Model created in COMSOL Multiphysics 6.4

Thin Conductive Layer Using the Transition Boundary Condition

Introduction

In electromagnetic simulations, such as transformers and converter stations, one often needs to include geometrically thin conductive layers. Explicitly meshing these thin layers can be computationally expensive and numerically challenging, especially when the layer thickness is much smaller than the wavelength of electromagnetic waves or the characteristic mesh size.

In COMSOL Multiphysics, you can approximate conductive layers by using the *Transition Boundary Condition* (*TBC*) or the *Impedance Boundary Condition (IBC*) features. Both the TBC and IBC features support not only frequency domain analysis but also time domain analysis. This example focuses on the TBC and demonstrates that it can produce accurate results in both time- and frequency-domain simulations. The model geometry used in this example was first proposed in Ref. 1, where a frequency-domain analysis is performed.

Model Definition

The 2D model shown in Figure 1 is a conducting layer consisting of two apertures. The aperture on the left is a conductor with a conductivity σ, whereas the right one is a small open aperture. The boundaries in blue are magnetically insulated. The excitation of the magnetic field is an oscillating line current, pointing out of the plane.

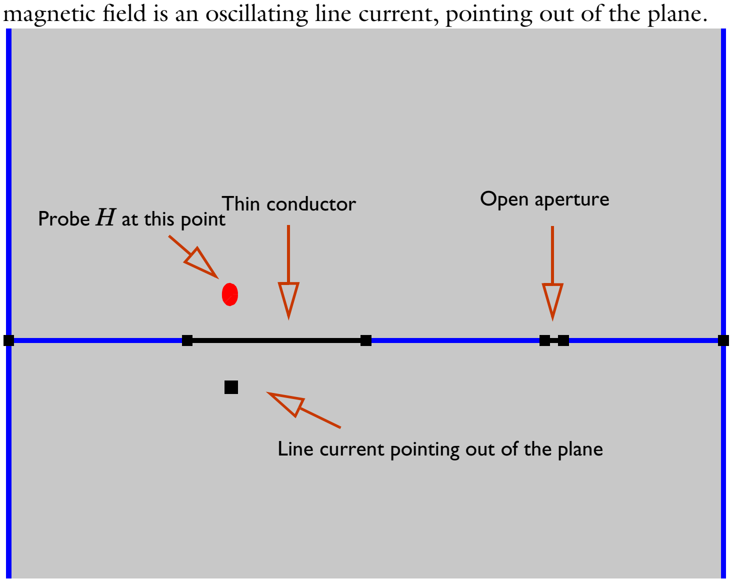


Figure 1: The geometry of the full-fidelity 2D model.

A layer being geometrically thin does not necessarily mean it is electrically thin under the external magnetic field. One needs to compare the layer's geometrical size with the characteristic skin depth to determine the layer's electrical type. There are 3 types of layers in EM simulations, depending on the ratio of the skin depth $\delta(\omega) = \sqrt{2/(\mu\sigma\omega)}$ and the layer's geometric thickness d_s. One can classify the electrical thickness of the layer according to the following definition: electrically very thin layer ($d_s/\delta < 0.5$), electrically thin layer ($0.5 \le d_s/\delta \le 20$), and electrically thick layer ($20 < d_s/\delta$).

To benchmark the simulation results using the TBC, one can compare them with the results from a model in which the interior of the layer is explicitly meshed and the skin effect is fully resolved, which will be referred to as the full-fidelity model.

First, a frequency-domain simulation is performed to calculate the magnetic field $\boldsymbol{H}$ at a point slightly above the layer, as indicated by the red dot in Figure 1. Next, a corresponding time-domain simulation is carried out by exciting the model with a time-dependent oscillating current. As will be demonstrated by this example, in both scenarios, the TBC produces accurate and reliable results.

Results (Frequency Domain)

The electrical thickness of the layer can be tuned by varying its conductivity σ. A parameter sweep over σ at a fixed frequency `fc=100` Hz is performed and for each σ, the norm of the magnetic field is calculated at a point located 2 mm above the layer.

As shown in Figure 2, for small values of d_s/δ the results from both the electrically very thin and electrically thin layer models agree well with those from the full-fidelity model. As the conductivity increases, the layer transitions from electrically very thin regime to electrically thin regime. In this transition region, one can observe a drop in the magnitude of $\boldsymbol{H}$.

When the conductivity is increased further, the layer effectively becomes electrically thick, thereby preventing the magnetic field from penetrating through it. This occurs because the skin depth becomes small for a highly conductive layer. In the thick-layer regime, the magnetic field in the shielding region is mainly due to leakage through the small open aperture. This is also illustrated in Figure 3: for small conductivities, the magnetic field in the region between the conducting layer and the line source has a nonzero component perpendicular to the layer. However, for large conductivities, the field lines near the conductor are almost entirely parallel to the layer, and the magnetic field in the shielding region originates solely from the open aperture, as expected.

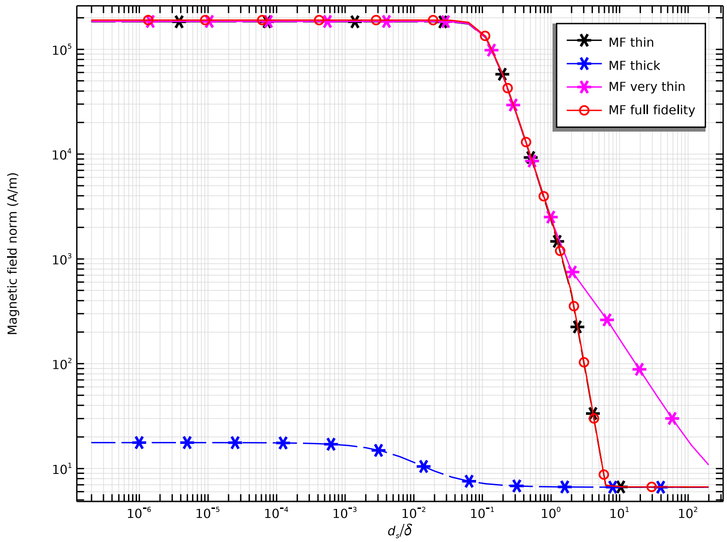


Figure 2: Magnetic field norm measured above the conductive layer as a function of d_s/δ.

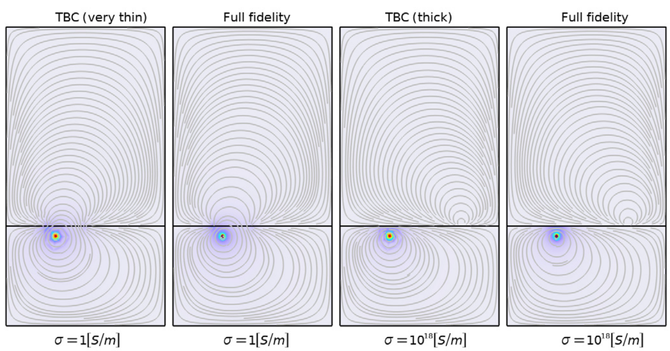


Figure 3: Magnetic field distribution (contour plots) for the thin- and thick-layer cases obtained with the TBC model, shown alongside their full-fidelity counterparts.

Results (Time Domain)

In the time-domain simulation, the model is excited with a time-dependent current $I(t)$ = `1000*sin(2*pi*fc*t)*exp(-t*fc)`, which is plotted in as a function of t in Figure 4.

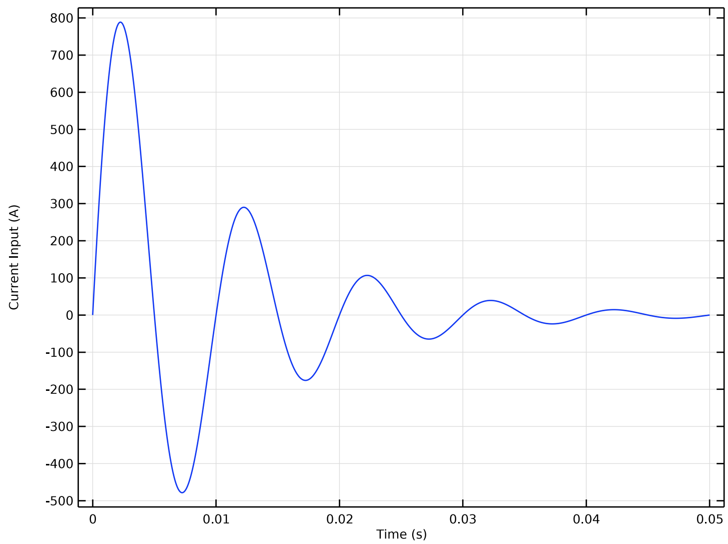


Figure 4: Current as a function of time.

Note that, to use the electrically thick layer in the TBC feature in the time domain, the **Compute Approximation** button must first be clicked before solving the model. This step computes a partial-fraction fit for the real and imaginary parts of the surface admittance Y_s for a wide range of frequencies, which is required for time-domain analysis. The accuracy of the partial-fraction fit (High, Normal, or Low) can be adjusted according to the user's needs. For electrically thin or very thin layers, the partial-fraction fit is unnecessary, as the approximation is precalculated automatically. For time-domain studies, a characteristic or center frequency (f_c) must be specified when choosing the electrically thick layer.

In Figure 5, the magnetic field $H(t)$ on the shielding side of the thick layer is probed at different points in time. The parameter used for Figure 5 is chosen such that $d_s/\delta = 48 > 20$. Good agreement between the TBC (thick layer) and the full-fidelity model is found, whereas the very thin layer (magenta) and the thin layer (black) options show clear deviations, as expected. This shows that choosing the correct type of layer is important.

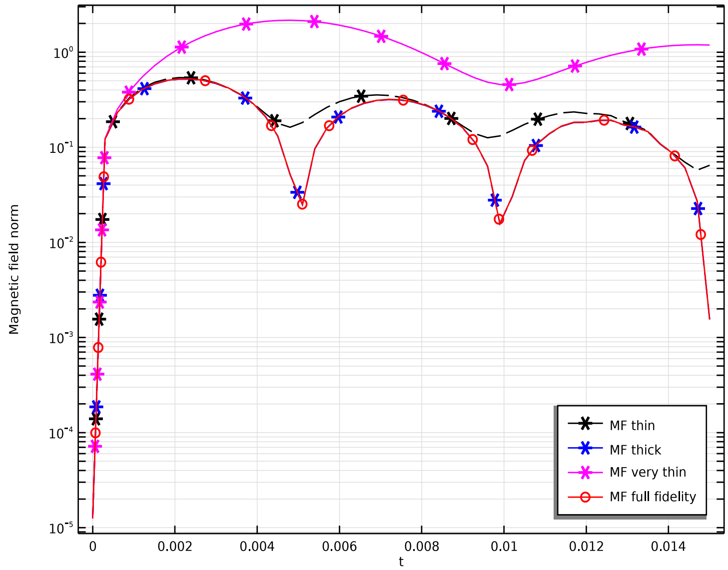


Figure 5: The magnitude of $H(t)$ probed above the electrically thick conductive layer.

Reference

1. G. Eriksson, "Efficient 3D simulation of thin conducting layers of arbitrary thickness," in *2007 IEEE International Symposium on Electromagnetic Compatibility*, pp. 1–6, IEEE, 2007.

Application Library path: `ACDC_Module/Verifications/thin_conductive_layer`

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**.
2 In the **Select Physics** tree, select **AC/DC > Electromagnetic Fields > Magnetic Fields (mf)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies > Frequency Domain**.
6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 In the table, enter the following settings:

Name	Expression	Value	Description
conductivity	6*10^16[S/m]	6E16 S/m	
current_input	10000*exp(2*i*fc*pi)	10000	
delta	sqrt(2/(mur*mu0_const*conductivity*fc*2*pi))	2.0547E-7 m	
fc	0.0000001[GHz]	100 Hz	
height_conductor	5[mm]	0.005 m	
height_upperplane	10[mm]	0.01 m	
mur	1	1	
period	1/fc	0.01 s	
ratio	height_layer/delta	48.669	
width_aperture	0.2[mm]	2E-4 m	
width_aperture_big	2[mm]	0.002 m	
width_shift	2[mm]	0.002 m	
width_whole	8[mm]	0.008 m	
height_layer	10[um]	1E-5 m	

Current Input Time

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global > Analytic**.

2 In the **Settings** window for **Analytic**, type `Current Input Time` in the **Label** text field.

3 Locate the **Definition** section. In the **Expression** text field, type `sin(2*pi*fc*t)*exp(-t/period)*1000`.

4 In the **Arguments** text field, type `t`.

5 In the **Function name** text field, type `current_input_time`.

6 Click **Plot**.

GEOMETRY 1

Upper Plane

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Geometry 1** node.

2 Right-click **Geometry 1** and choose **Rectangle**.

3 In the **Settings** window for **Rectangle**, type `Upper Plane` in the **Label** text field.

4 Locate the **Size and Shape** section. In the **Width** text field, type `width_whole`.

5 In the **Height** text field, type `height_upperplane`.

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Conductor

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, type `Conductor` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `width_whole`.

4 In the **Height** text field, type `height_conductor`.

5 Locate the **Position** section. In the **y** text field, type `-height_conductor`.

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 In the **x** text field, type `width_shift`.

5 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

6 In the **x** text field, type `width_aperture_big+width_shift`.

7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Line Segment 2 (ls2)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 In the **x** text field, type `width_shift*3`.

5 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

6 In the **x** text field, type `width_aperture+width_shift*3`.

7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Point 1 (pt1)

1 In the **Geometry** toolbar, click **Point**.

2 In the **Settings** window for **Point**, locate the **Point** section.

3 In the **x** text field, type `2.5[mm]`.

4 In the **y** text field, type `-0.5[mm]`.

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Form Union (fin)

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

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

TBC IN THE FREQUENCY DOMAIN

1 In the **Model Builder** window, click **Component 1 (comp1)**.

2 In the **Settings** window for **Component**, type `TBC in the Frequency Domain` in the **Label** text field.

THIN LAYER

1 In the **Model Builder** window, under **TBC in the Frequency Domain (comp1)** click **Magnetic Fields (mf)**.

2 In the **Settings** window for **Magnetic Fields**, type `Thin Layer` in the **Label** text field.

3 Click to expand the **Discretization** section.

Transition Boundary Condition 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Transition Boundary Condition**.
2 Select Boundary 6 only.
3 In the **Settings** window for **Transition Boundary Condition**, locate the **Transition Boundary Condition** section.
4 From the ε_{rb} list, choose **User defined**. From the μ_{rb} list, choose **User defined**. In the associated text field, type `mur`.
5 From the σ_b list, choose **User defined**. In the associated text field, type `conductivity`.
6 In the d_s text field, type `height_layer`.

Line Current (Out-of-Plane) 1

1 In the **Physics** toolbar, click **Points** and choose **Line Current (Out-of-Plane)**.
2 Select Point 5 only.
3 In the **Settings** window for **Line Current (Out-of-Plane)**, locate the **Line Current (Out-of-Plane)** section.
4 In the I_0 text field, type `current_input`.

Magnetic Insulation 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Magnetic Insulation**.
2 Select Boundaries 4, 7, and 9 only.
3 In the **Model Builder** window, right-click **Thin Layer (mf)** and choose **Copy**.

THICK LAYER

1 In the **Model Builder** window, right-click **TBC in the Frequency Domain (comp1)** and choose **Paste Magnetic Fields**.
2 In the **Messages from Paste** dialog, click **OK**.
3 In the **Settings** window for **Magnetic Fields**, type `Thick Layer` in the **Label** text field.

Transition Boundary Condition 1

1 In the **Model Builder** window, expand the **TBC in the Frequency Domain (comp1)** > **Thick Layer (mf2)** node, then click **Transition Boundary Condition 1**.
2 In the **Settings** window for **Transition Boundary Condition**, locate the **Transition Boundary Condition** section.
3 From the **Type** list, choose **Electrically thick layer**.
4 Locate the **Time Domain and Eigenfrequency** section. In the f_c text field, type `fc`.
5 From the **Accuracy** list, choose **High**.

6 Click **Approximation** in the upper-right corner of the **Time Domain and Eigenfrequency** section. From the menu, choose **Compute Approximation**.

THIN LAYER (MF)

In the **Model Builder** window, under **TBC in the Frequency Domain (comp1)** right-click **Thin Layer (mf)** and choose **Copy**.

VERY THIN LAYER

1 In the **Model Builder** window, right-click **TBC in the Frequency Domain (comp1)** and choose **Paste Magnetic Fields**.

2 In the **Messages from Paste** dialog, click **OK**.

3 In the **Settings** window for **Magnetic Fields**, type `Very Thin Layer` in the **Label** text field.

1 In the **Model Builder** window, expand the **TBC in the Frequency Domain (comp1)** > **Very Thin Layer (mf3)** node, then click **Transition Boundary Condition 1**.

2 In the **Settings** window for **Transition Boundary Condition**, locate the **Transition Boundary Condition** section.

3 From the **Type** list, choose **Electrically very thin layer**.

ADD COMPONENT

In the **Model Builder** window, right-click the root node and choose **Add Component** > **2D**.

GEOMETRY 2

Whole Layer

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, type `Whole Layer` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `width_whole`.

4 In the **Height** text field, type `height_layer`.

Big Aperture

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, type `Big Aperture` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `width_aperture_big`.

4 In the **Height** text field, type `height_layer`.

5 Locate the **Position** section. In the **x** text field, type `width_shift`.

Aperture

1 In the **Geometry** toolbar, click **Rectangle**.
2 In the **Settings** window for **Rectangle**, type Aperture in the **Label** text field.
3 Locate the **Size and Shape** section. In the **Width** text field, type width_aperture.
4 In the **Height** text field, type height_layer.
5 Locate the **Position** section. In the **x** text field, type width_shift*3.

Upper Plane

1 In the **Geometry** toolbar, click **Rectangle**.
2 In the **Settings** window for **Rectangle**, type Upper Plane in the **Label** text field.
3 Locate the **Size and Shape** section. In the **Width** text field, type width_whole.
4 In the **Height** text field, type height_upperplane.

Conductor

1 In the **Geometry** toolbar, click **Rectangle**.
2 In the **Settings** window for **Rectangle**, type Conductor in the **Label** text field.
3 Locate the **Size and Shape** section. In the **Width** text field, type width_whole.
4 In the **Height** text field, type height_conductor.
5 Locate the **Position** section. In the **y** text field, type -height_conductor.

Point 1 (pt1)

1 In the **Geometry** toolbar, click **Point**.
2 In the **Settings** window for **Point**, locate the **Point** section.
3 In the **x** text field, type 2.5[mm].
4 In the **y** text field, type -0.5[mm].
5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.
6 Click **Build All Objects**.
7 Click the **Zoom Extents** button in the **Graphics** toolbar.

Big Aperture (r2)

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

Upper Plane (r4)

1 In the **Model Builder** window, click **Upper Plane (r4)**.
2 In the **Settings** window for **Rectangle**, click **Build All Objects**.

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

FULLY RESOLVED LAYER IN THE FREQUENCY DOMAIN

1 In the **Model Builder** window, collapse the **Component 2 (comp2)** node.

2 In the **Model Builder** window, click **Component 2 (comp2)**.

3 In the **Settings** window for **Component**, type `Fully Resolved Layer in the Frequency Domain` in the **Label** text field.

ADD PHYSICS

1 In the **Home** toolbar, click **Add Physics** to open the **Add Physics** window.

2 Go to the **Add Physics** window.

3 In the tree, select **Recently Used** > **Magnetic Fields (mf)**.

4 Click the **Add to Fully Resolved Layer in the Frequency Domain** button in the window toolbar.

5 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

FULLY RESOLVED LAYER

1 In the **Settings** window for **Magnetic Fields**, type `Fully Resolved Layer` in the **Label** text field.

2 Select Domains 1, 3, 4, and 6 only.

Laminated Core 1

1 In the **Physics** toolbar, click **Domains** and choose **Laminated Core**.

2 In the **Settings** window for **Laminated Core**, locate the **Constitutive Relation B-H** section.

3 From the **Magnetization model** list, choose **Relative permeability**.

4 Select Domain 4 only.

5 From the μ_r list, choose **User defined**. In the associated text field, type `mur`.

6 Locate the **Stabilization** section. From the σ_{stab} list, choose **User defined**. In the associated text field, type `conductivity`.

Line Current (Out-of-Plane) 1

1 In the **Physics** toolbar, click **Points** and choose **Line Current (Out-of-Plane)**.

2 Select Point 7 only.

3 In the **Settings** window for **Line Current (Out-of-Plane)**, locate the **Line Current (Out-of-Plane)** section.

4 In the I_0 text field, type `current_input`.

MESH 2

Boundary Layers 1

In the **Mesh** toolbar, click **Boundary Layers**.

Boundary Layer Properties

1 In the **Model Builder** window, click **Boundary Layer Properties**.
2 In the **Settings** window for **Boundary Layer Properties**, locate the **Boundary Selection** section.
3 From the **Selection** list, choose **All boundaries**.
4 Locate the **Layers** section. In the **Number of layers** text field, type 4.

THIN LAYER (MF)

1 In the **Model Builder** window, under **TBC in the Frequency Domain (comp1)** click **Thin Layer (mf)**.
2 In the **Settings** window for **Magnetic Fields**, locate the **Discretization** section.
3 From the **Magnetic vector potential** list, choose **Cubic**.

THICK LAYER (MF2)

1 In the **Model Builder** window, under **TBC in the Frequency Domain (comp1)** click **Thick Layer (mf2)**.
2 In the **Settings** window for **Magnetic Fields**, locate the **Discretization** section.
3 From the **Magnetic vector potential** list, choose **Cubic**.

VERY THIN LAYER (MF3)

1 In the **Model Builder** window, under **TBC in the Frequency Domain (comp1)** click **Very Thin Layer (mf3)**.
2 In the **Settings** window for **Magnetic Fields**, locate the **Discretization** section.
3 From the **Magnetic vector potential** list, choose **Cubic**.

FULLY RESOLVED LAYER (MF4)

1 In the **Model Builder** window, under **Fully Resolved Layer in the Frequency Domain (comp2)** click **Fully Resolved Layer (mf4)**.
2 In the **Settings** window for **Magnetic Fields**, locate the **Discretization** section.
3 From the **Magnetic vector potential** list, choose **Cubic**.

FULLY RESOLVED LAYER IN THE FREQUENCY DOMAIN (COMP2), TBC IN THE FREQUENCY DOMAIN (COMP1)

Next, create time-domain studies by copying the TBC and fully resolved layer in the frequency domain.

1 In the **Model Builder** window, Ctrl-click to select **TBC in the Frequency Domain (comp1)** and **Fully Resolved Layer in the Frequency Domain (comp2)**.

2 Right-click and choose **Copy**.

TBC IN THE FREQUENCY DOMAIN 1 (COMP3)

In the **Model Builder** window, right-click the root node and choose **Paste Multiple Items**.

TBC IN THE TIME DOMAIN

1 In the **Messages from Paste** dialog, click **OK**.

2 In the **Settings** window for **Component**, type `TBC in the Time Domain` in the **Label** text field.

FULLY RESOLVED LAYER IN THE TIME DOMAIN

1 In the **Model Builder** window, click **Fully Resolved Layer in the Frequency Domain 1 (comp4)**.

2 In the **Settings** window for **Component**, type `Fully Resolved Layer in the Time Domain` in the **Label** text field.

THIN LAYER (MF5)

In the **Model Builder** window, expand the **Thin Layer (mf5)** node.

THIN LAYER (MF5)

Line Current (Out-of-Plane) 1

1 In the **Model Builder** window, expand the **TBC in the Time Domain (comp3)** > **Thick Layer (mf6)** node, then click **TBC in the Time Domain (comp3)** > **Thin Layer (mf5)** > **Line Current (Out-of-Plane) 1**.

2 In the **Settings** window for **Line Current (Out-of-Plane)**, locate the **Line Current (Out-of-Plane)** section.

3 In the I_0 text field, type `current_input_time(t)`.

THICK LAYER (MF6)

1 In the **Model Builder** window, expand the **TBC in the Time Domain (comp3)** > **Very Thin Layer (mf7)** node, then click **TBC in the Time Domain (comp3)** > **Thick Layer (mf6)** > **Line Current (Out-of-Plane) 1**.

2 In the **Settings** window for **Line Current (Out-of-Plane)**, locate the **Line Current (Out-of-Plane)** section.

3 In the I_0 text field, type `current_input_time(t)`.

VERY THIN LAYER (MF7)

1 In the **Model Builder** window, expand the **Fully Resolved Layer in the Time Domain (comp4)** > **Fully Resolved Layer (mf8)** node, then click **TBC in the Time Domain (comp3)** > **Very Thin Layer (mf7)** > **Line Current (Out-of-Plane) 1**.

2 In the **Settings** window for **Line Current (Out-of-Plane)**, locate the **Line Current (Out-of-Plane)** section.

3 In the I_0 text field, type `current_input_time(t)`.

FULLY RESOLVED LAYER (MF8)

1 In the **Model Builder** window, under **Fully Resolved Layer in the Time Domain (comp4)** > **Fully Resolved Layer (mf8)** click **Line Current (Out-of-Plane) 1**.

2 In the **Settings** window for **Line Current (Out-of-Plane)**, locate the **Line Current (Out-of-Plane)** section.

3 In the I_0 text field, type `current_input_time(t)`.

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 From the **Frequency unit** list, choose **GHz**.

4 In the **Frequencies** text field, type `fc`.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
conductivity	`10^range(0,0.5,18)`	`S/m`

Step 1: Frequency Domain

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

2 In the **Settings** window for **Frequency Domain**, locate the **Physics and Variables Selection** section.

3 In the **Solve for** column of the table, clear the checkboxes for **TBC in the Time Domain (comp3)** and **Fully Resolved Layer in the Time Domain (comp4)**.

ADD STUDY

1 In the **Study** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies** > **Time Dependent**.

4 Click the **Add Study** button in the window toolbar.

5 In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Time-Domain Study

1 In the **Settings** window for **Time Dependent**, type `Time-Domain Study` in the **Label** text field.

2 Locate the **Physics and Variables Selection** section. In the **Solve for** column of the table, clear the checkboxes for **TBC in the Frequency Domain (comp1)** and **Fully Resolved Layer in the Frequency Domain (comp2)**.

3 Locate the **Study Settings** section. In the **Output times** text field, type `range(0, 0.03*period, 1.5*period)`.

SWEEP OVER LAYER CONDUCTIVITY

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, type `Sweep over Layer Conductivity` in the **Label** text field.

TIME-DOMAIN STUDY

1 In the **Model Builder** window, click **Study 2**.

2 In the **Settings** window for **Study**, type `Time-Domain Study` in the **Label** text field.

SWEEP OVER LAYER CONDUCTIVITY

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

TIME-DOMAIN STUDY

Click **Compute**.

RESULTS

Cut Point 2D 1

Now "measure" the magnetic field at the point (2.5 mm, 2 mm), which is slightly above the layer for each calculation.

1. In the **Results** toolbar, click **Cut Point 2D**.
2. In the **Settings** window for **Cut Point 2D**, locate the **Point Data** section.
3. In the **x** text field, type `2.5[mm]`.
4. In the **y** text field, type `2[mm]`.

Cut Point 2D 2

1. Right-click **Cut Point 2D 1** and choose **Duplicate**.
2. In the **Settings** window for **Cut Point 2D**, locate the **Data** section.
3. From the **Dataset** list, choose **Sweep over Layer Conductivity/Solution 1 (2) (sol1)**.

Cut Point 2D 3

1. Right-click **Cut Point 2D 2** and choose **Duplicate**.
2. In the **Settings** window for **Cut Point 2D**, locate the **Data** section.
3. From the **Dataset** list, choose **Time-Domain Study/Solution 2 (7) (sol2)**.

Cut Point 2D 4

1. In the **Results** toolbar, click **Cut Point 2D**.
2. In the **Settings** window for **Cut Point 2D**, locate the **Point Data** section.
3. In the **x** text field, type `2.5[mm]`.
4. In the **y** text field, type `2[mm]`.
5. Locate the **Data** section. From the **Dataset** list, choose **Time-Domain Study/Solution 2 (8) (sol2)**.
6. Click **Plot**.

H vs. h/Delta

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `H vs. h/Delta` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 2D 1**.

MF Thin

1 Right-click **H vs. h/Delta** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, type `MF Thin` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 2D 1**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **TBC in the Frequency Domain (comp1)** > **Thin Layer** > **Magnetic** > **mf.normH - Magnetic field norm - A/m**.

5 In the **H vs. h/Delta** toolbar, click **Plot**.

6 Click the **y-Axis Log Scale** button in the **Graphics** toolbar.

7 Click the **x-Axis Log Scale** button in the **Graphics** toolbar.

MF Thick

1 Right-click **MF Thin** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **TBC in the Frequency Domain (comp1)** > **Thick Layer** > **Magnetic** > **mf2.normH - Magnetic field norm - A/m**.

3 In the **Label** text field, type `MF Thick`.

4 In the **H vs. h/Delta** toolbar, click **Plot**.

MF Very Thin

1 In the **Model Builder** window, right-click **H vs. h/Delta** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `mf3.normH`.

4 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 2D 1**.

5 From the **Solution parameters** list, choose **From parent**.

6 In the **H vs. h/Delta** toolbar, click **Plot**.

7 In the **Label** text field, type `MF Very Thin`.

8 In the **H vs. h/Delta** toolbar, click **Plot**.

9 Click **Plot**.

MF Fully Resolved Layer

1 Right-click **H vs. h/Delta** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Cut Point 2D 2**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Fully Resolved Layer in the Frequency Domain (comp2)** > **Fully Resolved Layer** > **Magnetic** > **mf4.normH - Magnetic field norm - A/m**.

5 In the **H vs. h/Delta** toolbar, click **Plot**.

6 In the **Label** text field, type `MF Fully Resolved Layer`.

7 In the **H vs. h/Delta** toolbar, click **Plot**.

MF Thin

1 In the **Model Builder** window, click **MF Thin**.

2 In the **Settings** window for **Point Graph**, locate the **x-Axis Data** section.

3 From the **Parameter** list, choose **Expression**.

4 In the **Expression** text field, type `height_layer/sqrt(2/(mur*mu0_const*conductivity*fc*2*pi))`.

5 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
MF thin

7 Select the **Show legends** checkbox.

8 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

9 From the **Color** list, choose **Black**.

10 Find the **Line markers** subsection. From the **Marker** list, choose **Asterisk**.

11 From the **Positioning** list, choose **Interpolated**.

12 In the **Number** text field, type `10`.

MF Thick

1 In the **Model Builder** window, click **MF Thick**.

2 In the **Settings** window for **Point Graph**, locate the **x-Axis Data** section.

3 From the **Parameter** list, choose **Expression**.

4 In the **Expression** text field, type height_layer/sqrt(2/(mur*mu0_const*conductivity*fc*2*pi)).

5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

6 From the **Color** list, choose **Blue**.

7 Find the **Line markers** subsection. From the **Marker** list, choose **Asterisk**.

8 From the **Positioning** list, choose **Interpolated**.

9 In the **Number** text field, type 12.

10 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

11 Select the **Show legends** checkbox.

12 In the table, enter the following settings:

Legends
MF thick

MF Very Thin

1 In the **Model Builder** window, click **MF Very Thin**.

2 In the **Settings** window for **Point Graph**, locate the **x-Axis Data** section.

3 From the **Parameter** list, choose **Expression**.

4 In the **Expression** text field, type height_layer/sqrt(2/(mur*mu0_const*conductivity*fc*2*pi)).

5 Locate the **Legends** section. Select the **Show legends** checkbox.

6 From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
MF very thin

8 Locate the **Coloring and Style** section. From the **Color** list, choose **Magenta**.

9 Find the **Line markers** subsection. From the **Marker** list, choose **Asterisk**.

10 From the **Positioning** list, choose **Interpolated**.

11 In the **Number** text field, type 14.

MF Fully Resolved Layer

1 In the **Model Builder** window, click **MF Fully Resolved Layer**.

2 In the **Settings** window for **Point Graph**, locate the **x-Axis Data** section.

3 From the **Parameter** list, choose **Expression**.

4 In the **Expression** text field, type `height_layer/sqrt(2/(mur*mu0_const*conductivity*fc*2*pi))`.

5 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
`MF full fidelity`

7 Select the **Show legends** checkbox.

8 Locate the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

9 From the **Positioning** list, choose **Interpolated**.

10 In the **Number** text field, type `16`.

11 From the **Color** list, choose **Red**.

H vs. h/Delta

1 In the **Model Builder** window, click **H vs. h/Delta**.

2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

3 Select the **x-axis label** checkbox. In the associated text field, type `\[d_{s}/\delta\]`.

4 In the **H vs. h/Delta** toolbar, click **Plot**.

H vs. h/Delta 1

1 Right-click **H vs. h/Delta** and choose **Duplicate**.

2 In the **Model Builder** window, click **H vs. h/Delta 1**.

3 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

4 From the **Dataset** list, choose **Cut Point 2D 3**.

5 Locate the **Plot Settings** section. In the **x-axis label** text field, type `t`.

MF Thin

1 In the **Model Builder** window, click **MF Thin**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Cut Point 2D 3**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `mf5.normH`.

5 Locate the **Data** section. From the **Solution parameters** list, choose **From parent**.

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

MF Thick

1 In the **Model Builder** window, click **MF Thick**.

2 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `mf6.normH`.

4 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 2D 3**.

5 From the **Solution parameters** list, choose **From parent**.

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

MF Very Thin

1 In the **Model Builder** window, click **MF Very Thin**.

2 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `mf7.normH`.

4 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 2D 3**.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Time**.

MF Fully Resolved Layer

1 In the **Model Builder** window, click **MF Fully Resolved Layer**.

2 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `mf8.normH`.

4 Locate the **Data** section. From the **Dataset** list, choose **Cut Point 2D 4**.

5 From the **Solution parameters** list, choose **From parent**.

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

7 In the **H vs. h/Delta 1** toolbar, click **Plot**.

H vs. t

1 In the **Model Builder** window, under **Results** click **H vs. h/Delta 1**.

2 In the **Settings** window for **1D Plot Group**, type `H vs. t` in the **Label** text field.

3 Locate the **Axis** section. Clear the **x-axis log scale** checkbox.

4 Locate the **Plot Settings** section.

5 Select the **y-axis label** checkbox. In the associated text field, type `Magnetic field norm`.

6 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

MF Thin

1 In the **Model Builder** window, under **Results** > **H vs. h/Delta** click **MF Thin**.

2 In the **Settings** window for **Point Graph**, click to expand the **Title** section.

3 From the **Title type** list, choose **None**.

MF Thick

1 In the **Model Builder** window, click **MF Thick**.

2 In the **Settings** window for **Point Graph**, locate the **Title** section.

3 From the **Title type** list, choose **None**.

MF Very Thin

1 In the **Model Builder** window, click **MF Very Thin**.

2 In the **Settings** window for **Point Graph**, locate the **Title** section.

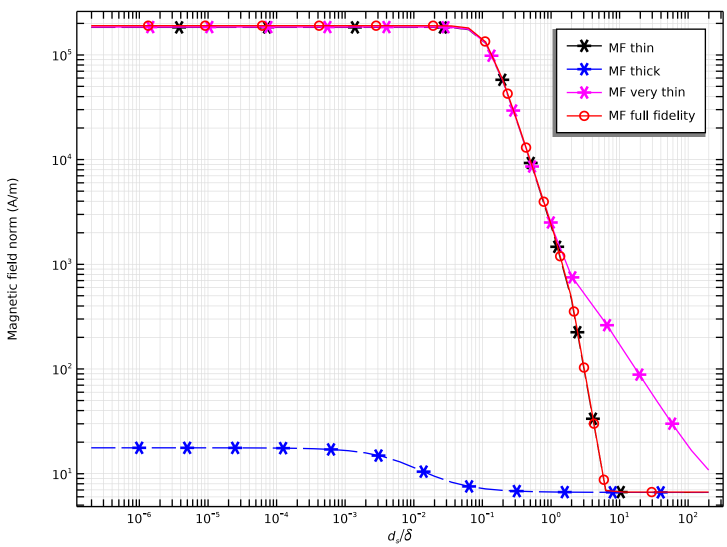
3 From the **Title type** list, choose **None**.

MF Fully Resolved Layer

1 In the **Model Builder** window, click **MF Fully Resolved Layer**.

2 In the **Settings** window for **Point Graph**, locate the **Title** section.

3 From the **Title type** list, choose **None**.



MF Thin

1 In the **Model Builder** window, under **Results** > **H vs. t** click **MF Thin**.

2 In the **Settings** window for **Point Graph**, locate the **Title** section.

3 From the **Title type** list, choose **None**.

MF Thick

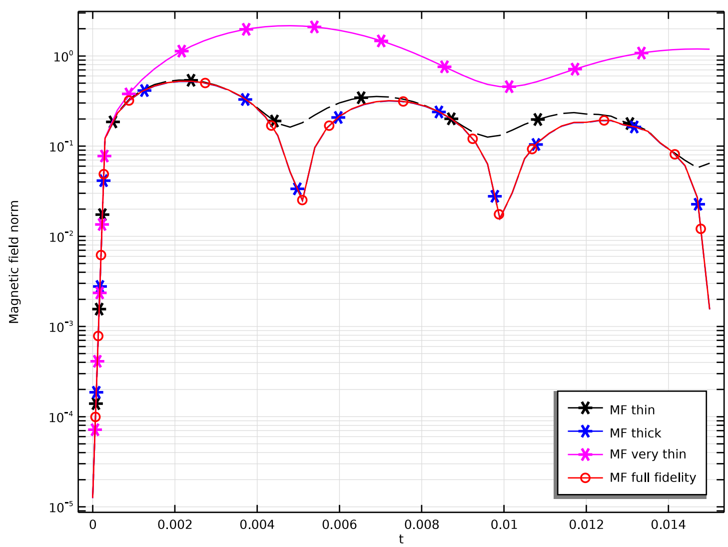
1 In the **Model Builder** window, click **MF Thick**.
2 In the **Settings** window for **Point Graph**, locate the **Title** section.
3 From the **Title type** list, choose **None**.

MF Very Thin

1 In the **Model Builder** window, click **MF Very Thin**.
2 In the **Settings** window for **Point Graph**, locate the **Title** section.
3 From the **Title type** list, choose **None**.

MF Fully Resolved Layer

1 In the **Model Builder** window, click **MF Fully Resolved Layer**.
2 In the **Settings** window for **Point Graph**, locate the **Title** section.
3 From the **Title type** list, choose **None**.



With the above steps, you have finished building and running the model. You can now compare your results with the figures shown above.