Model created in COMSOL Multiphysics 6.4

Submarine Cable 3 — Bonding Capacitive

Introduction

Based on the results from the *Capacitive Effects* tutorial (the previous tutorial in this series), it is justified to neglect the capacitive coupling between the screens and consider one single isolated phase, together with its screen. As opposed to the *Capacitive*, *Inductive*, and *Thermal Effects* tutorials, this tutorial uses a 2D axisymmetric geometry representing the entire 10 kilometers of cable.

For several bonding types, the build-up of charging currents and the corresponding losses in the screen are analyzed (verification is included). The model validates the assumption that the high phase potential induces a uniform charging current — one that barely depends on the screen potential — and so justifies the approach chosen in the *Capacitive* and *Inductive Effects* tutorials (chapters 2 and 4).

Model Definition

The geometry is fairly simple; it contains only one phase. More precisely, it contains the cross-linked polyethylene (XLPE), the semi-conductive compound and the lead sheath surrounding the main conductor of that one phase; see Figure 1.

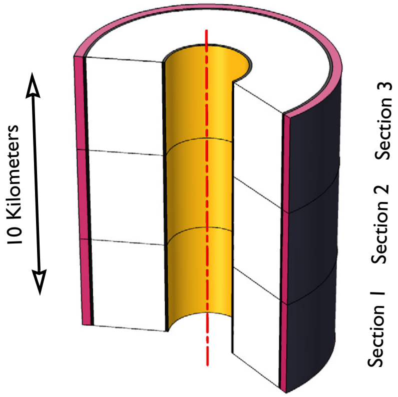

Figure 1: The cable's 2D axisymmetric geometry, including the semi-conductive compound (black), the cross-linked polyethylene (white) and the lead (red). The sections are used to reproduce the cross bonding configuration.

The use of a cylindrical coordinate system, together with the assumption that variations in the φ direction can be neglected, turns the geometry into a strongly simplified 2D axisymmetric representation, that is; a couple of rectangles.

THEORETICAL BASIS

When it comes to solving for the frequency domain current conservation problem, the methods used here are identical to the ones used in the *Capacitive Effects* tutorial. For more details on the involved theory, see the *Capacitive Effects* tutorial's theory section.

MODELING APPROACH

The tutorial starts with the basics; by applying a phase voltage to the innermost boundary and connecting the screen to ground at one end only. This configuration is effectively the same as Single-Point Bonding. In a second step, the other end of the screen is connected to ground as well. The resulting configuration is effectively the same as Solid Bonding.

In a third step the geometry is modified, splitting the cable in three equal sections. Apart from the connections made by the screen, the individual sections are electrically insulated. Each section is given a separate phase voltage showing a 120° phase shift with respect to the other two. The screen is still grounded at both ends of the cable. The resulting configuration is effectively the same as Cross Bonding.

The results are verified using simple analytical models, based on the assumption that the charging current does not vary along the cable — see section On Charging Currents. Finally, you will be encouraged to try dissimilar section lengths, as this is something the model from the *Capacitive Effects* tutorial cannot do.

ON CHARGING CURRENTS

It is worth making a note on the unique way the current conservation laws manifest themselves in this case. As discussed in the *Capacitive Effects* tutorial, the charging current I_c in A/km is given by:

$$I_c = j\omega C V_0, \tag{1}$$

where C refers to the capacitance in μF/km, and V_0 to the phase-to-ground voltage, of 127 kV. Strictly speaking, the value V_0 refers to the potential difference between the phase and the screen, so Equation 1 should only hold when the screen potential is precisely 0 V. In practice, however, it also holds when the deviation from zero is insignificant compared to the large value of the phase voltage. This includes screen voltages up to several kilovolts.

Since the charging current barely depends on the screen voltage, it can be considered a constant. And as it is a constant in A/km, we can follow a reasoning where the currents are assumed to build up linearly along the length of the cable, reaching a maximum at the bonded ends and the intersections. This reasoning is used throughout this tutorial, for discussing bonding types, making predictions, and analyzing results.

Note: All analytical models used — and all predictions made — for the build up of charging currents in the screens, are based on the assumption that the charging current does not depend on the screen potential: Its phase can vary in time and space, but its magnitude will be constant. The numerical model is there to test this assumption.

ON BONDING TYPES

Single-Point Bonding

In case of *single-point bonding*, each screen is electrically paired with the same phase across the entire length of the cable. Furthermore, it is bonded and connected to ground at one end only; see Figure 2. The phase potential will force a constant charging current that accumulates inside the screen. The screen currents build up linearly along the cable, reaching a maximum at the bonded end. At the floating end, the screen currents are zero and the screen potential reaches a maximum.

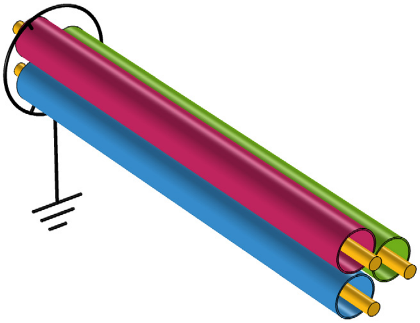

Figure 2: Schematic depiction of single-point bonding, where the screens (red, green, and blue) are bonded and grounded at one end only.

Because the screen potential at the floating end increases together with the cable's length, this configuration is suitable for shorter stretches only. Because of the increased risk of corrosion, it is mainly used for *terrestrial* purposes (as opposed to submarine)[1].

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[1] Treatment of the single-point bonding configuration within the context of this submarine cable tutorial series should therefore be seen as a *demonstration of a concept*, rather than a demonstration of a real-world application. Including these bonding types extends this tutorial series to a point where it is useful for demonstrating terrestrial applications as well.

Solid Bonding

In case of *solid bonding*, each screen is still paired with a single phase, but this time it is bonded and connected to ground at both ends; see Figure 3. For the capacitive problem, this means the cable is cut in half. That is; a solid bonded cable can be considered as two single-point bonded cables of half the total length, who's floating ends meet in the middle.

Now, the screen currents will build up in both directions, starting from zero at the center. At both ends they will reach a level that is one-half times the maximum screen current found for the single-point bonding configuration. The maximum screen potential will occur in the middle. Compared to the maximum screen potential from the single-point bonding configuration, it will be four times as small[2].

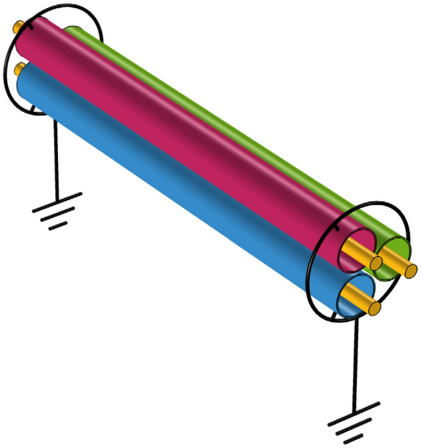

Figure 3: Schematic depiction of solid bonding, where the screens (red, green, and blue) are bonded and grounded at both ends.

Cross Bonding

Cross bonding shows the most sophisticated configuration — and conceptually, the most elegant one. In case of cross bonding, the total length of cable is split in three sections of equal length. From an electrical point of view, the screen is paired with a different phase for each section; see Figure 4.

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[2] As the voltage equals the current times the resistance, and both the average accumulated current, as well as the total resistance, are directly (linearly) proportional to the length of the cable.

As the charging currents for the three sections show a 120° phase shift, it is not the norm of the screen current that will change linearly along the cable (as was the case for the other two bonding types). Instead, it is the complex current itself, that develops linearly along the cable sections. It interpolates between the three points where the current reaches a maximum; intersection 1, intersection 2, and the combination of the two bonding points.

Since the currents at these three locations are 120° out of phase, the three points of maximum current form an equilateral triangle on the complex plane, centered around zero. Each side of the triangle represents the current difference[3] across one section, and has a length equal to one-third times the maximum screen current found for the single-point bonding configuration.

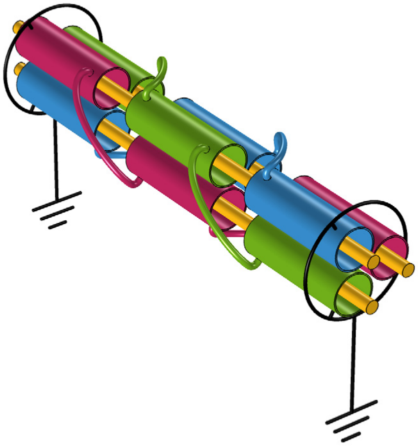

Figure 4: Schematic depiction of cross bonding, where the screens (red, green, and blue) are split in three cross-bonded sections of equal length.

The intersections increase the complexity of the cable system, and consequently, the risk of failure (due to leakage, corrosion and such). Therefore, like for single-point bonding, this configuration is not preferred for submarine cable systems[4].

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[3] This is analogous to a potential difference for voltage-driven problems.

[4] Treatment of the cross bonding configuration within the context of this submarine cable tutorial series should therefore be seen as a *demonstration of a concept*, rather than a demonstration of a real-world application.

ON SCALED SYSTEMS

The geometry is assumed to be 10 km long in the cable's axial direction. In the radial direction, it contains features of about 1 mm thick. This extreme aspect ratio leads to challenges for the geometry sequence, the physics, the mesh and the plots.

In order to avoid this situation, a scaled coordinate system is used. In the axial direction the coordinates are scaled by a factor of 10^5. This allows for having a 10 cm long geometry, that is perceived by the physics as 10 km: The stretched space leads to much lower values for the spatial derivative in $\mathbf{E} = -\nabla V$, so the electric field and the current density in the axial direction will be 10^5 times lower then what you would get for the unscaled 10 cm long model.

Since in-between the electric field $\mathbf{E}$ and the current density $\mathbf{J}$ there is still the factor of σ, from the current's viewpoint, the scaled system is equivalent to an anisotropic conductor. That is, the two effects are interchangeable: An unscaled system with an anisotropic conductivity can produce the same currents.

Conversely, an anisotropic conductivity can be used to partially compensate for the scaling. This is done in order to keep the model numerically stable. The numerical stability issues encountered here, are similar to those seen in the *Capacitive Effects* tutorial.

Results and Discussion

When using Single-Point Bonding, the current builds up to 55 A at the bonded end for each screen individually. The maximum screen potential becomes 83 V, and the total losses per screen evaluate to 1.5 kW.

When using Solid Bonding the current builds up to 28 A, the maximum screen potential becomes 21 V, and the total losses per screen evaluate to 0.38 kW.

Finally, when Cross Bonding is applied, the maximum current is 10.7 A. This current occurs at the two intersections and the bonded ends. The currents at these locations show a 120° phase shift with respect to one another. The maximum screen potential occurs half-way the cable. It has a norm of 6.9 V. The losses have been reduced to as little as 85 W.

Apart from a minor deviation caused by the anisotropic conductivity (see section On Scaled Systems) all results agree perfectly well with the analytic approximation, in which a linear accumulation of charging currents is assumed, see section On Charging Currents.

This validates the assumptions made in the *Capacitive Effects* tutorial. Perhaps more importantly, it shows that the capacitive problem and the inductive problem can be considered separate issues:

- Theoretically, the inductive phenomena can affect the capacitive problem by changing the screen potential, but as can be seen here, the capacitive behavior barely depends on this.
- Similarly, capacitive phenomena can affect the inductive problem by generating screen currents large enough to perturb the magnetic fields generated by the three phase currents. This, too, seems rather unlikely.

Therefore, this result validates the use of separate models for investigating inductive and capacitive effects, as is done in this tutorial series.

Reference

1. Video file `submarine_cable_z_animation_03_cross_bonding`,
available for download at www.comsol.com/model/cable-tutorial-series-43431.

Application Library path: `ACDC_Module/Tutorials,_Cables/submarine_cable_03_bonding_capacitive`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1. In the **Model Wizard** window, click **2D Axisymmetric**.
2. In the **Select Physics** tree, select **AC/DC** > **Electric Fields and Currents** > **Electric Currents (ec)**.
3. Right-click and choose **Add Physics**.
4. Click **Study**.
5. In the **Select Study** tree, select **General Studies** > **Frequency Domain**.
6. Click **Done**.

GLOBAL DEFINITIONS

This model uses a subset of the parameters already defined for the other tutorials. In order to gain access to them, you can load them all.

Geometric Parameters 1

1. In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2. In the **Settings** window for **Parameters**, type `Geometric Parameters 1` in the **Label** text field.
3. Locate the **Parameters** section. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `submarine_cable_a_geom_parameters.txt`.

Geometric Parameters 2

1. In the **Home** toolbar, click **Parameters** and choose **Add** > **Parameters**.
2. In the **Settings** window for **Parameters**, type `Geometric Parameters 2` in the **Label** text field.
3. Locate the **Parameters** section. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `submarine_cable_b_geom_parameters.txt`.

Electromagnetic Parameters

1. In the **Home** toolbar, click **Parameters** and choose **Add** > **Parameters**.

2. In the **Settings** window for **Parameters**, type `Electromagnetic Parameters` in the **Label** text field.
3. Locate the **Parameters** section. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `submarine_cable_c_elec_parameters.txt`.

DEFINITIONS

The cable is 10 km long and contains features of about 1 mm thick. This extreme aspect ratio leads to challenges for the geometry sequence, the physics, the mesh and the plots. In order to avoid this situation, the coordinate system is scaled in the axial direction by a factor of `Scab`; 10^5. This will make the cable seem 10 km, even though the actual geometry is only 10 cm long (see section On Scaled Systems).

Scaling System 2 (sys2)

1. In the **Definitions** toolbar, click **Coordinate Systems** and choose **Scaling System**.
2. In the **Settings** window for **Scaling System**, locate the **Domain Selection** section.
3. From the **Selection** list, choose **All domains**.
4. Locate the **Settings** section. Find the **Coordinate mapping** subsection. In the table, enter the following settings:

Coordinate	Expression	Unit
x3	Scab*z	m

GEOMETRY 1

The geometry contains only one phase. More precisely, it contains the insulators and the screen surrounding the main conductor of that one phase. In the 2D axisymmetric representation, this translates to a couple of rectangles. The first rectangle that is added will seem superfluous at first. It will be used to split the cable into sections later.

Rectangle 1 (r1)

1. In the **Geometry** toolbar, click **Rectangle**.
2. In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3. In the **Width** text field, type `Dins/2+Tpbs-Dcon/2`.
4. In the **Height** text field, type `Lcab/Scab`.

   (Note that the division by `Scab` compensates for the effects of the scaling system).
5. Locate the **Position** section. In the **r** text field, type `Dcon/2`.

Rectangle 2 (r2)

1 Right-click **Rectangle 1 (r1)** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, click to expand the **Layers** section.

3 In the table, enter the following settings:

Layer name	**Thickness (m)**
`Layer 1`	`Tscc`
`Layer 2`	`Tins`
`Layer 3`	`Tscc`

4 Select the **Layers to the left** checkbox.

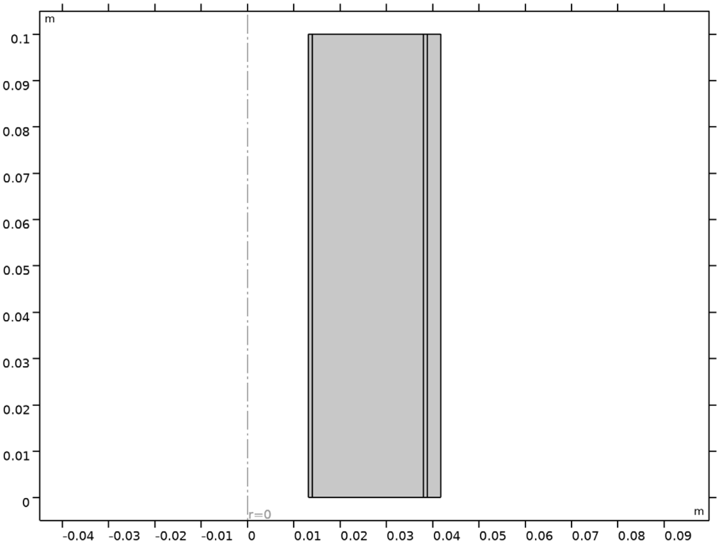
5 Clear the **Layers on bottom** checkbox.

Form Union (fin)

1 In the **Geometry** toolbar, click **Build All**.

2 Click the **Zoom Extents** button in the **Graphics** toolbar.

3 In the **Model Builder** window, click **Form Union (fin)**.



DEFINITIONS

The materials are roughly the same as those used in the *Capacitive Effects* tutorial. To start with, you can modify the **View** to show the material colors. Then, the materials will be added, they will be given an appropriate label, a selection and an appearance.

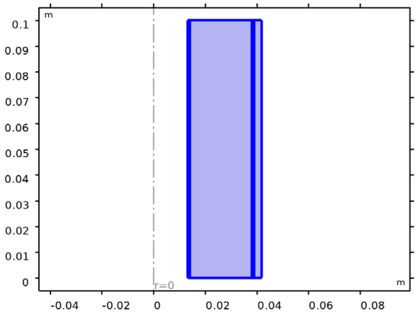
View 1

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Definitions** click **View 1**.
2. In the **Settings** window for **View**, locate the **Colors** section.
3. Select the **Show material color and texture** checkbox.

MATERIALS

Semiconductive compound

1. In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
2. In the **Settings** window for **Material**, type `Semiconductive compound` in the **Label** text field.
3. Click the **Zoom to Selection** button in the **Graphics** toolbar.



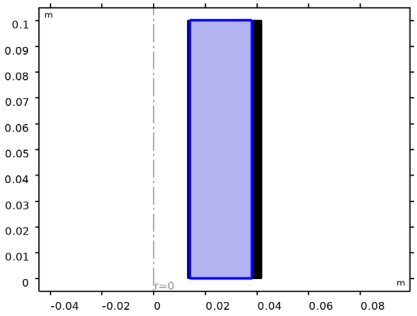
A good approach is to assign the first material to all domains by default. Subsequently, you can override it locally, using additional materials. This ensures every domain has access to material properties.

4. Click to expand the **Appearance** section. From the **Color** list, choose **Black**.

Cross-linked polyethylene (XLPE)

1. Right-click **Materials** and choose **Blank Material**.
2. In the **Settings** window for **Material**, type `Cross-linked polyethylene (XLPE)` in the **Label** text field.

3 Select Domain 2 only.



4 Click to expand the **Appearance** section.

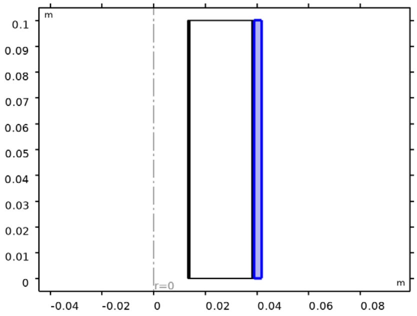
Notice that "white plastic" is the default setting. Leave it unchanged.

Lead

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Lead` in the **Label** text field.

3 Select Domain 4 only.



4 Click to expand the **Appearance** section. From the **Material type** list, choose **Lead**.

MATERIALS

Now, you will see that COMSOL starts detecting missing material properties. The properties that should be added are listed in the following table. Please check all of them for the correct value, even the ones that are already filled in. Note that for cases like this, *a convenient option is to copy-paste the values directly from this *.pdf file to COMSOL.*

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Materials**, add the following material properties:

	Label	sigma [S/m]	epsilonr
mat1	`Semiconductive compound`	`2[S/m]`	`2.25`
mat2	`Cross-linked polyethylene (XLPE)`	`1e-18[S/m]`	`Exlpe`
mat3	`Lead`	`Spbs`	`1`

Modeling Instructions — Single-Point Bonding

In case of single-point bonding, the screen is electrically paired with the same phase across the entire length of the cable. Furthermore, it is bonded and grounded at one end only, see section Single-Point Bonding.

From the *Capacitive Effects* tutorial, we know that about 5.5 A will leak from the central conductor each kilometer (as given by `Icpha`). Based on the assumption that the potential of the central conductor and the screen remains more or less constant along the cable, we expect that the charging currents in the screen will build up linearly (see section On Charging Currents). At the ground point, a total of `Lcab*Icpha` will leave the cable. This evaluates to about 55 A.

Since the current builds up linearly, the average current will be `1/2*Lcab*Icpha`, that is; (55 A)/2. Consequently, the screen potential at the free end of the cable will be `1/2*Lcab*Icpha*Lcab*Rpbs`, and the total RMS losses per phase, $|I|^2R/2$, will be `1/6*(Lcab*Icpha)^2*Lcab*Rpbs`. This evaluates to 83 V and 1.5 kW respectively (where the variable names refer to the parameters used throughout this tutorial series).

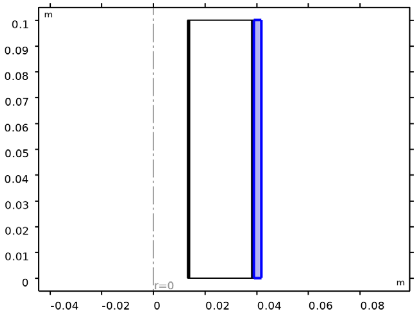
The expected 83 V raise seems to contradict the assumption of the screen potential being constant along the cable. Compared to the 127 kV on the main conductor however, it will be negligible. Let us see if we can reproduce these results. Start by introducing an anisotropic conductivity for the lead.

ELECTRIC CURRENTS (EC)

Current Conservation in Solids 2

1. In the **Physics** toolbar, click **Domains** and choose **Current Conservation in Solids**.

2 Select Domain 4 only.



3 In the **Settings** window for **Current Conservation in Solids**, locate the **Constitutive Relation Jc-E** section.

4 From the σ list, choose **User defined**. From the list, choose **Diagonal**.

5 Specify the σ matrix as

`Spbs/Scab`	`0`	`0`
`0`	`Spbs`	`0`
`0`	`0`	`Spbs`

In order to get the model numerically stable, you have now scaled the r-component of the conductivity. From an electrical viewpoint, the extreme aspect ratio caused by the coordinate transformation has been compensated for (see section On Scaled Systems).

This compensation will not influence the results significantly though, as even with this large scale factor, the lead is still by far the best conductor in the radial direction: The insulators will determine the current. This reasoning is similar to the one applied in the *Capacitive Effects* tutorial, when setting the conductors to 5 S/m.

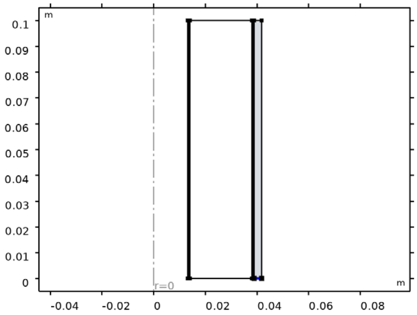
In the z direction however, the materials are placed in *parallel* (as opposed to *series*), and the lead will dominate. In this direction it is important to use a realistic value for the lead conductivity. The φ direction is of limited significance. Because of symmetry reasons, there will be no current flowing in that direction (the model solves for in-plane currents only).

Next, add a ground point and an electric potential for the central conductor.

Ground 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Ground**.

2 Select Boundary 11 only, (*on the bottom-right*).

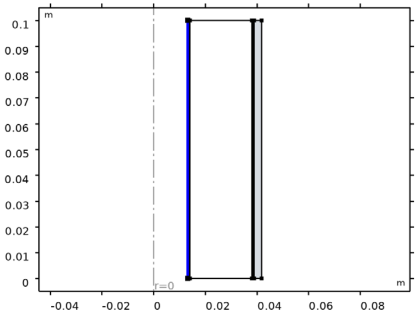


Phase 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Electric Potential**.

2 In the **Settings** window for **Electric Potential**, type `Phase 1` in the **Label** text field.

3 Select Boundary 1 only.



4 Locate the **Electric Potential** section. In the V_0 text field, type `(V0-(I0*Rcon*sys2.z))`.

Here, for the sake of completeness we have included an approximation of the potential drop caused by the currents in the main conductor, using the z-coordinate from the scaling system and the phase DC resistance. At the end of the cable, the potential drop should be about `I0*Rcon*Lcab`, that is; 311 V. Proceed by computing the solution.

STUDY 1

Step 1: Frequency Domain

1 In the **Model Builder** window, under **Study 1** click **Step 1: Frequency Domain**.

2 In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.

3 In the **Frequencies** text field, type `f0`.

4. In the **Study** toolbar, click **Compute**.

RESULTS

Electric Potential (ec)

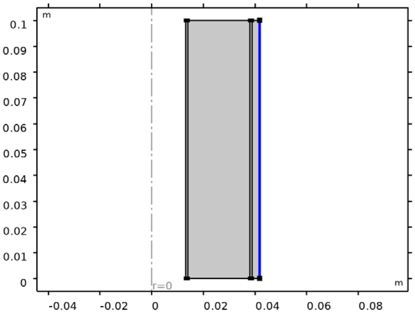
The default plot is not very informative in this case. Let us make some 1D plots to investigate the currents and voltages in the screen.

Electric Potential Norm, 1D (ec)

1. In the **Results** toolbar, click **1D Plot Group**.
2. In the **Settings** window for **1D Plot Group**, type `Electric Potential Norm, 1D (ec)` in the **Label** text field.

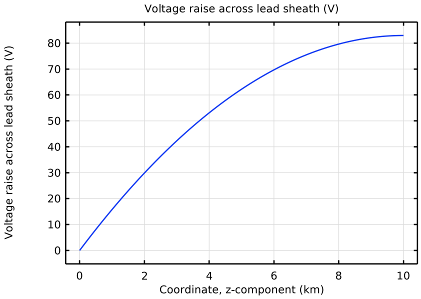
Line Graph 1

1. Right-click **Electric Potential Norm, 1D (ec)** and choose **Line Graph**.
2. Select Boundary 13 only.



3. In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
4. In the **Expression** text field, type `abs(V)`.
5. Select the **Description** checkbox. In the associated text field, type `Voltage raise across lead sheath`.
6. Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
7. In the **Expression** text field, type `sys2.z`.
8. From the **Unit** list, choose **km**.

9 In the **Electric Potential Norm, 1D (ec)** toolbar, click **Plot**.



The plot should look like half a parabola (upside down) and reach 83 V, as predicted. This suggests the assumption of the linear increase of screen currents along the cable is justified.

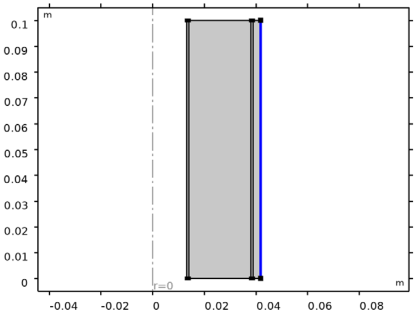
Let us check those currents, and the corresponding losses.

Electric Current Norm, 1D (ec)

1. In the **Results** toolbar, click **1D Plot Group**.
2. In the **Settings** window for **1D Plot Group**, type `Electric Current Norm, 1D (ec)` in the **Label** text field.

Line Graph 1

1. Right-click **Electric Current Norm, 1D (ec)** and choose **Line Graph**.
2. Select Boundary 13 only.



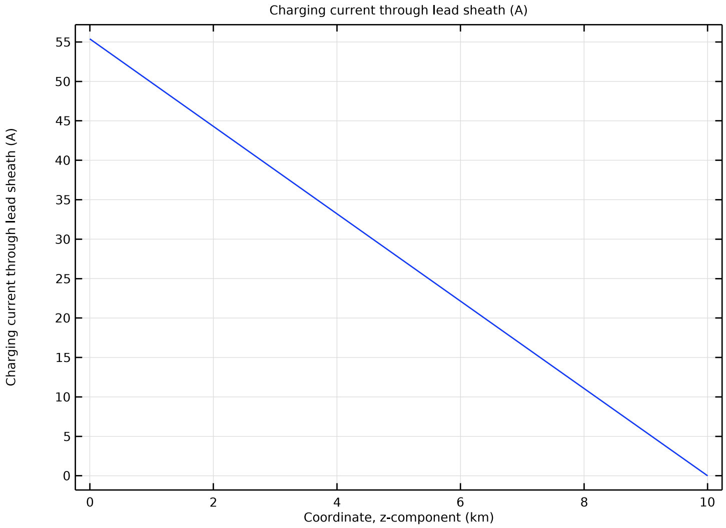
3. In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
4. In the **Expression** text field, type `ec.normJ*Apbs`.
5. Select the **Description** checkbox. In the associated text field, type `Charging current through lead sheath`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `sys2.z`.

8 From the **Unit** list, choose **km**.

9 In the **Electric Current Norm, 1D (ec)** toolbar, click **Plot**.



For this plot, you have multiplied the current density norm `ec.normJ` by the cross section of the lead sheath to get the total current per phase, along the cable. The current near the ground point should be 55 A.

Resistive Losses

1 In the **Results** toolbar, click 8.85 e-12 **More Derived Values** and choose **Integration** > **Surface Integration**.

2 In the **Settings** window for **Surface Integration**, type `Resistive Losses` in the **Label** text field.

3 Locate the **Selection** section. From the **Selection** list, choose **All domains**.

4 Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
`ec.Qh*Scab`	`W`	`Resistive losses`

5 Click **Evaluate**.

TABLE 1

1. Go to the **Table 1** window.

   For the losses, the quantity `ec.Qh` has been multiplied with `Scab`, to compensate for the scaling (as the integration operator is unaware of the scale factor). The total losses per phase should be about 1.5 kW (the value deviates from the analytical result by 0.5% or so, due to scaling the *r*-component of the lead conductivity).

   Notice that all domains have been selected here, while the analytical prediction only considers the screen. The fact that the results agree, suggests no significant losses occur in the insulators. This is according to our expectations, *feel free to check this.*

Now, one could argue single-point bonding is almost too simple to build a model for. Indeed, you can consider this a *verification*: We know now our general reasoning is sound and COMSOL is able to reproduce it within 1%, at least. The next bonding types will be a bit less obvious.

Modeling Instructions — Solid Bonding

In case of solid bonding, the screen is bonded and grounded at both ends, see section Solid Bonding. Since the charging current now only has half a cable to accumulate, the current near the ground points will be `1/2*Lcab*Icpha`, or 28 A. For the voltage and the losses a similar reasoning holds. We get `1/8*Lcab*Icpha*Lcab*Rpbs`, and `1/24*(Lcab*Icpha)^2*Lcab*Rpbs`, which evaluates to 21 V and 0.38 kW respectively.

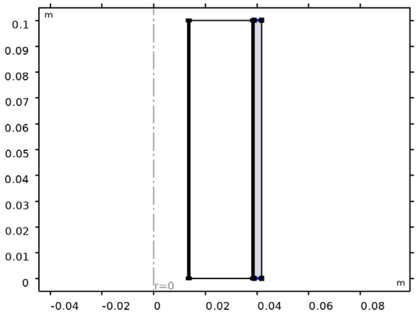
Proceed by reproducing this arrangement.

ELECTRIC CURRENTS (EC)

Ground 1

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Electric Currents (ec)** click **Ground 1**.

2 Select Boundaries 11 and 12 only.



STUDY 1

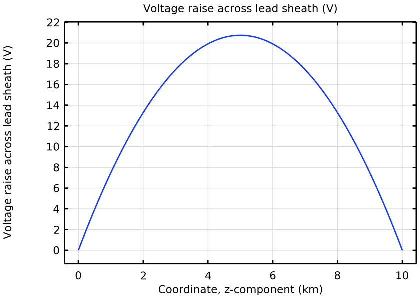
In the **Study** toolbar, click = **Compute**.

RESULTS

Electric Potential Norm, 1D (ec)

1 In the **Model Builder** window, under **Results** click **Electric Potential Norm, 1D (ec)**.

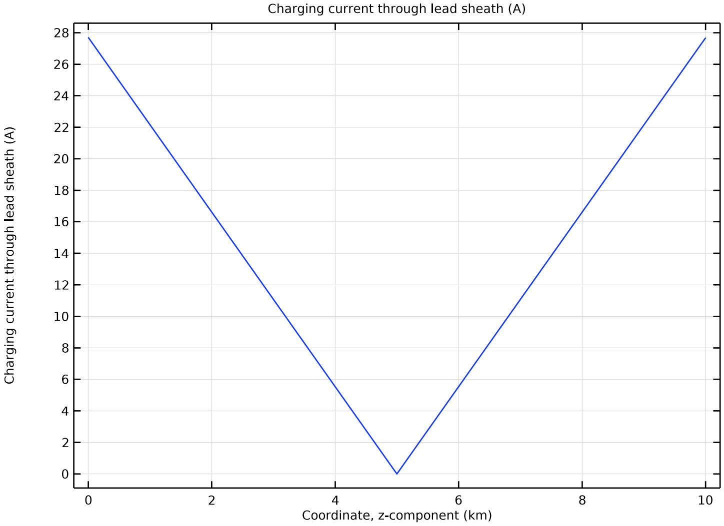
2 In the **Electric Potential Norm, 1D (ec)** toolbar, click **Plot**.



Electric Current Norm, 1D (ec)

1 In the **Model Builder** window, click **Electric Current Norm, 1D (ec)**.

2 In the **Electric Current Norm, 1D (ec)** toolbar, click **Plot**.



Resistive Losses

1 In the **Model Builder** window, under **Results > Derived Values** click **Resistive Losses**.

2 In the **Settings** window for **Surface Integration**, click **=** **Evaluate**.

TABLE 1

1 Go to the **Table 1** window.

The maximum potential is about 21 V, the maximum current is 28 A, and the total losses are about 0.38 kW per screen (as analytically predicted).

Modeling Instructions — Cross Bonding

In case of cross bonding, the total length of cable is split in three sections of equal length. From an electrical point of view, the screen is paired with a different phase for each section. Consequently, for a well balanced cable, the total net current that enters the screen is zero (see section Cross Bonding).

Let us proceed by reproducing this arrangement. Start by splitting the cable in three parts.

GEOMETRY 1

Rectangle 1 (r1)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Geometry 1** click **Rectangle 1 (r1)**.

2 In the **Settings** window for **Rectangle**, locate the **Layers** section.

3 In the table, enter the following settings:

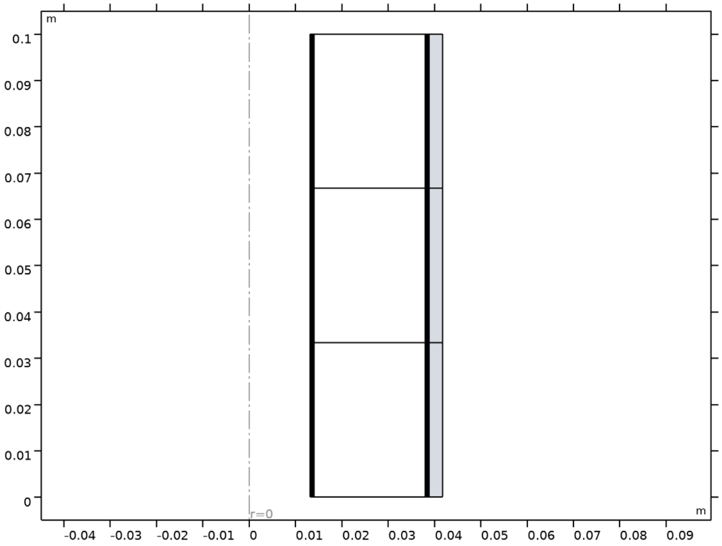
Layer name	**Thickness (m)**
`Layer 1`	`Lsec1*Lcab/Scab`
`Layer 2`	`Lsec2*Lcab/Scab`

Form Union (fin)

1 In the **Geometry** toolbar, click **Build All**.

2 Click the **Zoom Extents** button in the **Graphics** toolbar.

3 In the **Model Builder** window, click **Form Union (fin)**.

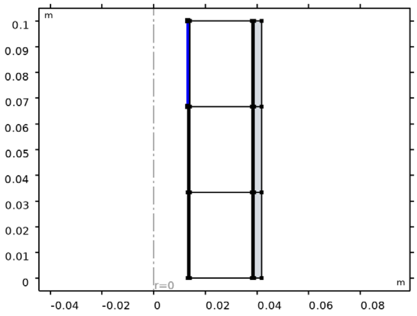


Now that the cable is divided in three equal sections, apply a different phase potential to each of them.

ELECTRIC CURRENTS (EC)

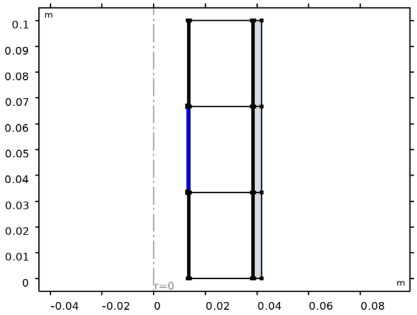
Phase 1

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Electric Currents (ec)** click **Phase 1**.
2. Select Boundary 5 only.



Phase 2

1. In the **Physics** toolbar, click **Boundaries** and choose **Electric Potential**.
2. In the **Settings** window for **Electric Potential**, type `Phase 2` in the **Label** text field.
3. Select Boundary 3 only.



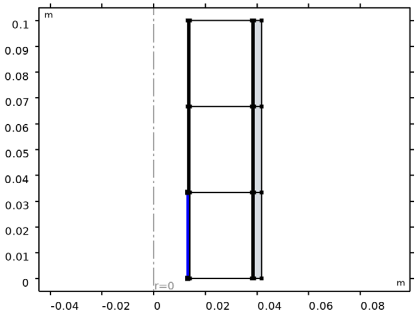
4. Locate the **Electric Potential** section. In the V_0 text field, type `(V0-(I0*Rcon*sys2.z))*exp(-120[deg]*j)`.

   Note that for longer expressions like this one, *the easiest way to go, is to copy-paste them directly from this *.pdf file to COMSOL.*

Phase 3

1. In the **Physics** toolbar, click **Boundaries** and choose **Electric Potential**.
2. In the **Settings** window for **Electric Potential**, type `Phase 3` in the **Label** text field.

3 Select Boundary 1 only.



4 Locate the **Electric Potential** section. In the V_0 text field, type `(V0-(I0*Rcon*sys2.z))*exp(+120[deg]*j)`.

Since we are in the frequency domain here, expressions like `exp(-120[deg]*j)` or `exp(-j*2*pi/3)` may be used to set a 120° phase shift between the AC voltages on the three main conductors.

Lastly, as the model now represents three separate phases (only the screen is electrically continuous), you will need to add some insulation in-between.

Electric Insulation 2

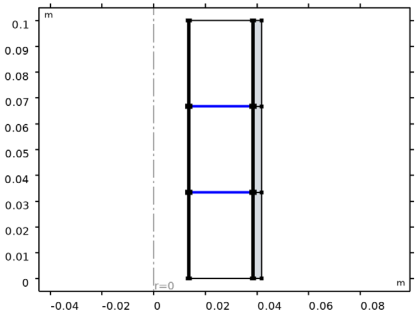
1 In the **Physics** toolbar, click **Boundaries** and choose **Electric Insulation**.

2 In the **Settings** window for **Electric Insulation**, locate the **Boundary Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `4, 6, 11, 13, 18, 20` in the **Selection** text field.

5 Click **OK**.



STUDY 1

In the **Study** toolbar, click **Compute**.

RESULTS

Electric Potential (ec)

These results are phase dependent. Therefore, the default plot **Electric Potential**, may be a bit deceiving. Create an animation to see what is going on.

Streamline 1

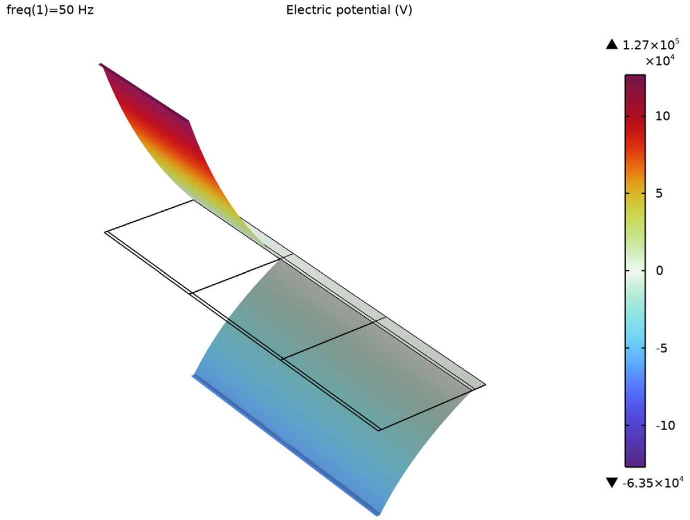
1. In the **Model Builder** window, expand the **Electric Potential (ec)** node.
2. Right-click **Streamline 1** and choose **Disable**.

Surface 1

1. In the **Model Builder** window, click **Surface 1**.
2. In the **Settings** window for **Surface**, locate the **Coloring and Style** section.
3. From the **Scale** list, choose **Linear symmetric**.

Height Expression 1

1. Right-click **Surface 1** and choose **Height Expression**.
2. In the **Electric Potential (ec)** toolbar, click **Plot**.
3. Click the **Go to Default View** button in the **Graphics** toolbar.
4. In the **Model Builder** window, click **Height Expression 1**.



Animation 1

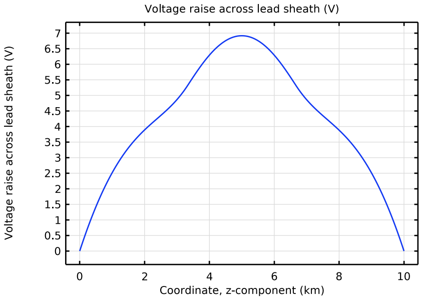
1. In the **Results** toolbar, click **Animation** and choose **Player**.

2. In the **Settings** window for **Animation**, locate the **Animation Editing** section.
3. From the **Sequence type** list, choose **Dynamic data extension**.
4. Locate the **Frames** section. In the **Number of frames** text field, type `60`.
5. Locate the **Playing** section. From the **Repeat** list, choose **Forever**.
6. Click the ▶ **Play** button in the **Graphics** toolbar (see the animation from ref. [1]).

   So the different phases are exchanging currents. Now, the currents will not have to build-up all the way to the ground point. Instead, they are compensated for within the cable. As a result, the average current, the potential and the losses in the screen are reduced significantly. Let us investigate to what extent this is the case.
7. Click the **Stop** button in the **Graphics** toolbar.

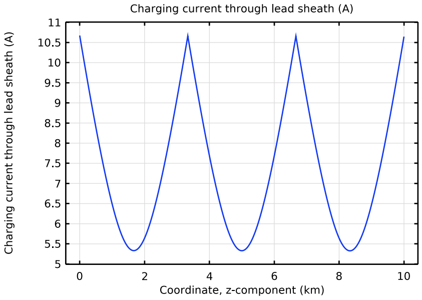
Electric Potential Norm, 1D (ec)

1. In the **Model Builder** window, under **Results** click **Electric Potential Norm, 1D (ec)**.
2. In the **Electric Potential Norm, 1D (ec)** toolbar, click **Plot**.



Electric Current Norm, 1D (ec)

1. In the **Model Builder** window, click **Electric Current Norm, 1D (ec)**.
2. In the **Electric Current Norm, 1D (ec)** toolbar, click **Plot**.



Resistive Losses

1. In the **Model Builder** window, under **Results** > **Derived Values** click **Resistive Losses**.
2. In the **Settings** window for **Surface Integration**, click = **Evaluate**.

TABLE 1

1. Go to the **Table 1** window.

   The maximum current is 10.7 A. This current occurs at the two intersections and the bonded ends. The maximum potential is about 6.9 V, and the total losses are about 85 W per screen.

What these results tell us is that from a loss point of view, cross bonding is not a bad idea. Secondly, we see that there is little or no effect of the bonding types on the charging currents: Since the 127 kV that is put on the central conductors is huge compared to any of the other potentials we have seen coming by (including the ones from the *Bonding Inductive* tutorial), the charging current will always be about 5.5 A/km. In other words, the reasoning proposed in section On Charging Currents, is valid.

Furthermore, we see that the resulting current densities are small compared to those in the *Inductive Effects* tutorial. As a result, there is only a weak coupling between the inductive and capacitive part of the device, justifying the approach chosen for these tutorials. Finally, one thing this model can do that most of the others cannot, is showing the effect of having sections of dissimilar length. Please feel free to change `Lsec1` and `Lsec3` — *be careful not to put them to zero though, as it changes the number of sections.*

You have now completed this tutorial, subsequent tutorials will refer to the resulting file as `submarine_cable_03_bonding_capacitive.mph`. The next tutorial in this series will include a detailed inductive analysis.

1. From the **File** menu, choose **Save As**.
2. Browse to a suitable folder and type the filename `submarine_cable_03_bonding_capacitive.mph`.