CROSS-BONDING FOR MV CABLE SYSTEMS: ADVANTAGES AND IMPACT ON ACCESSORIES DESIGN

Ladislaus KEHL
EUROPACABLE - TE Germany
lkehl@te.com

Ralf MEIER
EUROPACABLE – NKT Germany
ralf.meier@nkt.com

Dario QUAGGIA
EUROPACABLE - Prysmian Group Italy
dario.quaggia.ex@prysmiangroup.com

ABSTRACT

Aim of this paper is to explain the opportunity to introduce cross-bonding connections in Medium Voltage extruded cable systems with high current rating, as usually done on HV cable systems. Cross-bonding connections allow the reduction of problems due to the induced current circulation on metallic cable screen when MV cable systems are solidly bonded, i.e. simply connected to ground potential at the circuit ends.
A new type of MV joint with screen separation will be necessary for performing cross-bonding connections and consequently some specific tests will be required for the qualification of these joints.

1. INTRODUCTION

Cross-bonding grounding schemes are largely used on HV cable systems and they are very common above 72.5 kV voltage class, while classic MV cable systems are usually solidly grounded and without interchanging the cables' screens of the different phases, i.e. the cable metallic screen is directly connected to ground potential at both extremities, in correspondence of cable terminations.

Evolution of MV distribution grid is toward larger power cables with cross-sections above 630 mm², considering the need of increased energy distribution in both ways (supplied to users and received from them). As a result of the higher load currents, high circulating currents will be induced in the metallic screen of MV cables in solidly grounded systems.
Any kind of cable metallic screen is submitted to this phenomenon (Copper wires, Aluminum laminated sheath, Lead shield) but the cable screen could not be designed considering the real values of induced screen current.
High circulating currents in the cable screen can have following negative consequences on cables and accessories:

- High energy losses [1]
- Potential overheating of cables or reduced ampacity
- Overloading and damaging of grounding connections of terminations and screen connections in joints

Cross-bonding schemes can be used to mitigate the effects of induced circulating currents in the screens of MV cables with large cross-sections, leveraging this well-established technology applied for HV cables worldwide.

An insulated interruption of MV joint screen will be required for allowing the separated connection of both screen sides to the cross-bonding wires.

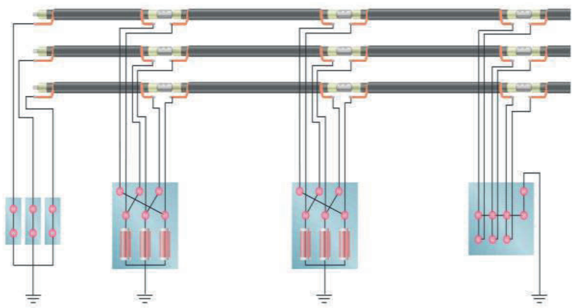

FIG. 1 Cross-bonding connection on HV cable system.

2. EFFECTS OF INDUCED CURRENT CIRCULATION IN MV CABLE SCREEN

Cable screens of MV cable systems in distribution networks are usually solidly bonded at both ends for safety reasons and the easiness of the installation. One of the purposes of the screen of the cables is to protect a person that hits the cable with an excavator or another metallic tool. Short circuit currents are flowing directly from the conductor to the screen and no harmful high voltage potential can reach the person above ground.
The continuity of the screen connection needs to be granted in all systems.
If the screen is solidly connected to the earth on both sides of the cable system, a closed electrical circuit is built through the ground that allows an induced AC current to flow continuously (FIG. 2).
The rms value of this induced current depends on several parameters like frequency, the cable construction, the laying arrangement of the three phases, the current flowing in the conductor itself and the length of the system. The screen current I_m for solid bonded screens can be calculated with the following formula:

$$I_m = \frac{I_n * \omega * \frac{\mu_0}{2\pi} * ln * \frac{2a}{d_m}}{\sqrt{R'_m{}^2 + X'_m{}^2}} \quad [2]$$

Where:
I_n: nominal conductor current;
a: distance between cables (see FIG. 1);
d_m: diameter over the metallic screen;
R'_m: screen resistance/km;
X'_m: screen impedance/km;
ω: 2π f = 314/s (for 50 Hz networks)
$\mu_0 = 4\pi * 10E^{-7} N/A^2$

Influence can be taken on the laying conditions and the screen treatment in order to reduce the current on the screen. A trefoil arrangement of the single core cables has a lower induction than a flat formation with a bigger distance "a" between the phases. Since the current induced in the screen could be however high for large conductor cross-sections with elevated values of I_n, other actions have to be taken into consideration to reduce it.

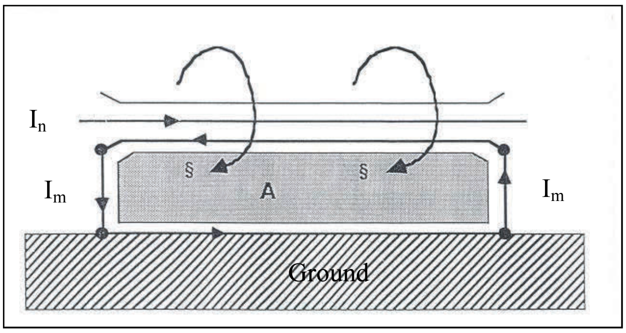

FIG. 2 Principle of induced screen current

In the past, MV distribution networks were often planned and built with an "n-1 safe strategy", that means that cable connections were redundant and continuously loaded around 50% of full load, so that only in case of failure it was loaded at 100% for a limited time. In addition, cable cross sections were of lower values (from 50sqmm to 240sqmm). In this case induced currents in the screens were considered acceptable, as additional losses and reduction of primary current in the conductor were minor.
Nowadays, MV cable systems are also established in renewable energy generation parks that are situated in most cases far away from the connection point of the network. Wind parks for example can have distances of more than 10 km far from the overhead line.
The energy is transported with MV extruded cables (20 – 30 kV rated voltage) and in some cases using the minimum calculated cross section, to reduce investment costs.
An example of typical MV cable used for these connections is the following: 800sqmm Al round stranded conductor with a 35sqmm copper wires screen for a load of 23 MW.
When the wind farm is working at full load, MV cables are highly loaded and the maximum allowable conductor temperature of 90°C for XLPE cable can be reached depending on laying depth, grouping and of course the screen treatment.
With solid bonding screen connection, the circulation of induced currents in the screen could put the cable system in a dangerous situation.

Measurements carried out in the field on XLPE cables with 50sqmm copper screen have shown induced current values up to 70A!

The effects of this service condition could be:

- Overheating of the cable and significant reduction of the system lifetime.
- Failures of the cable accessories connectors due to the thermo-dynamic cycles.
- Damages on joints and terminations because of the hot screen wires.

So MV cable connections are becoming more and more similar to HV cable systems. Therefore also for MV cable systems with high current rating is necessary to perform a correct system design, considering not only the amount of energy to be distributed or transported from point A to B with an optimized cable construction, but also suitable laying conditions and screen connections able to guarantee reliable service conditions, long lifetime and reduced losses.
The applied Cross-bonding systems in HV cable connections to reduce the induced screen currents can be also used in MV connections, although the planning and execution of this is a bit more intense and more knowledge of HV systems is needed.

3. DESCRIPTION OF CROSS-BONDING CABLE SYSTEMS

The name cross-bonding is related to the physical crossing of the cable screens in the joint pit. The joint design needs to be adapted for this purpose, but this will be described later.
In principle, the fact of having a geometrical phase distance of 120° in the 3phase AC network generators is taken and applied to the layout of the cable system.
The induced voltage in the screen is more or less in phase with the conductor current. Dividing the cable route in three equal lengths and connecting the screens from L1 to L2 after the first section, the phase of the L2 current then induces the voltage in the screen at 120° respect to the previous one.
After another section L2 will be "crossed" to L3.
The length of the cable section is responsible for the amplitude of the induced voltage.
Therefore, the lengths must be equal to have the same voltage level in all three phases.
In the ideal case that all sections are having the same lengths, the resulting voltage is zero and consequently no current will flow.

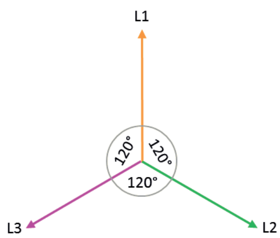

FIG. 3 Induced voltages in a symmetrical arrangement

Having in mind that there are tolerances in installing a system and laying the cables, normally there will be differences and with that a resulting voltage will be still induced and therefore a current will flow. However, this current will be much lower than in solidly bonded systems without cross-bonding.
Practical experiences have shown that in a solidly grounded system where a current of 50 A was measured on the screen, after the introduction of the cross-bonding connection, on the same system the current circulating on the screen was 5A, due to the not symmetrical sections.
In any case the reduction of current circulation on the screen was significant.

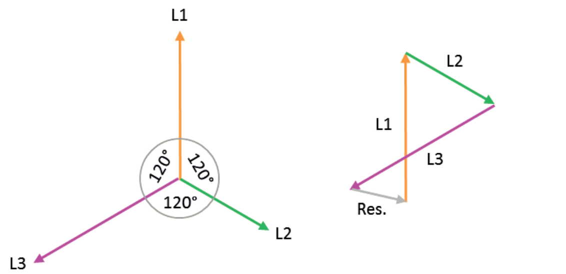

FIG. 4 Induced voltages in a non-symmetrical arrangement with resulting voltage vector

For very long systems, several cross-bonding connections can be made. In this case the system is divided into so-called minor sections that indicate the length from one joint to the next one and the major sections that contain a complete crossed screen system which can be repeated.

The outer sheath of cables and joints needs to be protected from steep, transient over-voltages injected into the cable system from exposed parts of the grid, e.g. lightning impulses from overhead lines or switching surges from equipment. To avoid punctures on the cable's outer insulation due to these over-voltages, Sheath Voltage Limiters (SVL) are used.
In HV cable systems SVL are located inside Link Boxes where cross-bonding leads are connected and transported (FIG. 5).
Several types of SVL are available in the market depending on the use in the field. More common types are made of Zinc Oxide elements.
Wall-mounted or underground applications are possible and need to be protected from moisture and dirt. Access to the SVLs is necessary to test them regularly on their functionality and to enable over-sheath testing with D.C. voltage.
Dimensioning of SVL is related to the continuously induced voltage in the screen and the expected short circuit current in the cable.
In case of a short circuit elsewhere in the network, where the current is flowing through the cable system, the SVL should not trip.
In cases where the transient over-voltages may not arise or the risk of damaging the outer sheath is negligible, the system can be designed without SVLs.
In MV grids the use of SVL is not considered necessary today but it could be used in future if the increase of cable lengths and rated currents will make it useful. Therefore, Link Boxes could be avoided in MV cross-bonding, putting simply in connection the three cross-bonding leads in a water-proof insulated box.

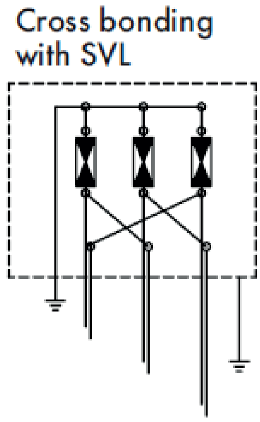

FIG. 5 Cross-bonding scheme of a Link Box with SVL where additionally PD sensors can be placed

As it not very common today to establish MV cable systems with Cross-bonding the possibility of applying the screen crossing afterwards is possible.
Even if a cable is laid and the joints are installed it can make sense to exchange them with Cross-bonding joints or cut the cable at the right position and connect the screens as described to reduce the screen current.

FIG. 6 Example of cross-bonding retrofitting on MV joints already in service, black bonding wires are visible

4. IMPACT OF CROSS-BONDING ON JOINT DESIGN

It is assumed that cross-bonding is only required and beneficial for single core cables with large cross sections at or beyond 630 mm². 3-core cables or twisted single core cables in general will very unlikely benefit from cross-bonding due to the narrow arrangement of the cores. No matter which cross-bonding scheme shall be applied to a MV cable system the following additional requirements need to be considered for MV joints:

- terminal for the cable screen to be interconnected to another cable screen terminal
- sufficiently high dielectric withstand capability between the individual cable screens (specifically between both sides of the joint but also between the joints and their cross-bonding connections)
- Prevent from moisture ingress into the cables and joints along the cross-bonding leads

The latter requirement is typically the most challenging one and there are at least two different concepts which can be followed. The first concept builds on an additional housing, which protects and seals all three cable joints and their cross-bonding connections. The second concept requires a modification of the existing joint design, breaking out the screen connection from the fully sealed joint and sealing and insulating the three cross-bonding connections individually and outside the three joints. The latter one appears to be the most flexible one since the arrangement of the three joints is not pre-defined by the additional casing and can be adjusted to the conditions on site. The downside is that all cross-bonding connections need to be sealed and insulated individually to prevent from moisture ingress and breakdown to ground.
On FIG. 7 and 8 examples of MV joints designed for cross-bonding applications are shown.

FIG. 7 Example of a heat shrink shield-break joint with sealed breakout integrated into the outer protection sleeve

For both concepts an electrically insulating section must be introduced into the joint which separates the cable screens at one side of the joint. For higher flexibility during the installation the joint body, it should remain symmetric which means that it shall be possible to establish the screen interruption on either side of the joint. This enables the jointer to decide during the installation on-site which cable screen is to be used to ground the joint body itself.

FIG. 8 Example of a cold shrink joint body with screen separation and copper mesh connected to the left side of the cable screen

In HV cable systems it is common to use either single core cross bonding leads or concentric leads whereby concentric leads are typically used in combination with accessible link boxes being located further away from the cable system itself. The individual connections are established in those boxes and can be removed for cable sheath testing of each individual cable segment. In MV cable systems link boxes are currently not used. Therefore, using single core cross bonding cables is the preferred method for MV systems. All connectors for jointing the single core cables with the joints' screen connection wires should be of blocked type to avoid penetration of water between joints. They also need to be insulated against ground and arranged in a way to avoid direct contact with each other to minimize the risk of electrical breakdown during short circuit conditions.

5. TESTS FOR QUALIFICATION OF MV SECTIONALIZED JOINTS

IEC 60502-2 recommends carrying out electrical tests of the cable and the accessories after the installation has been completed. Many utilities follow this recommendation and perform at least a d.c. voltage test of the over-sheath after installation. Cross-bonding as well as straight-through joints must be able to withstand this stress reliably.
Although the mentioned D.C. voltage test of the over-sheath is commonly carried out nowadays, HD 629-1 S3 dispenses with a specific withstand voltage test on all joints for qualification. Only the measurement of the insulation resistance between the screen and the environment at a voltage between 100V and 1000V according to EN 61442 is required. Following this practice, an extension of the insulation resistance tests (item 3 and 7 of Table 12 of HD 629-1 S3) should be adequate as well to cover the additional insulation between the two cable screens of cross-bonding joints. The advantage is that the corresponding measurements could be carried out at the same time without significant additional efforts.

The test requirements of HD 629-1 for insulation resistances could then simply be extended to:

- Conductor to screen(s) 10^3 MΩ minimum
- Screen(s) to water 50 MΩ minimum
- between screens 50 MΩ minimum (last measurement for shield-break joints only)

Some utilities have introduced additional requirements on joints like the so-called robustness test (see HN 33-E-03 and GSCC004). This test could also be easily extended by an insulation resistance measurement to cover shield-break joints after the thermal cycles.

Designers of shield-break joints should, however, keep in mind that the joints also need to pass typical commissioning tests carried out on-site. Following IEC 60502-2 a D.C. voltage test of the over-sheath is recommended after cable and accessory installation.
For test levels and duration reference is made to IEC 60229, which specifies "a D.C. voltage of 4 kV per millimeter of specified thickness of extruded over-sheath … with a maximum of 10 kV D.C. … for a period of 1 min.". In practice, on-site sheath integrity tests are typically carried out at 5 kV D.C. for 1 minute up to 15 minutes. Unless this test is carried out on all 3 phases simultaneously, the shield-break section within the joint needs to withstand this stress as well.

For cable systems where SVLs are considered necessary, additional impulse tests following IEC 60840 are recommended. Most utilities, which in the past have decided to apply cross-bonding schemes to selected MV cable systems, took the conservative approach to follow requirements of IEC 60840, defined for HV systems, being no MV Standards available on this subject up to now. They specified a D.C. test to be performed for 1 min. at 20 kV and impulse tests with an amplitude of 30 kV between shields and ground and 60 kV between the shields.
However, these test values seem to be too severe for MV cable systems and specific tests for MV cross-bonding should be standardized in future.

6. CONCLUSIONS

Cross-bonding connection of cables metallic screen is recommended for long MV cable systems with high rating currents (e.g. conductor cross-sections above 630 mm² with loads close to 100% for long periods).

In cross-bonded MV cables the induced current flowing on the metallic screens can be avoided or effectively reduced compared to traditional solidly grounded cable systems.
The advantage of induced current limitation due to cross-bonding is the reduction of losses, thermal ageing and risk of failures due to overheating of screen connections.

Cross-bonding connection needs the transposition of the screens dividing the cable lengths into at least 3 sections. Consequently, joints must have an insulated screen interruption that can be integrated in the MV joint or made close to it.

Retrofitting MV cable systems with cross-bonding joints is possible and may be performed even without replacing the joint's main insulation body.

A new specific testing procedure has been suggested for the qualification of MV cable systems designed for cross-bonding.

REFERENCES

[1] Dr. J. Jakubowski et. al., 2011, "Cross-bonding in middle voltage distribution grids, as a method of energy efficiency improvement", *21st International Conference on Electricity Distribution*, paper 0438.

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