



PLECS

Tutorial

Introduction to the PLECS Magnetic Domain

Tutorial Version 1.0

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1 Introduction

The aim of this exercise is to use the PLECS Magnetic components to design a transformer for a forward converter, including the saturation of the magnetic core. The example application, shown in Fig. 1, is a switched-mode power supply comprising a single-phase input rectifier that creates a DC voltage of approximately 325 V, and an output forward converter stage that steps the input DC voltage down to approximately 11 V. Isolation is provided in the form of a high-frequency transformer that was originally designed using a commonly-used electrical equivalent circuit.

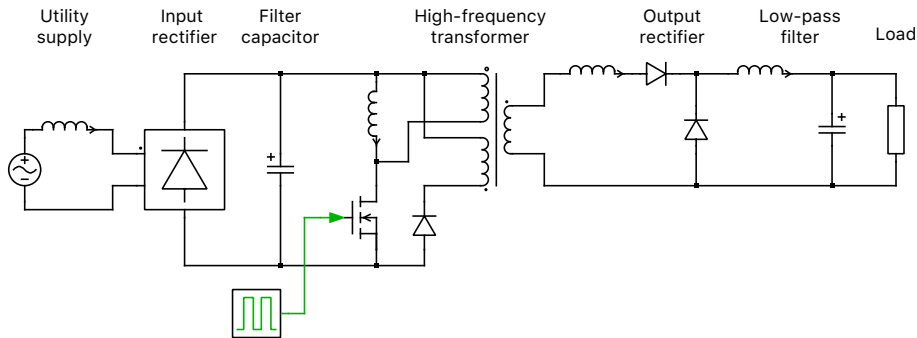


Figure 1: Electrical circuit of a switched-mode power supply

Before you begin Ensure the file `magnetics_domain_start.plecs` is located in your working directory. You should also have the reference files that you can compare with your own models at each stage of the exercise.

2 Adding Leakage Inductances to Idealized Forward Converter

The forward converter, shown in Fig. 1, is essentially a buck (step-down) converter with an isolation transformer. In the first tutorial you added a leakage inductance at the secondary side of the transformer, however a practical transformer is not completely coupled and in reality all windings have a small leakage inductance. Leakage inductances can not be connected in series with the primary and demagnetizing windings without further additions to the circuit, however.



Your Task: Open the file `magnetics_domain_start.plecs` that is the same as the last model you created in the introductory tutorial.

- 1 Add leakage inductances of $144e-8$ H to the primary and demagnetizing windings as shown in Fig. 2 and run the simulation.
 - ② Why does this create a problem? (Look at the conduction state of the semiconductors and try to find a path for the magnetizing inductance current.)
 - Ⓐ Since there is no path for the magnetizing current to take, leakage resistance needs to be added in order for the stored energy to be consumed after the switch turns off.
- 2 Add a resistance of $1e6 \Omega$ in parallel to both the switch and the diode in the tertiary winding, as well as the two diodes on the output side. From the **Simulation + Simulation parameters...**

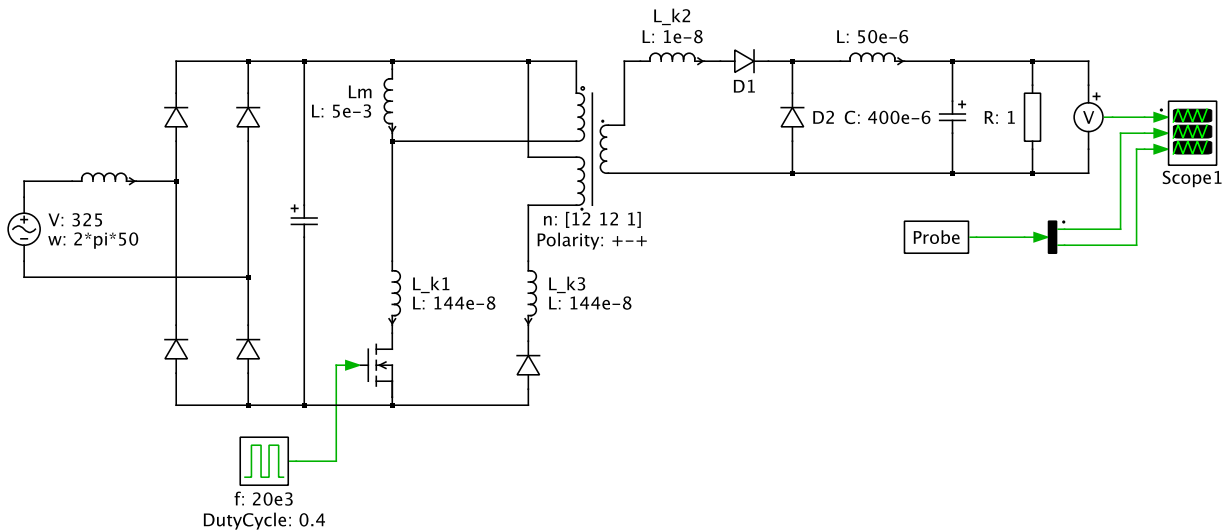



Figure 2: Transformer with leakage added on all three windings

menu, tighten the **Relative tolerance** parameter in the to be $1e-5$ and change the **Diode turn-on threshold** to 0.0001 to prevent the diodes from bouncing. Then re-run the simulation. The results should be similar to those for the model without the winding leakages. Note that stray capacitances may also exist in parallel to each semiconductor, however since the capacitance values are so small in reality, adding these to the model would slow down the simulation significantly, and are not considered in this exercise.

 At this stage, your model should be the same as the reference model: `magnetics_domain_1.plecs`.

3 Implement Transformer Using Magnetic Components

3.1 Design magnetic circuit using linear permeance

You will now replace the electrical equivalent circuit of the transformer with components from the Magnetic library. The key parameters for the main inductance of the magnetic core are shown below in Table 1. The length of the absolute flux path has already been divided by two, so the parameters can be used directly.

Table 1: Key parameters of the linear core elements shown in Fig. 3

Parameter	Calculation Variable	Value
Flux path length (m):	l_{core}	0.175
Cross-sectional area (m ²):	A_{core}	$2.7 \cdot 10^{-4}$
Saturation induction (T):	N/A	1.56
Unsaturated relative permeability:	$\mu_{r,\text{unsat}}$	45000



Your Task:

- 1 Remove the electrical circuit representing the transformer, including the ideal three-winding transformer and the four inductors. Connect the three broken electrical terminals to the magnetic domain using Winding components. Please observe the arrow direction of the windings shown in Fig. 3. Use 72 turns for the primary and demagnetizing windings (N_1 , N_3) and 6 turns for the secondary winding (N_2). Keep in mind that the secondary and the demagnetizing winding have to be wound with negative polarity. This can be configured in the component mask of each winding.
- 2 Add a Linear Core component at the top and bottom of the magnetic circuit and complete the loop by wiring together the core halves and windings. Also add an Air Gap component on each side of the circuit, as well as Leakage Flux Path components in parallel with each winding, as shown in Fig. 3. Enter the core parameters for the **Cross-sectional area**, **Length of flux path** and **Unsaturated relative permeability** using the values in Table 1. For a Linear Core the **Unsaturated relative permeability** is equal to the relative permeability μ_r .

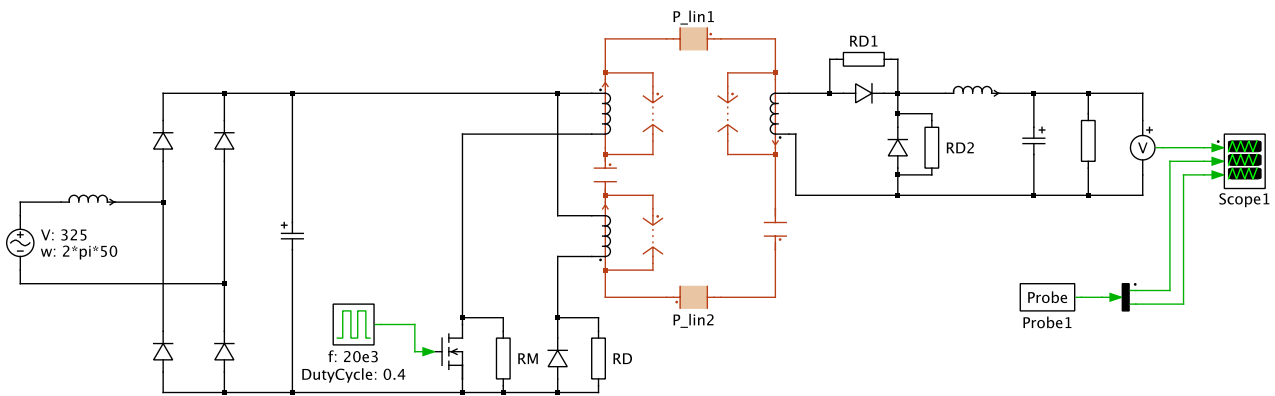


Figure 3: Forward converter with a magnetic circuit, including a linear core, air gaps, and winding leakages

3.2 Calculate the air gap



Your Task:

- 1 You first need to calculate the magnetic reluctance of a single core component. The equation for this is as follows:

$$R_{\text{mag,core}} = \frac{1}{\mu_0 \cdot \mu_{r,\text{unsat}}} \cdot \frac{l_{\text{core}}}{A_{\text{core}}} \quad (1)$$

where $\mu_0 = 4\pi \cdot 1e-7$ is the vacuum permeability constant and $\mu_{r,\text{unsat}}$, l_{core} and A_{core} are given above in Table 1.

- 2 Next we will assume a multiplication factor of 1.1 when calculating the air gap cross-sectional area to consider fringing effects. Therefore,

$$A_{\text{air-gap}} = 1.1 \cdot A_{\text{core}} \quad (2)$$

- 3 Then, we will calculate the total magnetic reluctance of the magnetic circuit and of each air gap. The equation for these are:

$$R_{\text{mag,total}} = \frac{N_1^2}{L_m} \quad (3)$$

where N_1 is the number of turns on the primary winding, and L_m is the desired magnetization inductance on the primary side ($5e-3$ H), and

$$R_{\text{mag,air-gap}} = \frac{R_{\text{mag,total}} - 2 \cdot R_{\text{mag,core}}}{2} \quad (4)$$

4 Finally, to calculate the length of a single air gap, we will use the following equation:

$$l_{\text{air-gap}} = R_{\text{mag,air-gap}} \cdot \mu_0 \cdot A_{\text{air-gap}} \quad (5)$$

Enter your calculated values into the component parameters or provide variables for the parameters and place all of your calculations and matching variables in the **Model initialization commands** window, which can be found in the **Initialization** tab from **Simulation + Simulation parameters...** menu item.

3.3 Calculate the leakage permeance



Your Task:

1 Calculate the leakage permeances for each of the three windings. In the first exercise, a leakage inductance of $1e-8$ H was used for the secondary winding (L_{k2}). We will assume that the magnetization reluctances for the leakage paths in each of the three windings are the same and therefore the leakage inductances are proportional to the squares of the number of winding turns. The equations for the leakage inductances for the primary and demagnetizing windings are as follows:

$$L_{k1} = \left(\frac{N_1}{N_2}\right)^2 \cdot L_{k2} \quad (6)$$

$$L_{k3} = \left(\frac{N_3}{N_2}\right)^2 \cdot L_{k2} \quad (7)$$

2 The equivalent permeance values for each leakage flux path are then calculated for each respective winding using:

$$P_{kn} = \frac{L_{kn}}{N_n^2} \quad (8)$$

3 Run the simulation and compare the results with that from the model of the transformer designed purely in the electrical domain. If you are not sure if your calculation results are correct, please check Table 2 for validation.



At this stage, your model should be the same as the reference model: `magnetics_domain_2.plecs`.

3.4 Add saturation to the magnetic core



Your Task:

- 1 Replace the two Linear Core components with Saturable Core components and configure the block parameters using the information in Table 1. You can leave the **Saturated relative permeability** parameter for the core components as the default value.
- 2 Choose a **coth** fitting function for the non-linear relationship between the field strength and flux density.
- 3 Add an XY Plot component to the model and measure the BH loop of one of the core components using a Probe block. By probing the field strength and flux density in a single Probe and wiring the output directly into an XY Plot, the relationship between the two signals will be displayed.
- 4 Increase the **Duty cycle** of the Pulse Generator from 0.4 to 0.6 and observe the changes in the BH loop.



At this stage, your model should be the same as the reference model: `magnetics_domain_3.plecs`.

4 Conclusion

This exercise has demonstrated a step by step approach for creating a practical model of a transformer. Comparisons are shown between an electrical equivalent circuit and circuits in the PLECS Magnetic domain with a linear core and then a core. The PLECS XY Plot allows the user to view the BH loop of a core component. The magnetic circuit can be easily extended for analysis of inherent losses. The Magnetic Resistance component can be connected in series or in parallel to a permeance, depending on the nature of the specific loss. Also, the Hysteretic Core block allows for implementing hysteretic losses due to magnetization cycles.

5 Calculation Results

Table 2 shows the calculation results from Sections 3.2 and 3.3 for the magnetic components.

Table 2: Calculated parameters for the magnetic components

Component	Parameter	Value
Air Gap (2)	Cross-sectional area (m ²)	$2.97 \cdot 10^{-4}$
Air Gap (2)	Length of flux path (m)	$1.892 \cdot 10^{-4}$
Leakage Flux Path (3)	Equivalent permeance	$2.778 \cdot 10^{-10}$

Revision History:

Tutorial Version 1.0 First release

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