

Inclusion of Wire Twisting Effects in Cable Impedance Calculations

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Abstract—Cable series impedance modeling is widely applied in electromagnetic transients calculations and power loss calculations. The calculations are usually performed in a 2D frame using FEM or alternative approaches like MoM-SO, thereby losing the 3D effects imposed by twisting of wire screens and armors. One of the implications of using 2D modeling for three-core and closely packed single-core cables is that currents will always circulate among the individual wires of each wire screen or armor. However, in the case of twisted screens/armors where the wires are insulated from each other, such current circulation will in reality not exist. As a result, the calculated impedances become incorrect, as well as the induced currents and losses on individual conductors. A procedure is introduced for preventing such false current circulations in a 2D calculation frame by simple manipulation of the system impedance matrix. The approach is demonstrated for the modeling of single-core and three-core cables, with and without an external armor. It is shown that the representation of the wire screen/armor armor with respect to current circulations can substantially influence the calculated result, both for the 50/60 Hz impedance and the cable transient behavior. The use of tubular screen representations is also investigated.

Index Terms—Cable, twisting, screen, armor, impedance, modeling, transients.

I. INTRODUCTION

PROPER design of underground cable systems requires the ability to calculate the cable impedances and conductor losses with adequate accuracy while considering the frequency-dependent effects resulting from eddy current effects in the conductors (skin and proximity effects). For studies of electromagnetic transients in power systems, it is common to apply EMTP-type tools. These tools have built in so-called "Cable Constants" (CC) support routines which permit to calculate the impedance matrix as function of frequency with respect to the cable conductors, based on a description of the cable geometry and material properties [1]. The frequency-dependent impedance matrix is used along with

the shunt capacitance matrix for generating parameters for appropriate cable models, for instance traveling wave type models [2],[3]. These models permit efficient time domain simulations while including the frequency dependent effects of the impedance matrix.

Existing CC tools consider systems of parallel, round conductors (solid or hollow) buried in earth. Analytical expressions are used which consider only skin effects [1],[4] while ignoring any proximity effects. This modeling leads to quite accurate results in many practical situations, but the proximity effects need to be considered for three-core cables and systems of closely packed single-core cables. The proximity effect can be included by use of finite element method (FEM) [5],[6] but at the expense of long run times. Recently, the powerful MoM-SO method [7] was introduced as an alternative to FEM, offering fast and robust computations by utilizing a harmonic expansion of an equivalent surface current representation.

In many cable designs, some of the cable parts are twisted for reasons related to manufacturing and mechanical properties. One example is that of twisted wire screens and external armors. The correct modeling of such systems requires a 3D calculation procedure to represent the fields produced by the helical conductor paths in the cable. One specific implication of the twisting is that the current may follow the individual wires in a helical path if the wires are insulated from each other, thereby affecting the effective impedance seen from the cable phases. If one applies a 2D tool (e.g. FEM, MoM-SO, or analytical [8]) for such system, the voltage induction along the wires in a given screen will differ, resulting in false currents that circulate among the wires. As a result, incorrect results arise for the current distribution on wires and other conductors, and thereby the effective impedance seen from the cable phases.

In this work we show a procedure for improving the accuracy of 2D tools by allowing the user to choose between alternative assumptions for (twisted) wire screens and (twisted) wire armors. The individual wires are either 1) insulated from each other, or 2) assumed in galvanic contact (bonded). The two conditions are imposed by a proper manipulation of the impedance matrix of conductors. The effects of the two alternative assumptions are demonstrated for the impedance and transient overvoltages on three parallel single-core cables featuring wire screens, and for a three-core armored cable. In addition, the use of a tubular conductor representation is evaluated, for faster computations.

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II. CURRENT DISTRIBUTION ON WIRE SCREENS AND ARMORS

The modeling of twisted wire screens and armors requires to consider the actual current path in the individual wires. For instance, if a screen/armor surrounds three symmetrically arranged current carrying conductors whose sum of currents is zero (e.g. positive sequence excitation), the solution by MoM-SO [7] or FEM will produce an uneven induction in the wires since twisting is ignored. As a result, net currents are induced in the wires which circulate internally in the screen/armor. In reality, however, the net current in each wire should be zero due to the twisting if one assumes that the individual wires are insulated from each other. At the same time, a non-zero net current will flow in each wire for a zero sequence excitation. A different scenario arises if one assumes that the wires are in continuous contact so that the current can freely shift from one wire to another. This results in an uneven current distribution on the screen.

In order to deal with these two situations, two alternative ways of modeling twisted screens and armors have been implemented in MoM-SO.

1. **Insulated wires.** All wires in a given screen carry an identical net current, implying that the wires are insulated from each other. This condition is achieved by simple manipulations of the impedance matrix.
2. **Bonded wires.** Currents are allowed to circulate among the wires internally in the screen, implying that the wires are in galvanic contact along the length of the cable system. This condition is achieved by ignoring the twisting altogether.

III. COMPUTATIONAL PROCEDURE

A. Conductors And Phases

Consider a cable system consisting of N conductors which are initially assumed to be parallel and straight. The earth return is represented by a separate conductor. The per-unit-length series impedance is given in the frequency domain as

$$-\frac{d\mathbf{v}(\omega)}{dx} = \mathbf{Z}(\omega)\mathbf{i}(\omega) = (\mathbf{R}(\omega) + j\omega\mathbf{L}(\omega))\mathbf{i}(\omega) \quad (1)$$

where \mathbf{v} and \mathbf{i} are complex vectors of length N and \mathbf{R} and \mathbf{L} are square matrices of dimension N .

The conductors associated with a wire screen or a stranded armor will be bundled into a single, equivalent conductor. In this work we will use the term "phase" to denote such an equivalent conductor as well as single conductors that are not bundled.

Wire screens/armors are to be modeled by the two alternative options described in Table I. It is assumed that the wires within each screen/armor are identical. In order to illustrate the steps in the computational procedure, the seven-conductor example in Fig. 1 will be used which consists of a mix of insulated and bonded screens/armors.

TABLE I. MODELING OPTIONS FOR TWISTED WIRE SCREEN/ARMOR

Option	Assumption
Insulated	Wires are insulated from each other
Bonded	Wires are in continuous contact

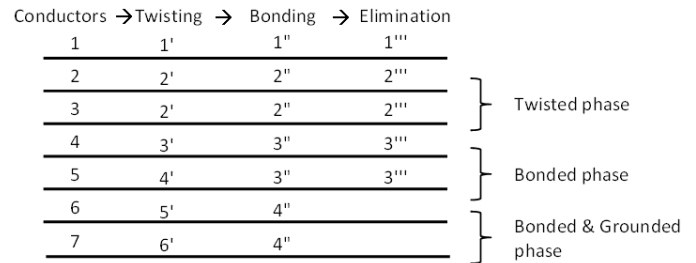


Fig. 1. System of seven conductors. Renumbering of conductors following twisting, bonding and elimination of reference conductor.

B. Applying the Insulated Wires Condition

Assume that n conductors make up a twisted phase. Insulated wires implies that the phase current divides equally among the n conductors, due to rotational symmetry and because the wires are insulated from each other. This condition is enforced by calculating the average of the n columns of \mathbf{Z} associated with the n conductors, $\mathbf{z}_{\text{ave,col}}$. The column in \mathbf{Z} associated with the first of the conductors is replaced with $\mathbf{z}_{\text{ave,col}}$ and the remaining $(n-1)$ columns are deleted.

The insulated wires condition further implies that along one pitch length of the screen/armor, the voltage drop is equal for the n conductors. This voltage drop will be taken as the average of voltages on the individual conductors. The condition is enforced by calculating the average of the n rows of \mathbf{Z} associated with the n conductors, $\mathbf{z}_{\text{ave,row}}$. The row in \mathbf{Z} associated with the first of the conductors in the twisted phase is replaced with $\mathbf{z}_{\text{ave,row}}$, and the remaining $(n-1)$ other rows are deleted.

As a result, the dimension of \mathbf{Z} is reduced by $(n-1)$ rows and $(n-1)$ columns.

The twisting condition is applied successively to all twisted phases, giving

$$-\frac{d}{dx}\mathbf{v}' = \mathbf{Z}'\mathbf{i}' \quad (2)$$

A connection matrix \mathbf{P}_1 is created which relates the voltage and current before (\mathbf{v}, \mathbf{i}) and after twisting $(\mathbf{v}', \mathbf{i}')$,

$$\mathbf{i} = \mathbf{P}_1^T \mathbf{i}' \quad (3)$$

$$\mathbf{v}' = \mathbf{P}_1 \mathbf{v} \quad (4)$$

For the example given in Fig. 1 we have

$$\mathbf{P}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/2 & 1/2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

C. Applying the Bonding Condition

Bonding of conductors into a phase implies that the voltage drop along the conductors in the phase are the same, and that the phase current is equal to the sum of the conductor currents in that phase. The currents in the conductors are however allowed to be different. This condition is enforced by a

connection matrix \mathbf{P}_2 which relates the voltage and current before (\mathbf{v}' , \mathbf{i}') and after bonding (\mathbf{v}'' , \mathbf{i}''),

$$\mathbf{i}'' = \mathbf{P}_2 \mathbf{i}' \quad (6)$$

$$\mathbf{v}' = \mathbf{P}_2^T \mathbf{v}'' \quad (7)$$

For the given example, we have

$$\mathbf{P}_2 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \quad (8)$$

The bonding gives a new impedance matrix \mathbf{Z}'' as follows. From (2) we have

$$\mathbf{i}' = -(\mathbf{Z}')^{-1} \frac{d}{dx} \mathbf{v}' \quad (9)$$

Inserting (6) and (7) in (9) we get

$$\mathbf{i}'' = -\mathbf{P}_2 (\mathbf{Z}')^{-1} \frac{d}{dx} \mathbf{P}_2^T \mathbf{v}'' \quad (10)$$

or

$$\mathbf{i}'' = -\frac{d}{dx} [\mathbf{P}_2 (\mathbf{Z}')^{-1} \mathbf{P}_2^T] \mathbf{v}'' \quad (11)$$

and we see that

$$-\frac{d}{dx} \mathbf{v}'' = \mathbf{Z}'' \mathbf{i}'', \quad \mathbf{Z}'' = [\mathbf{P}_2 (\mathbf{Z}')^{-1} \mathbf{P}_2^T]^{-1} \quad (12)$$

Note that the bonding process is applied after the twisting process in Section III-B. That way, also the equivalent phases of twisted screens/armors can be freely bonded with other phases/conductors.

D. Elimination of Reference Phase

One of the phases is the (equivalent) reference phase. The reference phase typically consists of the ground return which may have been bonded with other phases (e.g. screens and armors) into an equivalent phase. For the example in Fig. 1, the reference conductor consists of conductors 6 and 7.

For a unit current flowing only in phase # m we can write (assuming the reference phase comes last),

$$-\frac{d}{dx} \mathbf{v}'' = \mathbf{Z}'' \begin{bmatrix} 0 \\ \vdots \\ i_m'' = 1 \\ 0 \\ \vdots \\ -i_m'' = -1 \end{bmatrix}, \quad (13)$$

It follows that the return current is eliminated by subtracting the column associated with the reference phase from all other columns. Finally, the column associated with the reference phase is deleted, giving a matrix \mathbf{Z}'''_a which has one less column than rows,

$$-\frac{d}{dx} \mathbf{v}'' = \mathbf{Z}'''_a \mathbf{i}'''. \quad (14)$$

The voltages with respect to the reference phase are

$$-\frac{d}{dx} (\mathbf{v}'' - v_{ref}) = -\frac{d}{dx} \mathbf{v}''' = \mathbf{Z}'''_b \mathbf{i}''', \quad (15)$$

where \mathbf{Z}'''_b is obtained from \mathbf{Z}'''_a by subtracting the row associated with the reference phase from the other phases, and finally deleting that row. The (square) matrix \mathbf{Z}'''_b is the sought matrix.

E. Calculation of Currents on Conductors

We are given a prescribed set of currents \mathbf{i}''' on the remaining phases (which typically will be the three phase conductors of the cable). Using (14) we get the voltage \mathbf{v}'' on these phases and the reference phase. The voltage (\mathbf{v}') on all phases and on conductors within bonded phases is calculated using (7), and the associated current (\mathbf{i}') is obtained from \mathbf{v}' by the inverse of (2). Finally, the current \mathbf{i} on all conductors in the system are obtained by (3).

The procedure is mathematically carried out as follows,

$$\mathbf{i} = \{\mathbf{P}_1^T (\mathbf{Z}')^{-1} \mathbf{P}_2^T \mathbf{Z}'''_b\} \mathbf{i}''' = \mathbf{H} \mathbf{i}''' \quad (16)$$

Matrix \mathbf{H} allows the current to be calculated on all conductors for any specified current application on phases.

IV. APPROXIMATE REPRESENTATION BY TUBULAR CONDUCTORS

The use of an explicit representation of a stranded wire screen by its conductors greatly increases the computation time for establishing the impedance matrix. It can therefore be advantageous to use an equivalent representation by a tubular conductor.

In the bonded wire situation, such representation is straightforward with the MoM-SO method [7] since the required uneven current distribution in the equivalent tubular conductor is automatically included.

In the case that the wires are to be treated as insulated, representation by a tubular conductor is still possible in MoM-SO by enforcing that the current distribution around the circumference of the tube is uniform. In MoM-SO, the conductor current on a tubular conductor is represented by an equivalent surface current on both the outer and inner surface.

The respective surface currents are given as

$$J_s^{(p)}(\theta) = \frac{1}{2\pi a_p} \sum_{k=-K}^K J_k^{(p)} e^{jk\theta} \quad (17)$$

$$\tilde{J}_s^{(p)}(\theta) = \frac{1}{2\pi \tilde{a}_p} \sum_{k=-K}^K \tilde{J}_k^{(p)} e^{jk\theta} \quad (18)$$

with moments $J_k^{(p)}$ and $\tilde{J}_k^{(p)}$, and conductor outer and inner radius a_p and \tilde{a}_p .

It follows that a uniform current distribution around the circumference is achieved by specifying in (17) and (18) zero order ($K=0$) for the harmonic expansion. As a result, only skin effect will exist in that conductor. We refer the reader to [7] for a detailed description of MoM-SO as well as its extension to multi-layered earth in [9].

V. EXAMPLE: THREE SINGLE-CORE CABLES

A. Cable System

We consider a system of three 66 kV single-core cables in tight (trefoil) formation as shown in Fig. 2. Each cable features a 1000 mm² copper conductor and a copper wire screen. Details of the cables are given in Table II. The cables are buried in an infinite earth with resistivity 100 Ω·m.

For a tubular representation, each screen is represented by a thin tube having the same DC resistance and conductivity as the wire screen. The equivalent thickness is 0.22541 mm.

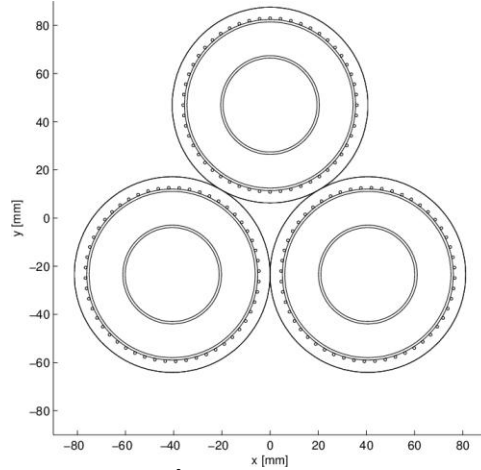


Fig. 2. Three 66 kV 1000 mm² Cu cables

TABLE II
SINGLE-CORE CABLE DATA

Item	Property
Copper core	$d=39$ mm, $R_{dc}=0.0176$ Ω/km
Inner semicon	$t=1$ mm
Insulation	$t=14$ mm, $\epsilon_r=2.3$
Outer semicon	$t=1$ mm
Wire screen	$t=1.12$ mm, 52 wires, $\sigma=58 \cdot 10^6$ S/m
Insulating jacket	$t=4$ mm, $\epsilon_r=2.3$

B. Current Distribution on Conductors at 50 Hz

The calculation is performed using MoM-SO in the four alternative ways shown in Table III. The screen conductors are assumed to be grounded and are eliminated from the system of conductors along with the ground return. This is achieved by first applying the twisting condition to the three screens, then bonding the screens and the ground return conductor into the reference phase which is finally eliminated.

TABLE III
SCREEN MODELING ALTERNATIVES

Alternative	Modeling
#1	Bonded wires: detailed representation
#2	Bonded wires: tubular representation
#3	Insulated wires: detailed representation
#4	Insulated wires: tubular representation

Fig. 3 shows the current density at 50 Hz with a 1 A current application on the phase conductors, with bonded and detailed representation of the wire screen (#1). The plot displays the absolute value of the complex-valued current densities. It is observed that the current distribution is very uneven on both

the phase conductors and the wire screens due to proximity effects. The current distribution with the tubular conductor (#2) is found to be very similar (not shown). It is remarked that the total current on the three screens are 120° phase shifted with respect to each other.

Fig. 4 shows the same result with insulated, detailed representation of the wire screen (#3). The distribution of net currents between the wires within each screen is now uniform as expected, while the uneven current distribution on the phase conductors persists.

Fig. 5 shows the same result with insulated wires by the tubular conductor representation (#4). The current density is seen to be very similar to that by the explicit wire representation in Fig. 4.

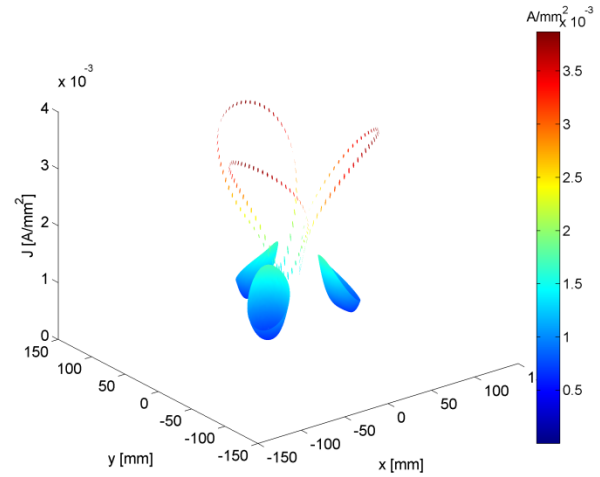


Fig. 3. Current density with "bonded wire" condition.

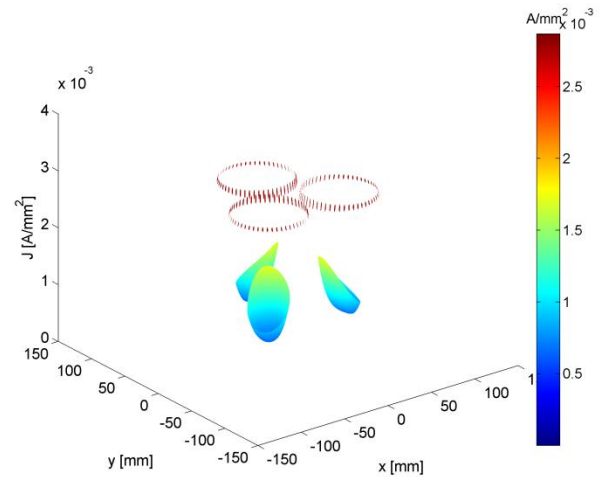


Fig. 4. Current density with "insulated wire" condition.

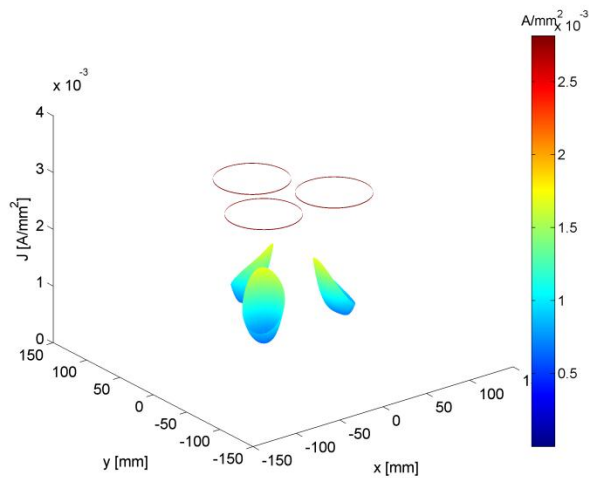


Fig. 5. Current density with "insulated wire" condition and approximation by tubular conductor with 0th order harmonic expansion for the inner (17) and outer (18) surface.

C. Positive Sequence Impedance

The resulting positive sequence series impedance $Z=R+jX$ is calculated for the cable system, again with the screen conductors assumed to be continuously grounded.

Table IV shows the calculated result at a few discrete frequencies between 50 Hz and 5 kHz, with the detailed wire representations (#1 and #3). It is observed that there is a noticeable difference in both the resistance (R) and the reactance (X). The difference is highlighted in Fig. 6 which shows the difference between the two computations in percent by (19), where A can be either R or X .

$$diff = 100\% \cdot \frac{A_{wire} - A_{bonded}}{A_{bonded}} \quad (19)$$

When switching from the bonded to the insulated condition, the difference in R is seen to change from negative to positive as frequency increases, reaching a maximum of 10% at about 1 kHz. At higher frequencies, the difference diminishes as the currents start forming coaxial loops which prevents magnetic interaction between the three cables, thereby giving a near-coaxial current distribution in conductors and shields.

TABLE IV. POSITIVE SEQUENCE RESISTANCE AND REACTANCE. DETAILED WIRE REPRESENTATION

f [Hz]	Bonded (#1)		Insulated (#3)	
	R [Ω]	X [Ω]	R [Ω]	X [Ω]
50	0.0315	0.0990	0.0303	0.0998
250	0.1518	0.3659	0.1521	0.3834
1000	0.3345	0.9574	0.3686	0.9616
5000	0.4890	4.1189	0.5000	4.1076

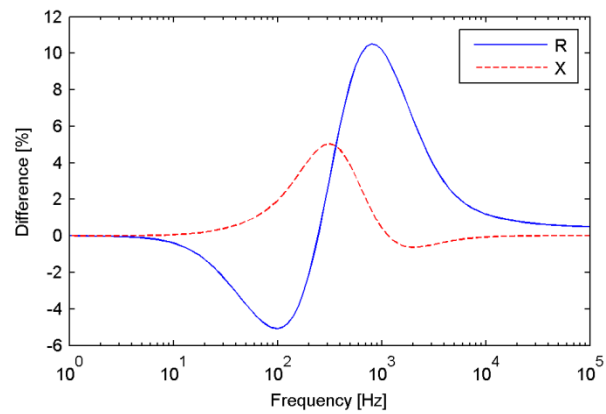


Fig. 6. Relative change in positive sequence resistance and reactance, when switching from detailed bonded to detailed insulated wire representation.

Table V shows the same result as in Table IV when calculating the impedance using the tubular wire representation. The impedance values agree very closely with those in Table IV (detailed representation), being smaller than 2% in deviation.

TABLE V. POSITIVE SEQUENCE RESISTANCE AND REACTANCE. TUBULAR REPRESENTATION OF WIRE SCREENS

f [Hz]	Bonded (#2)		Insulated (#4)	
	R [Ω]	X [Ω]	R [Ω]	X [Ω]
50	0.0315	0.0990	0.0303	0.0998
250	0.1522	0.3666	0.1524	0.3845
1000	0.3390	0.9547	0.3751	0.9576
5000	0.4993	4.0812	0.5064	4.0668

D. Modal Propagation Characteristics

For calculation of electromagnetic transients, the significance of the bonded vs. insulated screen representations is very much dependent on the wave types that are excited in the cable system. To see this, the impedance matrix was recalculated but this time without eliminating the screen conductors. Using the resulting 6x6 matrices for impedance and capacitance, the six modal velocities were calculated as function of frequency, see Fig. 7. The error with use of the tubular representations is moderate as only a slightly lower velocity can be observed for the intersheath modes at high frequencies.

E. Transient Overvoltages

The intersheath modes are known to be important in studies of induced sheath overvoltages, and for transients on crossbonded cable systems. To demonstrate the effect of the wire modeling, we consider the 20 km cable case in Fig. 8 where the cable is connected to a three-phase 50 Hz source at the sending end with the screens grounded at both ends. An ideal ground fault occurs at the cable sending end at voltage maximum. Parameters are generated for the Universal Line Model (ULM) [3] for each 10 km section based on the impedance and capacitance matrix, and utilized in a time domain simulation in PSCAD.

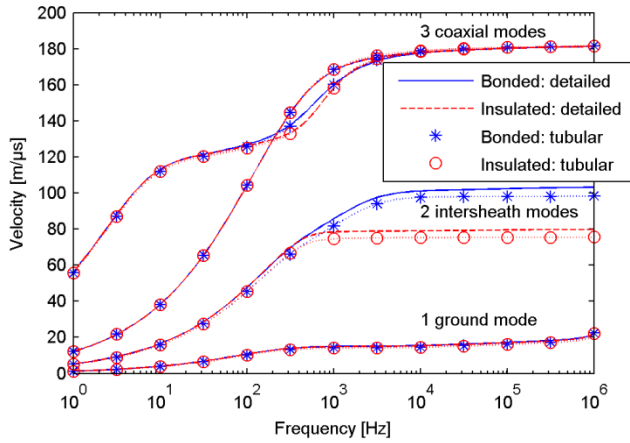


Fig. 7. Modal velocities

Fig. 9 shows the simulated conductor voltage on the cable mid-point in the phase that experiences the ground fault. The treatment of wires as bonded or insulated is seen to have only a minor effect on the waveform.

Fig. 10 shows the induced sheath voltage at the cable midpoint. It is clearly seen that the choice of detailed wire modeling by the bonded or insulated condition substantially influences the wave shapes of the sheath overvoltage. It is further seen that representation by a tubular conductor gives a reasonably accurate result, although the deviations from the detailed wire representation are noticeable.

It is remarked that the transient screen overvoltage is non-zero along the cable, even when the screens are grounded at both ends. If they are excessive, intermediate grounding of the screen conductors may be necessary [11].

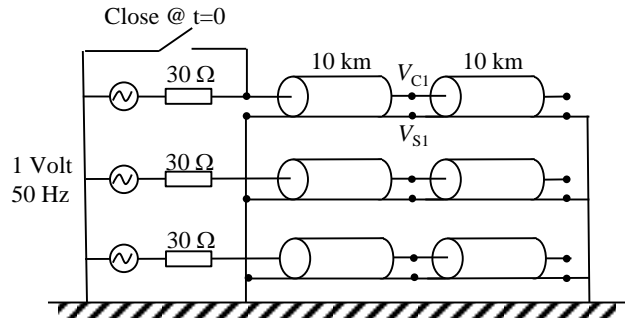


Fig. 8. Ground fault initiation

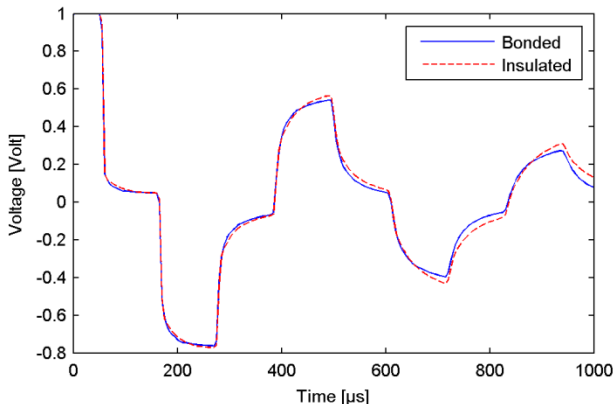


Fig. 9. Conductor voltage V_{C1} on cable midpoint. Detailed representation.

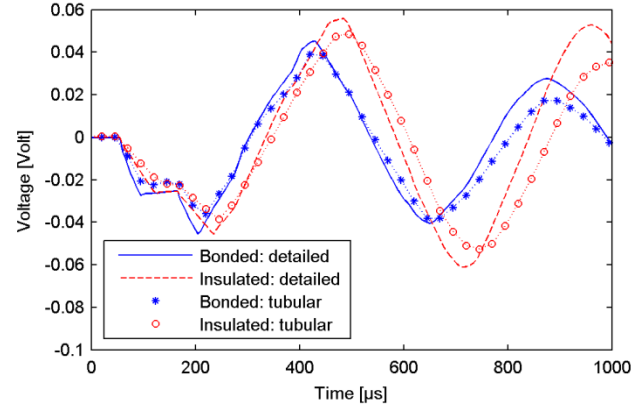


Fig. 10. Induced sheath overvoltage V_{S1} on cable midpoint.

VI. EXAMPLE: THREE-CORE ARMORED CABLE

A. Cable System

We consider a 145 kV three-core armored cable as shown in Fig. 11. Each core features a 800 mm^2 Cu conductor and a tubular lead sheath. Details of each cable are given in Table VI. The armor consists of 108 wires of diameter 5.6 mm with conductivity $\sigma=5.94 \cdot 10^6 \text{ S/m}$ and assumed permeability $\mu_r=80$. The cable is assumed to be located in an infinite sea with conductivity $\sigma=3.33 \text{ S/m}$.

With tubular representation of the armor, we assume a tube thickness equal to the wire diameter. The conductivity is reduced to $\sigma=4.49 \cdot 10^6 \text{ S/m}$ to maintain the original DC resistance of the armor. The permeability is maintained unchanged, $\mu_r=80$.

With both the detailed and tubular representations, the armor along with metallic screens and sea return is eliminated from the system of conductors.

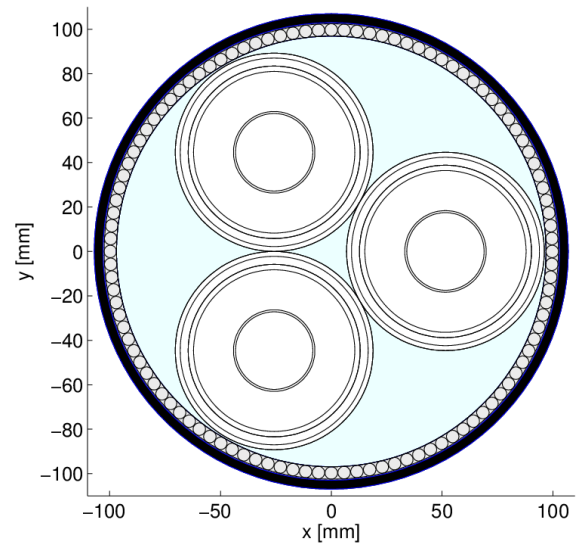


Fig. 11. Armored three-core cable

TABLE VI
SINGLE-CORE CABLE DATA

Item	Property
Copper core	$d=34.9$ mm, $Rdc=0.0204$ Ω/km
Inner semicon	$t=0.91$ mm
Insulation	$t=18.0$ mm, $\epsilon_r=2.3$
Outer semicon	$t=2.41$ mm
Lead sheath	$t=3.61$ mm, $\sigma=4.9 \cdot 10^6$ S/m
Insulating jacket	$t=2.2$ mm, $\epsilon_r=2.3$

B. Current Distribution on Conductors at 50 Hz

A 1 A positive sequence current is applied to the three phase conductors with the screen conductors continuously grounded by the twisting/bonding/elimination process in Section III. The calculation is performed using MoM-SO in the four alternative ways defined in Table III. It is observed from the current densities in Fig. 12 (absolute values) that both eddy currents and net currents are flowing in the armor wires. With the insulated condition (Fig. 13), only eddy currents circulate in the armor wires. The total current on the armor is zero.

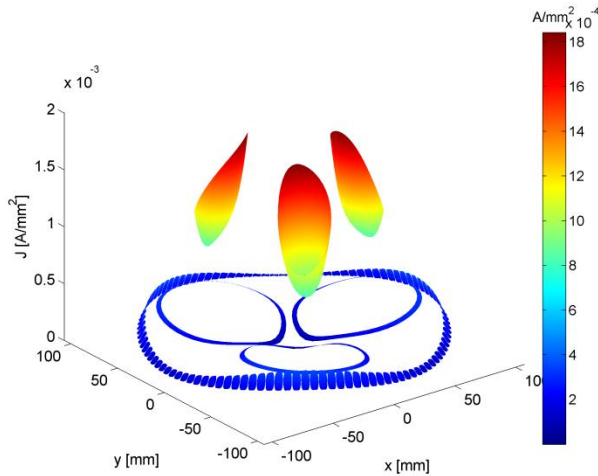


Fig. 12. Current density with "bonded wire" condition.

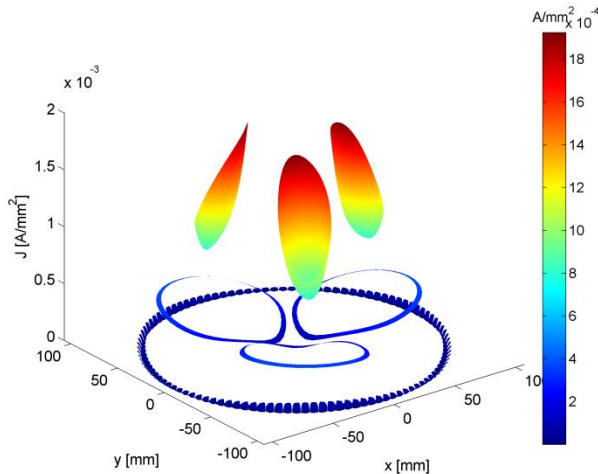


Fig. 13. Current density with "insulated wire" condition.

C. Positive Sequence Impedance

The positive sequence impedance is calculated with respect to the phase conductors with the screen conductors

continuously grounded and eliminated, see Table VII. The insulated wire representation gives at 50 Hz a resistance which is lower than in the bonded case, but becomes higher as frequency increases. The difference is explicitly shown in Fig. 14, reaching 20% at 200 Hz.

TABLE VII. POSITIVE SEQUENCE RESISTANCE AND REACTANCE. DETAILED REPRESENTATION OF WIRE SCREENS

f [Hz]	Bonded (#1)		Insulated (#3)	
	R [Ω]	X [Ω]	R [Ω]	X [Ω]
50	0.0432	0.1070	0.0403	0.1152
250	0.1334	0.3815	0.1613	0.3886
1000	0.2633	1.1959	0.2753	1.1824
5000	0.4476	5.4096	0.4458	5.4043

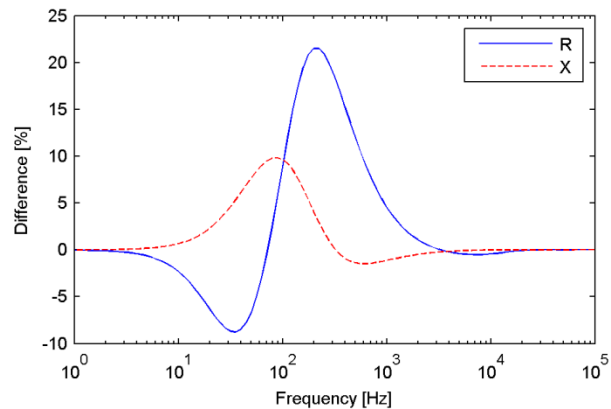


Fig. 14. Relative change in positive sequence resistance and reactance, when switching from detailed bonded to detailed insulated wire representation.

The result with a tubular representation is shown in Table VIII and the deviation compared to the explicit representations in Table VII is shown in Table IX. Significant deviations are seen to result, especially at the lowest frequencies. Here, the induced current flowing in the screen conductors is too small to prevent the magnetic field from penetrating the armor. The air gaps between the magnetic armor wires will now greatly affect the magnetic field and must therefore be explicitly represented.

TABLE VIII. POSITIVE SEQUENCE RESISTANCE AND REACTANCE. TUBULAR REPRESENTATION OF WIRE SCREENS

f [Hz]	Bonded (#2)		Insulated (#4)	
	R [Ω]	X [Ω]	R [Ω]	X [Ω]
50	0.0501	0.1160	0.0352	0.1129
250	0.1545	0.3775	0.1647	0.4125
1000	0.2673	1.1859	0.3026	1.1745
5000	0.4460	5.4079	0.4422	5.3951

TABLE IX. DEVIATION BETWEEN RESULTS IN TABLES VIII (TUBULAR REPRESENTATION) AND VII (DETAILED REPRESENTATION).

f [Hz]	Bonded (#2)		Insulated (#4)	
	R [%]	X [%]	R [%]	X [%]
50	16.0	8.4	-12.7	-2.0
250	15.8	-1.1	2.1	6.2
1000	1.5	-0.8	9.9	-0.7
5000	-0.4	0.0	-0.8	-0.2

D. Modal Propagation Characteristics

Fig. 15 shows the modal propagation velocities with respect to the six conductors. The velocities are shown for the four armor modeling assumptions in Table III. As expected, the coaxial modes are only affected by the modeling assumption at lower frequencies (below a few kHz) due to the screening effect of the sheath conductors. With detailed wire modeling, the insulated representation gives at high frequencies a substantially lower velocity for both the intersheath modes and the ground mode. Use of tubular representations is seen to give a reasonably good result at high frequencies, in particular for the intersheath modes.

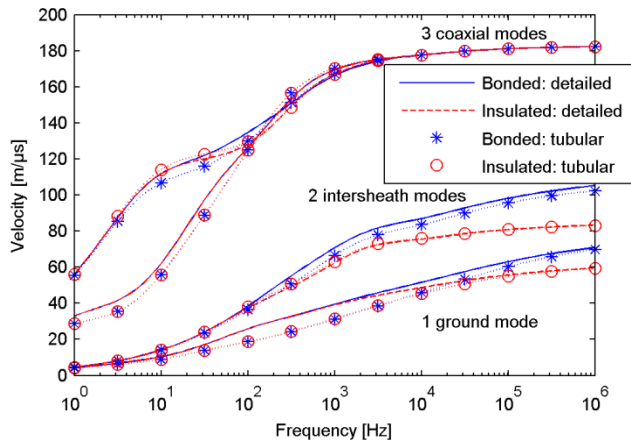


Fig. 15. Modal velocities

E. Transient Overvoltages

Using the frequency-dependent impedance and capacitance matrix for the system, parameters are calculated for the Universal Line Model (ULM) assuming 20 km cable length, similarly as with the previous example of three single-core cables. The ULM cable model is used in simulation of transient overvoltages for the situation in Fig. 8.

Fig. 16 shows the result for the mid-point screen voltage. With the detailed representations, both the bonded and wire modeling lead to a very similar result for the first peak voltage, although a quite noticeable difference in the voltage develops with time. The use of tubular representation gives a slightly too low peak value. Still, the overall agreement between the four approaches is considered quite good in this example.

VII. COMPUTATIONAL CONSIDERATIONS

For use in electromagnetic transient studies, it is desirable to use a tubular representation of screen and armors when possible to save computation time. For instance, the generation of 121 frequency samples for the armored cable example required about 30 s with a detailed representation of the armor strands, but only 2.3 s with the tubular representation.

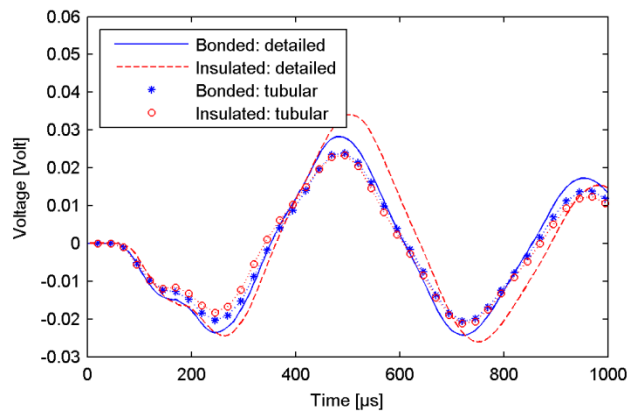


Fig. 16. Induced sheath overvoltage V_{S1} on cable midpoint.

VIII. DISCUSSION

The "insulated wires" condition assumes that each twisted phase (screen/armor) in the system completes one or several complete rounds of positions with respect to every other twisted phase in the system so that the induction in all wires in a given screen/armor become identical. However, in the case of practical cable lengths where each screen/armor undergoes a large number of rounds, this assumption is not required to be fulfilled since the uneven component of the voltage induction among the wires along the full cable length will be small compared to the average induction.

It was shown that the wire screen can be represented with a tubular conductor with little loss of accuracy. This result is due to the small wire diameter and large wire separation, both contributing to making proximity effects between wires small.

This work only considers the longitudinal current component of the wire currents. In reality, the twisting also leads to a circular current component which generates a longitudinal magnetic flux component similarly to a solenoid. A simplified procedure for including this solenoid effect in the impedance matrix was proposed in [10].

Another effect not accounted for is that the twisting causes the magnetic field produced by the phase conductors to have a vector component parallel to the steel wires in addition to the transverse component [12]. Since the steel wires are magnetic, the longitudinal field component may appreciably affect the impedance seen from the phase wires. The longitudinal component increases with increasing pitch angle.

This work described the handling of twisting effects in the context of the MoM-SO method. The approach can also be utilized within the analytical computational framework existing in the CC routines found in EMT tools. Here, it is only required to replace the tubular representation of wire screens/armors with an explicit representation by individual conductors. The handling of the insulated/bonding can then be applied as described in this work. The limitation is that each conductor will only include skin effect.

In the case of FEM computations, it can be very time consuming to establish the full impedance matrix associated with all conductors in the system. The impedance matrix is calculated column by column, each requiring a separate FEM solution. However, when one is only interested in the

impedance and losses associated with a pure positive sequence current application, it is still possible to realize both the bonded and insulated wire condition using a single FEM calculation. The procedure is described in Section IV-B in [6].

As a final remark, the authors are of the opinion that measurements should be performed in order to properly verify the presented models. Such measurements were not available at the time of writing.

IX. CONCLUSIONS

This paper has introduced a new approach for modeling cables with twisted wire screens and armors which prevents currents from circulating between the individual wires. This "insulated" representation is an alternative to the commonly applied "bonded" representation that is implicitly assumed in 2D computations and which causes currents to circulate among the wires. The main findings are as follows.

1. Modeling by an insulated wire representation is achieved by a straightforward modification of the impedance matrix via an averaging process.
2. Application to a system of three single-core cables and an armored three-core cable shows that the two modeling approaches (insulated, bonded) give different values for the positive sequence impedance at 50/60 Hz and at harmonic frequencies. The deviation at 50 Hz was 7% for the resistance and 8% for the reactance. At lower harmonic frequencies, even higher deviations resulted.
3. The two modeling approaches also give different results for transient overvoltages that involve intersheath waves and ground waves, e.g. induced sheath overvoltages.
4. Non-magnetic wire screens can be represented by equivalent tubular conductors with a good accuracy. The insulated representation is handled in MoM-SO by representing the tubular conductor by a 0th order surface current at the inner and outer surfaces.
5. Tubular representation of magnetic armors should be used with care. Substantial errors can result at 50/60 Hz and at harmonic frequencies, although transient wave shapes can be sufficiently accurate.

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XI. BIOGRAPHIES

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