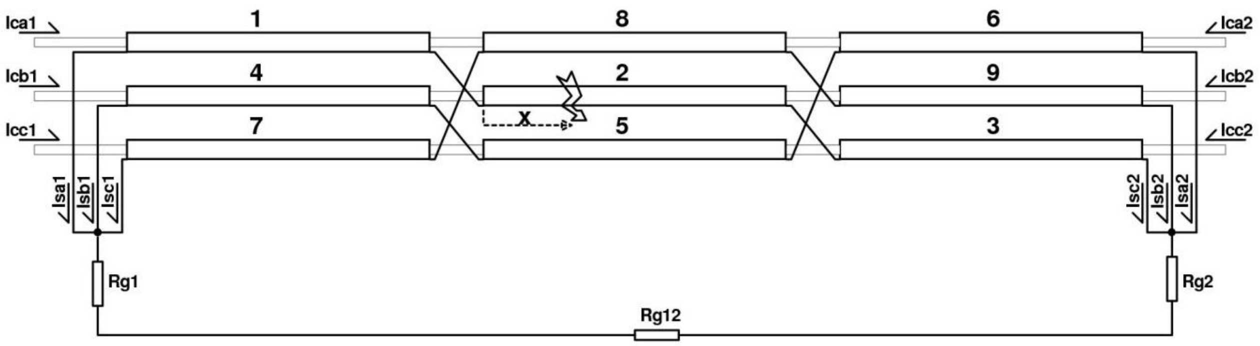

Figure 6.MS fault in minor part 2. The fault phase is and thefault screen is A

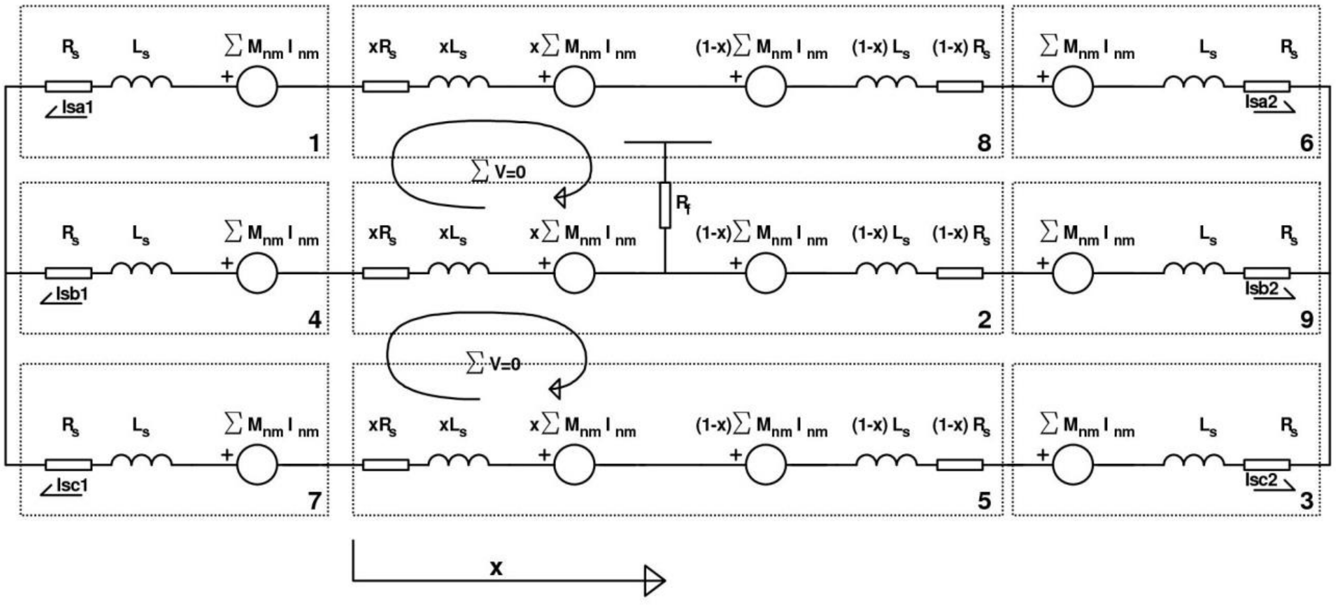

Figure 7. Concentrated parameter model of screen nets for the case raised