# Small-Signal Analysis of an Inductor

## *Introduction*

This example uses the model Inductor in an Amplifier Circuit from the *AC/DC Module Application Library* without the circuits definition. This model consists of an inductor with a nonlinear magnetic core that shows a changing inductance when the current increases. In this example you investigate the small-signal inductance as a function of current through the inductor.

> **!** For the correct evaluation of small-signal lumped parameters like electrical impedance and inductance, understanding the `lindev` operator is mandatory. Please consult the section on *Small-Signal Analysis, Prestressed Analysis, and Harmonic Perturbation Plot Settings* in the *COMSOL Multiphysics Reference Manual*.

**Application Library path:** `ACDC_Module/Devices,_Inductive/small_signal_analysis_of_inductor`

## *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>Electromagnetic Fields>Magnetic Fields (mf)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Small-Signal Analysis, Frequency Domain**.

6 Click **Done**.

### GLOBAL DEFINITIONS

Import the model parameters from a text file.

*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 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `small_signal_analysis_of_inductor_parameters.txt`.

## GEOMETRY 1

*Circle 1 (c1)*

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

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type `dr`.

4 In the **Sector angle** text field, type `180`.

5 Locate the **Rotation Angle** section. In the **Rotation** text field, type `-90`.

6 Click **Build Selected**.

*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 `3*cr`.

4 In the **Height** text field, type `il*1.5`.

5 Locate the **Position** section. In the **z** text field, type `-il*1.5/2`.

6 Right-click **Rectangle 1 (r1)** and choose **Build Selected**.

*Rectangle 2 (r2)*

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 `coor-coir`.

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

5 Locate the **Position** section. In the **r** text field, type `coir`.

6 In the **z** text field, type `-il/2`.

7 Right-click **Rectangle 2 (r2)** and choose **Build Selected**.

*Rectangle 3 (r3)*

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 `(coor-coir)*2`.

4 In the **Height** text field, type `il*1.1`.

5 Locate the **Position** section. In the **r** text field, type `coir*0.8`.

6 In the **z** text field, type `-il/2*1.1`.

7 Right-click **Rectangle 3 (r3)** and choose **Build Selected**.

### *Fillet 1 (fil1)*

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

Next, select all ten points in the internal of the geometry as follows:

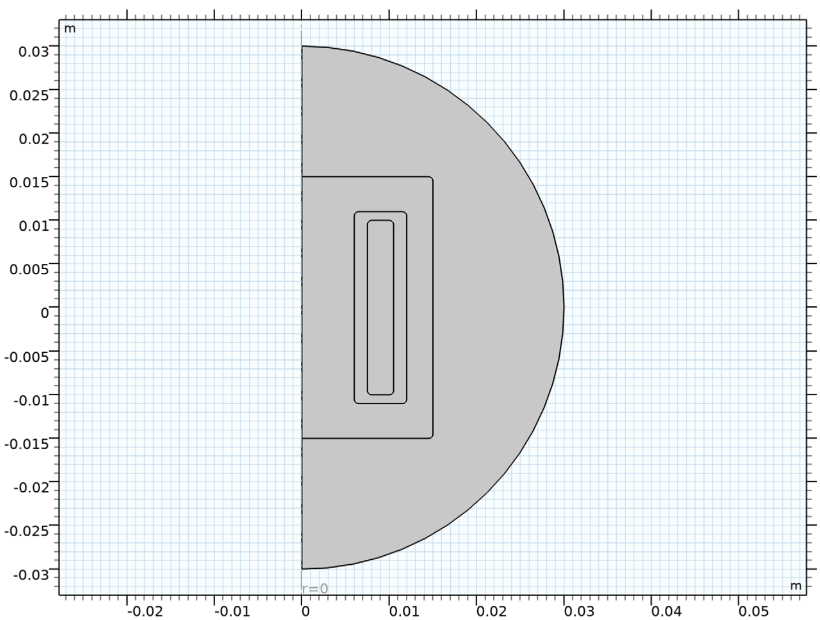
2 Click the **Select Box** button in the **Graphics** toolbar.

3 Using the mouse, enclose the internal vertices in a box to select them.

4 In the **Settings** window for **Fillet**, locate the **Radius** section.

5 In the **Radius** text field, type `fr`.

6 Click **Build All Objects**.




The geometry is now complete.

### ADD MATERIAL

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

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

3 In the tree, select **Built-in>Air**.

4 Click **Add to Component** in the window toolbar.

5 In the tree, select **Nonlinear Magnetic>Low Carbon Steel>Low Carbon Steel 1006**.

6 Click **Add to Component** in the window toolbar.

7 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

### MATERIALS

#### *Low Carbon Steel 1006 (mat2)*

Select Domain 2 only.

### MAGNETIC FIELDS (MF)

The nonlinear inductor must use a different constitutive relation for the magnetic field. Thus a separate **Ampère's Law** feature must be entered for this.

#### *Nonlinear Core*

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Magnetic Fields (mf)** and choose **Ampère's Law**.

2 In the **Settings** window for **Ampère's Law**, type `Nonlinear Core` in the **Label** text field.

3 Select Domain 2 only.

4 Locate the **Constitutive Relation B-H** section. From the **Magnetization model** list, choose **B-H curve**.

5 Locate the **Constitutive Relation Jc-E** section. From the $\sigma$ list, choose **User defined**. In the associated text field, type `1000`.

   Usually, laminated core is used to decrease the eddy current loss. Here we set a user defined conductivity to simulate such an effect.

Define the coil with the static excitation.

#### *Coil 1*

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

2 Select Domain 4 only.

3 In the **Settings** window for **Coil**, locate the **Coil** section.

4 In the **Coil name** text field, type `coil`.

5 From the **Conductor model** list, choose **Homogenized multiturn**.

6 Locate the **Homogenized Multiturn Conductor** section. In the $N$ text field, type `cn`.

7 In the $\sigma_{\text{coil}}$ text field, type `csigma`.

8 In the $a_{\text{coil}}$ text field, type `cwc`.

9 Locate the **Coil** section. In the $I_{\text{coil}}$ text field, type `cIdc`.

Add the time-harmonic excitation.

### *Harmonic Perturbation 1*

1 In the **Physics** toolbar, click **Attributes** and choose **Harmonic Perturbation**.

2 In the **Settings** window for **Harmonic Perturbation**, locate the **Harmonic Perturbation** section.

3 In the $I_{\text{coil}}$ text field, type `cIac`.

## DEFINITIONS

Define a scalar variable based on the ratio between magnetic flux density and magnetic field. The variable can be interpreted as the relative permeability in a linear material or for small field strength. Plotting this variable is useful to visualize the saturation status of the iron core.

### *Variables 1*

1 In the **Home** toolbar, click **Variables** and choose **Local Variables**.

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

3 In the table, enter the following settings:

| **Name** | **Expression** | **Unit** | **Description** |
|---|---|---|---|
| `mur` | `mf.normB/(mu0_const*mf.normH)` | | `Relative Permeability` |

The stationary solver will sweep the value of the parameter `cIdc` (DC bias current) over a range from 1 mA to 50 mA. The stationary solution computed at each point will be used as linearization point for the corresponding frequency-domain perturbation step. Thus you need to set up a continuation sweep in the stationary solver.

## STUDY 1

### *Step 1: Stationary*

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

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

**3** Select the **Auxiliary sweep** check box.

**4** Click **Add**.

**5** In the table, enter the following settings:

| **Parameter name** | **Parameter value list** | **Parameter unit** |
|---|---|---|
| cIdc (DC current bias) | `range(1,1,50)` | `mA` |

*Step 2: Frequency Domain Perturbation*

**1** In the **Model Builder** window, click **Step 2: Frequency Domain Perturbation**.

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

**3** From the **Frequency unit** list, choose **kHz**.

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

Apply to the frequency-domain solver the same sweep that was applied to the stationary solver. This ensures that the stationary parameter (the DC current) is recognized properly.

**5** Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

**6** Click **Add**.

**7** In the table, enter the following settings:

| **Parameter name** | **Parameter value list** | **Parameter unit** |
|---|---|---|
| cIdc (DC current bias) | `range(1,1,50)` | `mA` |

Solution stability benefits from tightening the nonlinear tolerance for the stationary step.

*Solution 1 (sol1)*

**1** In the **Study** toolbar, click **Show Default Solver**.

**2** In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Stationary Solver 1**.

**3** In the **Settings** window for **Stationary Solver**, locate the **General** section.

**4** In the **Relative tolerance** text field, type `1e-6`.

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

## RESULTS

*Coil Inductance*

**1** In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Coil Inductance` in the **Label** text field.

*Global 1*

1 Right-click **Coil Inductance** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields>Coil parameters>mf.LCoil_coil - Coil inductance - H**.

   The Global Plot can be used to plot physical quantities from the stationary solution, from the harmonic perturbation solution, or in other cases available in the **Expression evaluated for** list. The **Compute differential** check box is used to compute the differential of the physical quantity around the linearization point. In the case of lumped parameters, the differential should not be computed, since they are defined as the ratio of two differentials. Leave that option unchecked.

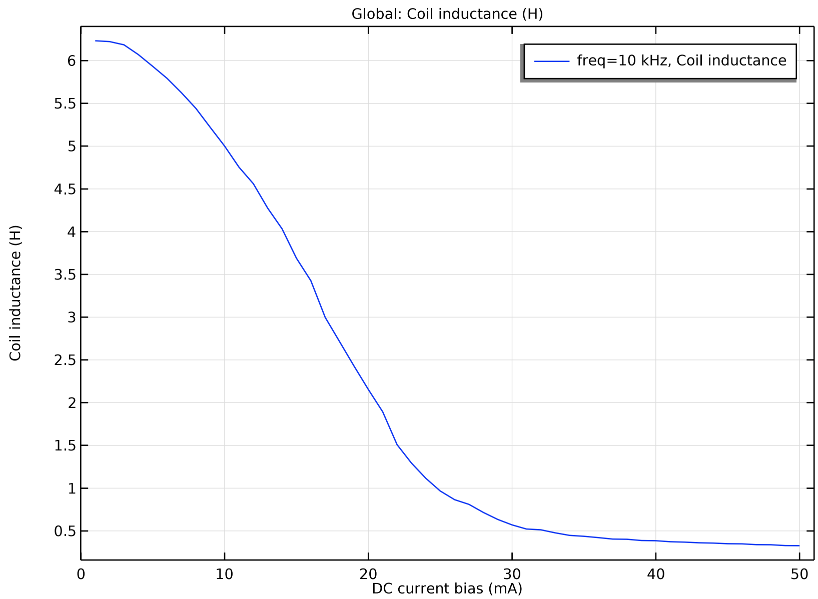
3 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

4 In the **Expression** text field, type `cIdc`.

5 From the **Unit** list, choose **mA**.

6 In the **Coil Inductance** toolbar, click **Plot**.

   The plot will show the inductance of the component at different values of the bias currents.The inductance drops significantly as a consequence of the saturation of the core. The saturation can be visualized by plotting the relative permeability of the iron core.




The small signal inductance is plotted versus the DC bias current.

### *Surface 1*

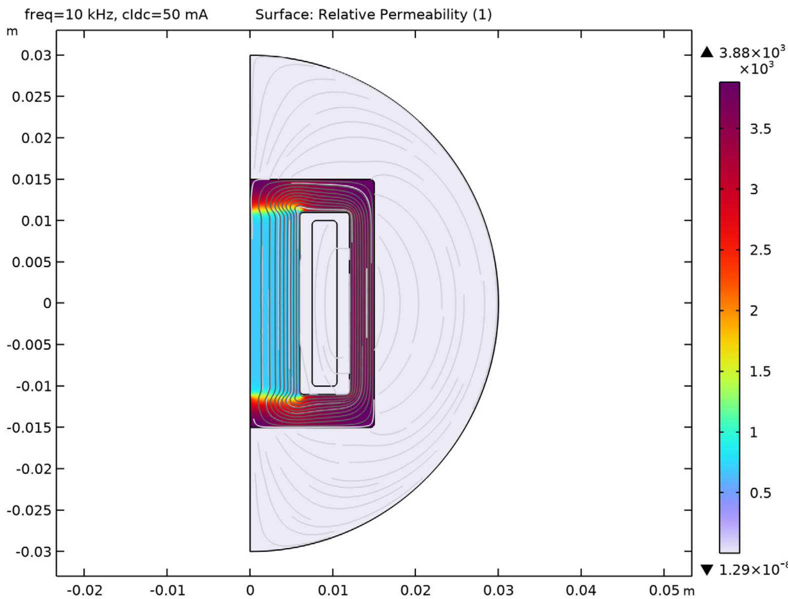
1 In the **Model Builder** window, expand the **Magnetic Flux Density Norm (mf)** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>mur - Relative Permeability**.

3 Locate the **Expression** section. From the **Expression evaluated for** list, choose **Static solution**.

**4** In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.

The plot shows that the relative permeability of the inner core has dropped well below the value at zero field of 3882.




The Harmonic Perturbation subfeature can be added to a wide range of source features in the AC/DC Module. A linear perturbation study can be manually performed on any other source by using the `linper` operator as shown next.

## MAGNETIC FIELDS (MF)

### *Coil 1*

**1** In the **Model Builder** window, under **Component 1 (comp1)>Magnetic Fields (mf)** click **Coil 1**.

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

**3** In the $I_{\mathrm{coil}}$ text field, type `cIdc + linper(cIac)`.

### *Harmonic Perturbation 1*

In the **Model Builder** window, right-click **Harmonic Perturbation 1** and choose **Disable**.

## STUDY 1

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

#### RESULTS

*Magnetic Flux Density Norm (mf)*

Inspect the results again and confirm they did not change.