

A Comparison of Special Bonding Techniques for Transmission and Distribution Cables under Normal and Fault Conditions

Roberto Candela, Antonio Gattuso
Prysmian Electronics srl

Palermo, Italy

Eleonora Riva Sanseverino, Gaetano Zizzo
Department of Engineering
University of Palermo
Palermo, Italy

Massimo Mitolo
Electrical Department
Irvine Valley College
Irvine, USA

Abstract—In this paper, a review of the existing special bonding techniques for medium voltage (MV) and high-voltage (HV) cables is presented. Special bonding techniques have the purpose of reducing sheath currents, thereby limiting copper losses and the reduction of the ampacity of cables. The literature review shows various bonding techniques and how these have evolved over the years thanks to new technologies. Simulations of each technique are performed in MATLAB/Simulink, to compare their strengths and drawbacks both under normal conditions and in the presence of a single-line-to-ground fault.

Keywords—special bonding techniques, reactance bonding, cross bonding, sheath bonding transformers.

I. INTRODUCTION

As reported by IEEE standard 575-2014 [1], the valuable characteristics of single-core cables, which include low power losses and high dielectric strength, have promoted their large diffusion in high-voltage (HV) and medium-voltage (MV) power networks. The issues associated with their use, such as currents and voltages induced in metal sheaths and the stress on the insulation have also been studied [2], [3].

This paper presents the analysis of special bonding techniques for the metal sheaths, discusses their relevant characteristics and provides indications regarding strengths and drawbacks of each technique.

Although a similar analysis is present in literature [4], this paper offers the results of MATLAB/Simulink simulations of the most common special bonding techniques, to allow a comparison of their effectiveness both under normal and ground fault conditions. The model used for the simulations has been presented in [5], [6] and is based on the same approach proposed by CIGRE in [7].

The paper is organized as follows:

- Section II describes the single-core cables used nowadays and discusses in which cases it is convenient to adopt special bonding techniques;
- Section III lists the various special bonding techniques described in technical literature [1], [4], [8]-[12], [15];
- In Section IV the mathematical model for simulating the various special bonding techniques implemented in MATLAB/Simulink is presented;
- In Section V, simulations are performed both under normal and ground fault conditions for the special bonding techniques and the results are discussed;

- Section VI reports the conclusions of the work.

II. SINGLE-CORE CABLES FOR MV AND HV SYSTEMS

The IEEE standard 575-2014 [1] provides indications for the cable types currently in use in distribution and transmission power lines.

Single-core cables use a coaxial design, where different layers are wrapped around the conductor (copper or aluminum, in strands or solid construction):

- Insulation: generally impregnated paper, EPR or XLPE;
- Metal sheath: concentrically applied or helically applied;
- Semiconducting layers.

The sheath is usually covered with an extruded polyethylene layer (PE), which protects the sheath from corrosion phenomena.

The most common sheath configuration for distribution-class cables is concentric wires. For transmission-class cables, which incorporate an impervious moisture barrier to protect the insulation from water treeing, tubular lead sheaths are normally employed. The tubular sheaths are extruded as a continuous layer over the cable core, and also provide the function of the metal sheath. Recent cable designs have replaced lead with extruded corrugated aluminum sheaths and various combinations of corrugated and flat copper tapes in conjunction with copper wires.

The varying magnetic field, generated by the current flow through the central conductor, couples with the metal sheath and any other adjacent conductor; if the sheath is part of a conductive loop, a current is induced through it. Resistive losses, due to the currents circulating in the sheaths, contribute to an increase in the cable temperature, which therefore, reduces its ampacity.

In the presence of heavier loads and in circuits with single-core cables, the losses due to sheath currents can be large.

The losses in the sheaths also increase with the spacing between cables, in particular when they are connected to ground at several points. Single-core cables are usually installed with a higher spacing, for example when they are placed in separate ducts or when they are directly buried in spaced configurations. When the cables are spaced, the currents circulating in the sheaths are significantly higher. A greater spacing reduces the effects of mutual heating, but increases the magnetic coupling effect, therefore, the losses

due to sheath currents increase, with a consequent reduction in the cable ampacity.

The sheath design optimization consists of balancing the choices between designs, materials, electrical properties, and economics in the selection of the cable metal sheaths [1]. For distribution-class cables, sheath losses may be reduced by increasing the impedance of the sheath, through a reduction of its metal content. However, this solution may compromise the ability of the sheath to carry ground-fault currents during the fault clearing time. In particular, the fault duration as a design parameter for the sheath must include the delay introduced by the possible failure of the primary protective device before the operation of the backup protection. The maximum allowable sheath temperature is usually specified for the worst-case condition and the amount of metal of the sheath is provided as a fraction of the cross-sectional area of the conductor.

Based on the above, the reduction of sheath losses is achieved through sheath grounding methods, usually referred to as special bonding techniques.

Studies have shown that if the electric loops comprising the sheath are interrupted (e.g., single-end sheath bonding), the sheath currents are reduced, however a sheath voltage rise, even hazardous, may occur at the end of the cable run. Special connections between cable sheaths and ground have been developed to limit sheath voltages, and, at the same time, minimize the sheath currents.

Such special connections are usually employed to transmission lines, characterized by longer runs and higher currents; however, they can also be used for distribution circuits, where the reduction in copper losses are beneficial.

Early cable design called for the sheath to be in direct contact with the soil, which also caused corrosion problems. To lower the risk of step voltages, limits have been recognized for the permissible sheath voltage. The application of special bonding techniques may cause significant voltages on the sheath during ground-faults and other abnormal operating conditions; therefore, insulating electrical properties are exploited, to meet the voltage requirements.

In this contest, it is important to take into account cost considerations, as they may not justify the application of special bonding techniques for distribution cables, which consists of multipoint solidly grounded connections of the metal sheath.

III. SPECIAL BONDING TECHNIQUES

The purposes of the special bonding techniques are:

- reduction in the power losses of the sheaths, and increase the cable ampacity;
- reduction in the voltage normally induced in the sheaths and between sheath and the ground;
- limit overvoltage during fault or abnormal operating conditions.

It is also important to avoid excessive power losses through the sheath bonding devices and limit size and cost of such devices. The major special bonding techniques are listed in the following sections.

A. Solid bonding

The sheaths are bonded together and solidly grounded at specific points (Fig.1).

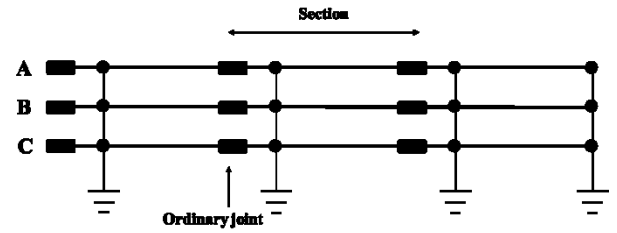


Fig. 1. Solid bonding technique.

This technique is simple and does not require special devices. However, sheath losses may be high, especially if cables are in separate wireways.

B. Bonding one end only of sheaths to an auxiliary cable

Only one end of every length of sheath are bonded together and to a dedicated auxiliary cable (Fig. 2.)

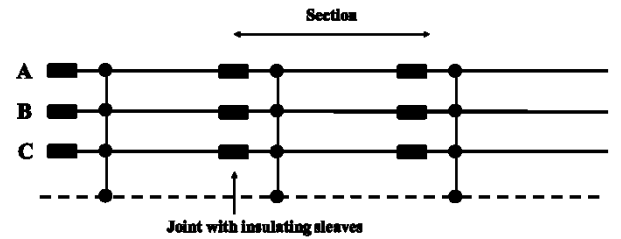


Fig. 2. Bonding to auxiliary cable.

This solution may be rather expensive due to the presence of an extra duct and auxiliary cable. As reported in [4], this arrangement has been adopted by utilities for cables connecting potheads, transformer neutrals, etc, where other bonding techniques may not be readily applicable.

C. Reactance bonding

This type of bonding was implemented for the first time in 1914 by L. Emanuelli [9]. Induced voltages in sheaths (e.g., lead pipes) increase with the length of cables and the load current magnitude. For compensating the induced voltages, Emanuelli used a transformer in which the primary winding is connected in series with the conductor, whereas the secondary winding is connected to the sheath properly sectioned. The transformer is designed to obtain the secondary winding voltage equal and opposite to that induced in the sheath.

In 1920, P. Capdeville [10] replaced the transformer with impedances connected in series with the cable sheaths with their mid-points grounded.

Another method was implemented by R. W. Atkinson in 1924 [11]. Iron core reactance coils are connected in series with the sheaths and grounded at their mid-points. An additional result provided by the iron cores is the limitation to the magnitude of sheath voltages under fault conditions. In fact, during normal operation, the iron cores operate close to saturation and draw a low exciting current. However, in correspondence with a sheath voltage increase caused by abnormal currents, the iron cores saturates considerably reducing its overall impedance. A high current will circulate and the induced voltage in the sheath is therefore reduced. This system presents some issues:

- Circulation of third harmonic sheath currents caused by the iron core that operates near the saturation point;
- The saturation condition of the iron core can be reached with normal operating currents;
- Considerable cost.

An example of reactance bonding is shown in Fig. 3.

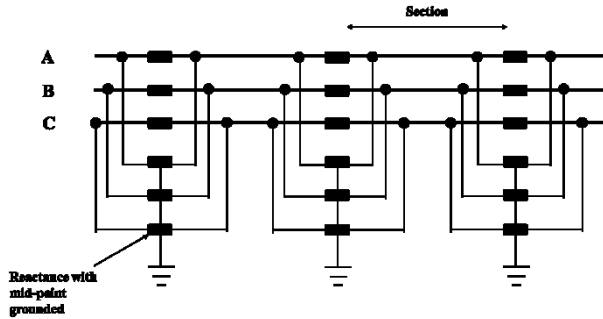


Fig. 3. Reactance bonding technique.

D. Resistance bonding

This type of connection is similar to the reactance bonding, with resistances used in place of reactors. This solution presents much greater thermal issues than reactance bonding and, for this reason, is not commonly used.

E. Cross-bonding: general considerations

Cross-bonding is realized by subdividing the cable shield into sections, referred to as minor sections; each minor section is the length of the cable between sheath sectionalizing insulators, and between sheath insulators and sheath end-bells at the cable terminations [1]. The sheaths are cross-bonded so as to cancel the total sheath induced voltage in three consecutive sections and obtain a considerable reduction of the sheath currents.

In particular, the sheath currents vary according to the following factors:

- Cable laying: if the cables are laid at the ends of an equilateral triangle, a perfect balance of the voltages is obtained, thereby eliminating completely the sheath currents;
- Distance between cables: as already said, by spacing the cables, a variation in the induced currents in the sheaths is obtained;
- Difference in length between cables: if the cables of a multiphase system have different lengths, an imbalance of the currents in the sheaths occurs.

The various types of cross-bonding connections, are explained in the next sections.

F. Continuous cross-bonding

In 1914, Emanuelli first proposed the continuous cross-bonding of cable sheaths along the complete line [9] (Fig. 4). This method can be used for cables with different lengths of minor sections, with a number of minor sections not multiple of three. As per IEEE standard 575-2014 [1], the sheaths may be connected together and grounded at the beginning and at the end of the line.

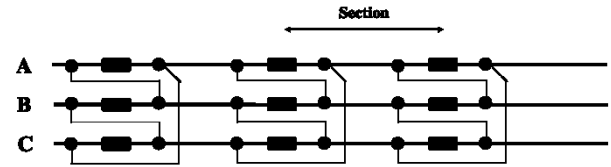


Fig. 4. Continuous cross-bonding technique.

G. Sectionalized cross-bonding

This cross-bonding system, also called Kirke-Searing bonding [1], is used when the number of minor sections is multiple of three. This method ensures a perfect compensation of sheath currents when cables lay at the top of an equilateral triangle and when the cable lengths are perfectly equal. Otherwise, the total induced sheath voltage may still cause the circulation of a current. The sheaths are grounded every three sections (Fig. 5).

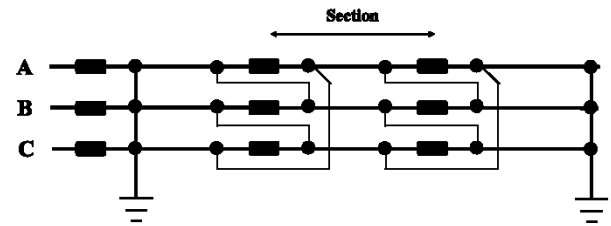


Fig. 5. Sectionalized cross-bonding technique.

H. Modified sectionalized cross-bonding

This version can also be used when the number of minor sections is not divisible by three. The voltages can be balanced by dividing a minor section into two subsections with the following one of the two sequences:

- Subsection - minor section - minor section - subsection;
- Subsection - minor section - subsection - minor section.

I. Mixed systems

When the number of the minor sections is not divisible by three, a system consisting of a mixture of sectionalized cross-bonding and single-point bonding may be implemented.

An example of a mixed system is the one proposed in [12]. In this bonding connection method, cross-bonding is carried out together with the use of reactors placed in series with one of the cross-connected sheaths (Fig. 6), to achieve a further reduction of the current. This system allows lower currents compared to cross-bonding in the case of a not perfectly balanced system.

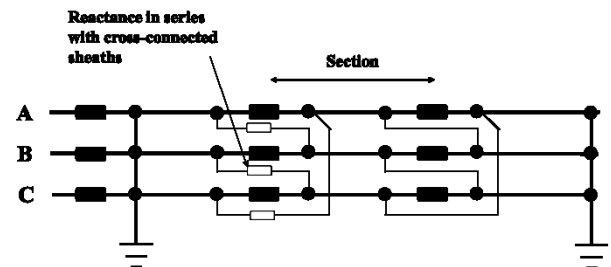


Fig. 6. Mixed system technique.

J. Sheath bonding transformers

Reference [4] proposed a type of sheath connection employing a transformer. The transformer has three primary windings wound around an iron core, and a single delta-connected secondary winding wound around the three legs of the transformer. A cheaper version may also be realized by replacing the secondary winding with a copper bar.

The characteristics of this solution are:

- High three-phase and minimum single-phase impedance;
- Very low losses;
- Absence of harmonic currents;
- Low installation costs.

However, as reported in [8], problems of overvoltages in the use of multiple sheath bonding transformers have been identified. Therefore, a careful study before installation is required. This technology was subsequently modified and patented [13]. In the newer version, two iron cores are present to prevent the induced voltages in one of the cores from affecting the other. The secondary winding is no longer present, whereas the primary windings are zig-zag connected to reduce eventual single-phase fault currents. Finally, a special bonding connection that uses Voltage Transformers and Current Transformers has been proposed quite recently in [14]. The purpose of this technology is to generate electromotive forces (e.m.f.) equal and opposite to those of the sheaths (Fig. 7). The primary winding of Transformer 1 in Fig. 7 is an extension of the phase conductor, therefore, the primary current is the load current. The secondary winding of Transformer 2 is the “abcd” loop shown in Fig. 7. In the secondary winding, two e.m.f. E_t and E_c induced by Transformer 1 are presents. By realizing the transformers to have $E_t + E_c = 0$, no current will flow in the sheath.

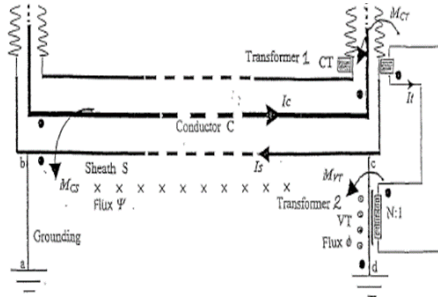


Fig. 7. Special bonding technique proposed in [14].

This solution is convenient for the following reasons:

- The voltage between the sheaths, and between sheaths and ground is nominally null;
- In case of fault, there is no risk of sheath insulation failure;
- The method is passive and adjusts automatically to the prevailing load current through the cable.

IV. MATHEMATICAL MODEL

With regard to the implementation of the mathematical model of a minor section, Carson's theory was used to define

the self- and mutual-impedances of underground conductors taking into account the effect of ground [17]-[20]. Self- and mutual-impedances of conductors and shields are triggered by the effects of magnetic fields, generated by a current-carrying conductor in the presence of other conductors and the ground, and are given by the following formulas:

Self-impedance per unit of length:

$$\dot{z} = r + \pi^2 \cdot f \cdot 10^{-4} + j \cdot \omega \cdot \frac{\mu_0}{2 \cdot \pi} \cdot \ln \frac{2 \cdot H_E}{0.78 \cdot r_c} \quad (1)$$

Mutual-impedance per unit of length:

$$\dot{z}_m = \pi^2 \cdot f \cdot 10^{-4} + j \cdot \omega \cdot \frac{\mu_0}{2 \cdot \pi} \cdot \ln \frac{2 \cdot H_E}{D} \quad (2)$$

where:

- r is the electrical resistance of the conductor per unit of length [Ω/km];
- D is the distance between the two conductors [m];
- f is the frequency of the current [Hz];
- l is the length of the conductor [km];
- ω is the angular frequency of the system [rad/s];
- μ_0 is the magnetic permeability of air [H/km];
- $2H_E$ is the distance between the equivalent conductor representing the earth and the conductor [m];
- r_c is the radius of the conductor [m];
- ρ_E is the soil resistivity [Ωm].

and:

$$H_E = 330 \cdot \sqrt{\frac{\rho_E}{f}} \quad (2)$$

The same formula was used to evaluate the impedance of the sheaths, taking into account its electrical resistance and the size of the equivalent conductor.

Based on the above equations, the model of a minor section was implemented in MATLAB/Simulink environment, as shown in Figure 8. The model includes the cable's capacitances between the phase conductors and the sheaths and allows the simulation of various configurations of a generic line composed by more minor sections.

As shown in Figure 8, A, B and C are the phase conductors and SA, SB and SC are the cable sheaths. The capacitance, the self- and the mutual-impedance blocks adopted in the circuit representation of the minor sections have been highlighted in Fig. 8.

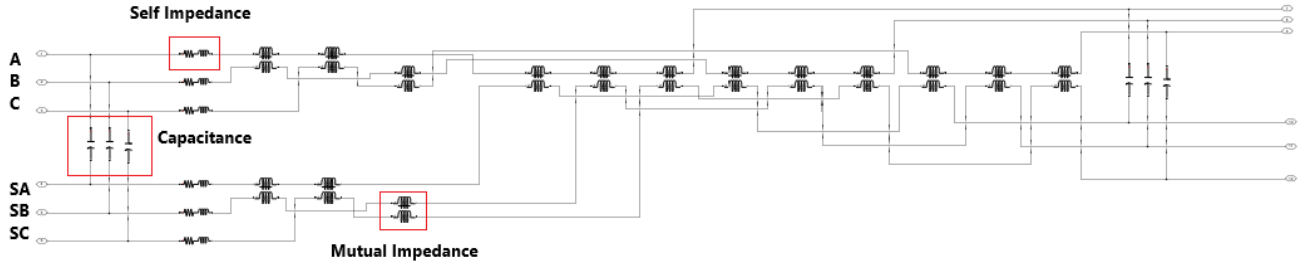


Fig. 8. Representation of a minor section in Matlab/Simulink environment.

V. COMPARISON BETWEEN SPECIAL BONDING TECHNIQUES

In this section, the above-described special bonding techniques are compared through simulations in MATLAB/Simulink environment, for the case of a line operating in Italy, both under normal and single-line-to-ground fault conditions

The simulated cases are the following:

- Case 1: reactance bonding;
- Case 2: resistance bonding;
- Case 3: continuous cross-bonding;
- Case 4: sectionalized cross-bonding;
- Case 5: mixed system;
- Case 6: single-sheath bonding.

The line, with a total length of 1380 m, is divided into 5 minor sections. The minor sections, for technical reasons, have different lengths:

- Minor section 1: 407 m;
- Minor section 2: 197 m;

- Minor section 3: 233 m;
- Minor section 4: 220 m;
- Minor section 5: 323 m.

The supply voltage is 380 kV, the load current through the line is 1,500 A. The cable is laid flat and the distance between two adjacent conductors is 20 cm. Table I lists the technical specification of the cable.

TABLE I. TECHNICAL SPECIFICATION OF THE CABLE.

Cable data	
Size	2500 mm ²
Sheath resistance	0.085 Ω/km
Ø	143 mm

A. Normal Operating Conditions

1) Case 1: reactance bonding

The model is shown in Figure 9 (a detailed explanation of how the simulation model was performed is presented in [5]). The red box in Fig. 9 identifies the reactor (1 Ω) with the mid-point grounded connected to the sheath, as represented in Fig. 3. The values of the sheath currents and voltages are shown in Table II.

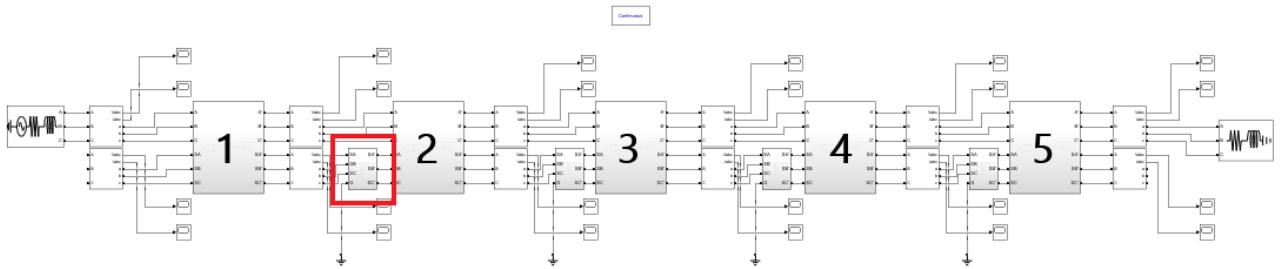


Fig. 9. Simulink model – Case 1: reactance bonding.

The results show low value of currents and voltages, however this method is not ideal due to high dissipation problems.

2) Case 2: resistance bonding

The model is the same as in Fig. 9 but, in this case, the red box identifies the resistor. The resistors have been chosen with the same impedance as the reactors of Case 1, so as to compare the results with the same impedance. The values of the sheath currents and voltages are listed in Table III.

The results show that, with the same impedance, the results are similar to case 1. However, in this case higher energy losses occur.

TABLE II. VOLTAGES AND CURRENTS – CASE 1: REACTANCE BONDING.

Sheath	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	22	15.6	45	31.8
B	14	9.9	28	19.8
C	19	13.4	37	26.2

TABLE III. VOLTAGES AND CURRENTS – CASE 1: RESISTANCE BONDING.

Sheath	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	20.6	14.6	41.3	29.2
B	14	9.9	28	19.8
C	18.4	13	36.8	26

3) Case 3: continuous cross-bonding

The model is shown in Fig. 10. In this case, the sheaths are cross-connected at the end of each minor section. The values of the sheath currents and voltages are reported in Table IV. In this case, the currents circulating in the sheaths are quite high due to the absence of any compensation; this method is therefore not recommended for this line.

TABLE IV. VOLTAGES AND CURRENTS – CASE 3: CONTINUOUS CROSS-BONDING.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	37	26.2	217	153.5
B	48	33.9	451	319
C	30	21.2	395	279.3

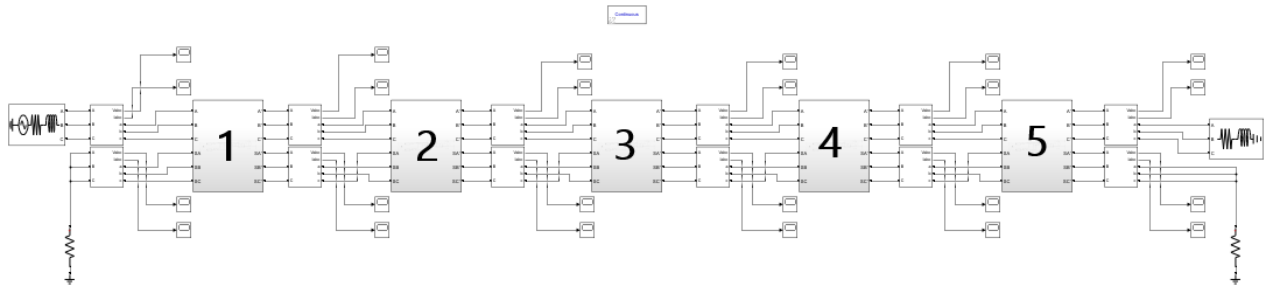


Fig. 10. Simulink model – Case 3: continuous cross-bonding.

4) Case 4: sectionalized cross-bonding

The model is shown in Fig. 11. In this case, the screens are cross-connected between sections 2, 3 and 4. The values of the sheath currents and voltages are reported in Table V.

Compared to the previous case, the currents are significantly reduced, whereas the voltages are practically unchanged. This configuration is preferable to the that of Case 3.

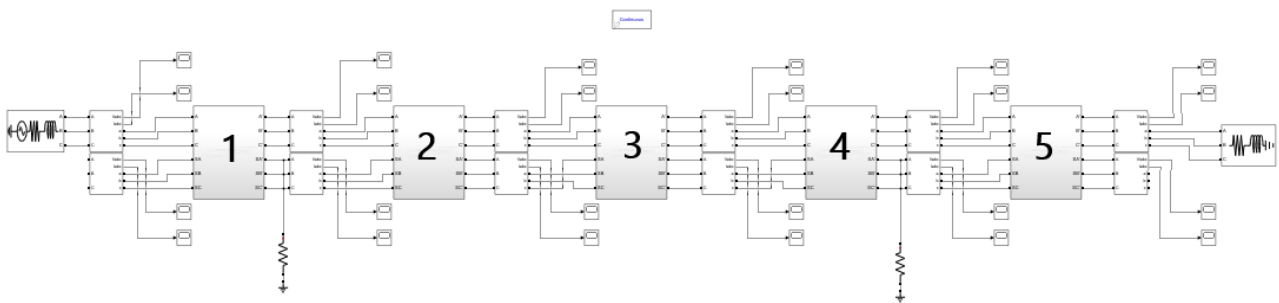


Fig. 11. Simulink model – Case 4: sectionalized cross-bonding.

TABLE V. VOLTAGES AND CURRENTS – CASE 4: SECTIONALIZED CROSS-BONDING..

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	47	33.2	69	48.8
B	22	15.6	32	22.6
C	44	31.1	97	68.6

5) Case 5: mixed system

The model of the line is shown in Fig. 12. In this case, the screens are cross-connected between sections 2, 3 and 4; in series with the cross-connected sheaths, three reactors of value 0.1Ω are installed. The values of the sheath currents and voltages are reported in Table VI. This configuration is the most effective, since the magnitude of the sheath currents is lower than that of all the other cases.

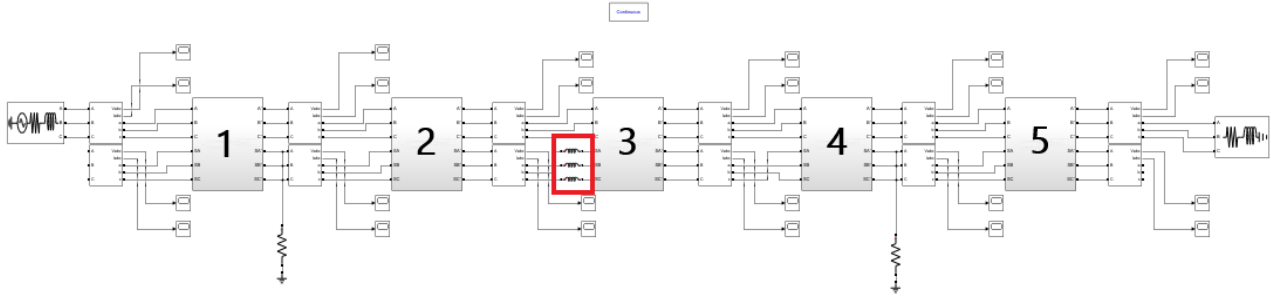


Fig. 12. Simulink model – Case 5: Mixed system.

TABLE VI. VOLTAGES AND CURRENTS – CASE 5: MIXED SYSTEM.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	46	33.5	32	22.6
B	22	15.6	8	5.7
C	42	29.7	67	47.4

6) Case 6: single-sheath bonding

The sheaths are cross-connected between sections 2, 3 and 4 and the sheath of one cable used as a bonding conductor. The values of the sheath currents and voltages are reported in Table VII. In this configuration, modest sheath currents flow and the highest current circulates through the sheath used as the bonding conductor.

TABLE VII. VOLTAGES AND CURRENTS – CASE 6: SINGLE-SHEATH BONDING.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	44.5	31.5	8.8	6.2
B	23.1	16.3	33.4	23.6
C	40.7	28.8	9	6.4

B. Fault conditions

The six special bonding techniques are compared in the event of a single-line-to-ground fault. The fault is simulated occurring between phase A and ground, at the beginning of the simulation and has a duration of $t_F=0.3$ s.

Tables VIII to XIII show the values of the sheath currents and voltages for the six cases.

TABLE VIII. VOLTAGES AND CURRENTS – CASE 1: REACTANCE BONDING.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	2380	1680	4740	3350
B	1980	1400	3950	2790
C	1740	1230	3480	2460

TABLE IX. VOLTAGES AND CURRENTS – CASE 2: RESISTANCE BONDING.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	2850	2010	5700	4030
B	2480	1750	4950	3500
C	2230	1580	4460	3150

TABLE X. VOLTAGES AND CURRENTS – CASE 3: CONTINUOUS CROSS-BONDING.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	4270	3020	6580	4650
B	4850	3430	19950	14100
C	3230	2280	11800	8340

TABLE XI. VOLTAGES AND CURRENTS – CASE 4: SECTIONALIZED CROSS-BONDING.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	3480	2460	14540	10280
B	3450	2240	15350	10850
C	3610	2550	16750	11850

TABLE XII. VOLTAGES AND CURRENTS – CASE 5: MIXED SYSTEM.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	3540	2500	14000	9900
B	3380	2390	14470	10230
C	3480	2460	15220	10760

TABLE XIII. VOLTAGES AND CURRENTS – CASE 6: SINGLE-SHEATH BONDING.

	Voltages		Currents	
	Peak value [V]	RMS value [V]	Peak value [A]	RMS value [A]
A	2950	2090	10	7
B	3220	2280	40800	28850
C	2730	1930	10	7

In Case 1 (i.e., reactance bonding), the sheath currents are in the order of thousands of Amperes and the voltages of hundreds of Volts.

In Case 2 (i.e., resistance bonding), the simulation provided results similar to those of Case 1. These results were expected since Reactance and Resistance Bondings are implemented for the case study with the same impedance, and they present the same behaviour also in normal operation.

In Case 3 (i.e., Continuous cross-bonding), the sheath currents are much higher than in the previous cases, with potentially dangerous situations.

In Case 4 (i.e., sectionalized cross-binding), currents and voltages are similar respect to Case 3 but are more

fairly distributed. Therefore, case 3 and 4 show the same effects different from operation conditions.

In Case 5 (i.e., mixed system), the results are similar to the previous case.

In Case 6 (i.e., single-sheath bonding), in the presence of a fault, the current affects only one of the three sheaths, and is much higher than in the previous cases.

VI. CONCLUSIONS

In this paper, based on [21], the authors have reviewed the major special bonding techniques present in technical literature and commonly adopted in practice.

This study has discussed strengths and weaknesses of the special bonding techniques for cable lines.

Simulations of special bonding techniques were performed for a cable transmission line in Italy through computer models devised by the authors for both normal and fault conditions. The differences between each technique have been showed with a numerical example.

The simulations have confirmed that some special bonding configurations can bring benefits to the system in normal operating conditions, reducing sheath currents and losses.

Finally, the simulations have shown that the mixed system and single-sheath bonding are the most effective configurations for the line under study under normal operating conditions. However, the excessive current present in phase B under fault conditions for the single-sheath bonding configuration, make the mixed system technique the most effective.

ACKNOWLEDGEMENT

This work has been carried out within the framework of the International Research Agreement titled “*Innovative Solutions for Safety in Power Systems*,” between the University of Palermo (Italy) and the Irvine Valley College (USA).

REFERENCES

- [1] IEEE Standard 575, 2014: IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV Through 500 kV.
- [2] A. Imburgia, P. Romano, G. Chen, G. Rizzo, E. Riva Sanseverino, F. Viola, G. Ala, “The Industrial Applicability of PEA Space Charge Measurements, for Performance Optimization of HVDC Power Cables”, *Energies*, Vol. 12, article No. 4186.
- [3] A. Imburgia, P. Romano, G. Ala, E. Riva Sanseverino, G. Giglia, “The Role of Right Interpretation of Space Charge Distribution for Optimized Design of HVDC Cables”, *IEEE Transactions on Industry Applications*, Vol. 55, No. 6, 2019, pp. 7165-7174.
- [4] H. Halperin, K. W. Miller, “Reduction of Sheath Losses in Single-Conductor Cables”, *Transactions of the American Institute of Electrical Engineers*, Vol. 48, No. 2, 1929, pp. 399-414.
- [5] A. Campocchia, E. Riva Sanseverino, G. Zizzo. “A mathematical approach to study interconnected earthing systems inside MV networks”, *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, Vol. 26, No. 5, 2007, pp. 1364-1391.
- [6] M. Mitolo, R. Musca, M. Tartaglia, G. Zizzo. “Electrical safety analysis in the presence of resonant grounding neutral”, *IEEE Transactions on Industry Applications*, vol. 55(5), 2019, pp. 4483-4489.
- [7] “Sheath bonding systems of ac transmission cables – design, testing, and maintenance”, *CIGRE*, No. 797, 2020-

- [8] F. O. Wollaston, K. H. Kidd “Cable Sheath Jacket Requirements to Withstand Abnormal Voltage Stresses”, *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems*, Vol. 80, No. 3, 1961, pp. 1116-1123.
- [9] “Innovazioni nei Metodi di Posa dei Cavi Elettrici per Correnti Alternate Monofasi”, Italian Patent No. 140,762, Pirelli, Milano, 1914.
- [10] “Montage Special des Lignes en Cables Souterrains”, French Patent No. 517,446-X11-6, La Canalisation Electrique, 1920.
- [11] “Electrical Cable Installation”, U. S. Patent No. 1,512,443, R. W. Atkinson, 1924.
- [12] “Bonding Circuit for Reducing Sheath Current of Power Cable Line”, U. S. Patent No. 3857071A.
- [13] “Sheath Bonding Transformer”, U. S. Patent No. 2087475A.
- [14] “Reduction of Sheath Losses in High Voltage Cables”, International Patent No. WO2002027890A1.
- [15] L. Li, J. Yong, W. Xu, “Single Sheath Bonding – A New Method to Bond/Ground Cable Sheaths”, *IEEE Transactions on Power Delivery*, Vol. 35, No. 2, 2020, pp. 1065 – 1068.
- [16] R. Candela, A. Gattuso, M. Mitolo, E. Riva Sanseverino, G. Zizzo, “A Comparison of Special Bonding Techniques for Transmission and Distribution Cables”, 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 9-12 June 2020, Madrid (Spain).
- [17] J. R. Carson, “Wave Propagation in Overhead Wires with Ground Return”, *Bell Systems Technical Journal*, vol. 5, 1926, pp. 539–554.
- [18] IEEE Standard 367, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault.
- [19] IEC Standard 60909-3, Short-circuit currents in three-phase a.c. systems – Part 3: currents during two separate simultaneous line-to-earth short circuits and partial short-circuits currents flowing through earth.
- [20] R. Candela, A. Gattuso, M. Mitolo, E. Riva Sanseverino, G. Zizzo, “A Model for the Study of Sheath Currents in Medium Voltage Cables for Industrial Application”, 56th IEEE Industrial & Commercial Power Systems (I&CPS) Technical Conference, 2020, virtual conference.
- [21] R. Candela, A. Gattuso, M. Mitolo, E. Riva Sanseverino, G. Zizzo, “A Comparison of Special Bonding Techniques for Transmission and Distribution Cables”, 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 9-12 June 2020, Madrid (Spain).



Roberto Candela received the master's degree in electrical engineering and the Ph.D. degree in electrical engineering from the University of Palermo, Palermo, Italy, in 1996 and 2001, respectively. Since 1996, he has been with the Research Group of Electrotechnics at the University of Palermo. Since December 2004, he has been a Researcher with the University of Palermo, where he teaches basic electrical engineering and electrotechnics and foundations of informatics. His research interest include the optimization methods for diagnosis in dielectrics material for high voltage application and development of technologies for the signals treatment and diagnosis of insulating system through partial discharges measurements. In 2006, he developed and patented a new sensor for measuring partial discharges in wireless mode that is on the base of Pry-Cam product range. Since 2012, he has been a CEO of Prysmian Electronics, Palermo, Italy, a company of Prysmian group, responsible worldwide for energy asset management systems.



Antonio Gattuso received the master's degree in Electrical Engineering in 2019 at the University of Palermo, Italy. In 2020 he started a collaboration with the Department of Engineering of the same University and Prysmian Electronics company. His current research interests include electrical safety, grounding systems, transmission and distribution power lines, cables' sheaths.



Massimo Mitolo (Fellow, IEEE) received the Ph.D. degree in electrical engineering from the University of Napoli "Federico II," Italy. He is currently a Full Professor of electrical engineering with the Irvine Valley College, Irvine, CA, USA, and also a Senior Consultant in the matter of failure analysis and electrical safety

with Engineering Systems Inc., ESI. He has authored over 140 journal papers and books, including the "Electrical Safety of Low-Voltage Systems" (McGraw-Hill), the "Laboratory Manual for Introduction to Electronics: A Basic Approach" (Pearson), and the "Analysis of Grounding and Bonding Systems" (CRC Press). His research interests include the analysis and grounding of power systems and electrical safety engineering. Dr. Mitolo is a Fellow of the IEEE in recognition "for contributions to the electrical safety of low-voltage systems," and a Fellow of the Institution of Engineering and Technology (IET) of London. He is a registered Professional Engineer in the state of California and in Italy. He is active within the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society (IAS) in numerous committees and working groups. He is a recipient of the James E. Ballinger Engineer of the Year 2013 Award from the Orange County Engineering Council. He has received numerous recognitions and best paper awards, among which are the IEEE "Ralph H. Lee I&CPS Department Prize Paper Award," the IEEE "I&CPS 2015 Department Achievement Award," and the IEEE Region 6 "2015 Outstanding Engineer Award." He currently serves both as an Associate Editor and a Guest Editor for the IEEE IAS Transactions. He is currently the Deputy Editor-in-Chief of the IEEE Transactions on Industry Applications.



Eleonora Riva Sanseverino received the master's degree in electrical engineering from the University of Palermo, Italy, in 1995, and the Ph.D. degree in electrical engineering, in 2000. She has been an Associate Professor of electrical power systems with the University of Palermo, since 2002, where she has also been a Full

Professor, since November 2019. She is currently a scientific coordinator of various research projects with research organizations and companies. She is also responsible of various research and teaching cooperation agreements with foreign institutions and private

companies. These include European institutions Aalborg University, Denmark, Chalmers University of Technology, Sweden, and extra-European institutions, such as Electric Power University and the Institute of Energy Science both in Hanoi, Vietnam. She has authored more than 250 articles on international journals, edited books and book chapters, and conference proceedings. She is the Editor in Chief of the UNIPA Springer Series. She is also the Coordinator of the Ph.D. in Energy with the University of Palermo.



Gaetano Zizzo (SM'17) is Associate Professor of Electrical Power Systems at the University of Palermo, Italy, where he obtained his M.S. degree in 2002 and his Ph.D. degree in Electrical Engineering in 2006. Since 2006 he works at the Engineering Department of the same university. In 2017 he was elected Senior Member

IEEE as a member of the Industry Application Society. He is involved in the activities of the IEEE Standard Association. His current research interests include electrical safety, power systems design, management, and optimization, energy blockchain, smart grids, microgrids and stability analysis.