



PLECS

*Tutorial*

## Modeling a Switched-Mode Power Supply using PLECS

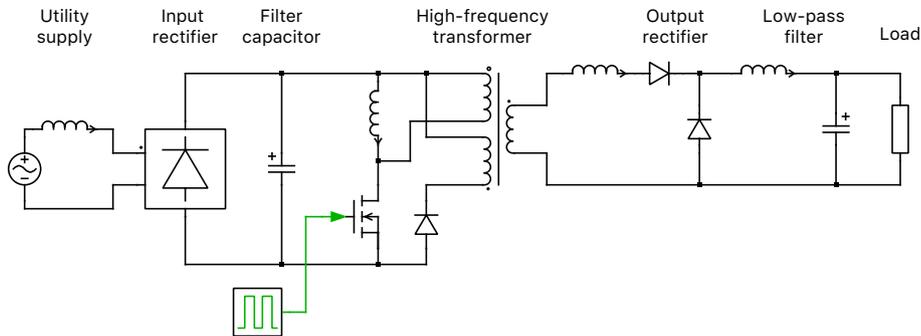
Tutorial Version 1.0

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# 1 Introduction

The aim of this exercise is to use PLECS to create a detailed model of a two-stage power electronic converter. 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. Since the focus of this exercise is on modeling the switching converter rather than the control system, the forward converter is operated in open-loop control mode with a fixed duty cycle. The specific learning goals for this exercise



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

are listed as follows:

- Create a detailed model of a DC-DC converter in a step by step approach.
- Learn a few useful keyboard shortcuts.
- Gradually add more nonlinear details to your simulation.
- Estimate the transformer saturation limit.
- Establish diode overvoltages and overcurrents.

**Before you begin** Ensure you have the reference files that you can compare with your own models at each stage of the exercise.

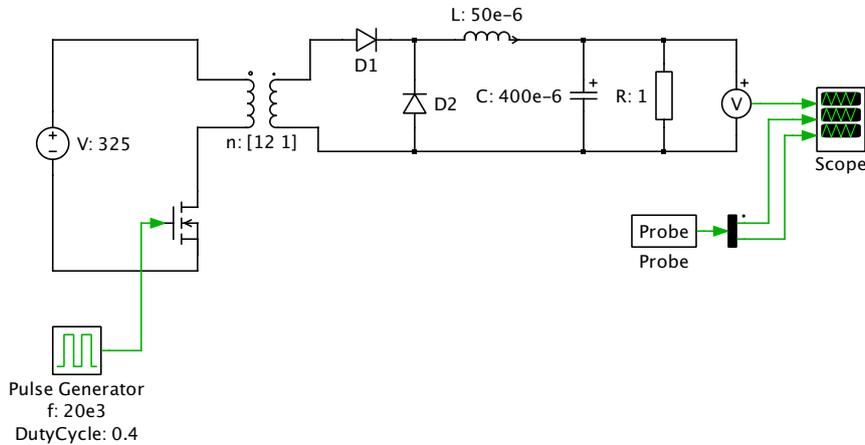
## 2 Idealized Forward Converter

The forward converter, shown in Fig. 2, is essentially a buck (step-down) converter with an isolation transformer. When the MOSFET is on, diode  $D_1$  is forward biased and conducts the inductor current, which increases during the on interval. When the MOSFET is switched off, the inductor current commutates from  $D_1$  to  $D_2$  and begins to decrease. If inductor current never decreases to zero during the off interval, the converter is said to operate in continuous conduction mode. More detailed information about the operation of the forward converter can be found in [1].

The approach that you will use to model the power supply is to start with a basic model of the forward converter as shown in Fig. 2. For this step, you will assume the transformer to be ideal and you will model the input rectifier stage using a fixed DC voltage. In the following steps you will add more details to the component models and include an input rectifier stage.



**Your Task:** Model the idealized forward converter shown in Fig. 2. Be sure to use the ideal MOSFET component from the library. Use a Pulse Generator block with a frequency of  $20 \times 10^3$  Hz and a duty cycle of 0.4 to control the switch. Display the load voltage using the PLECS Scope. Monitor the MOSFET and inductor currents by dragging these components into a Probe block and checking the **Current** signals. Use a Signal Demultiplexer block to display the MOSFET and inductor currents on separate scope plots. Adjust the simulation **Time span** to 3 ms (found in the **Simulation + Simulation Parameters** menu, or press **Ctrl+E**), but leave all other parameters as their defaults and run the simulation (**Simulation + Run** or **Ctrl+T**).



**Figure 2: PLECS circuit of idealized forward converter**



Does the converter operate in continuous or discontinuous conduction mode?



After the startup transient settles, it is in continuous conduction mode. In continuous conduction mode, the steady-state inductor current is always greater than zero.



At this stage, your model should be the same as the reference model:  
Forward\_Converter\_1.plecs.

## 3 Practical Forward Converter

### 3.1 Including the transformer magnetizing inductance

In a practical forward converter design, the magnetizing inductance of the transformer must be modeled to ensure that the magnetizing current does not reach saturation levels.



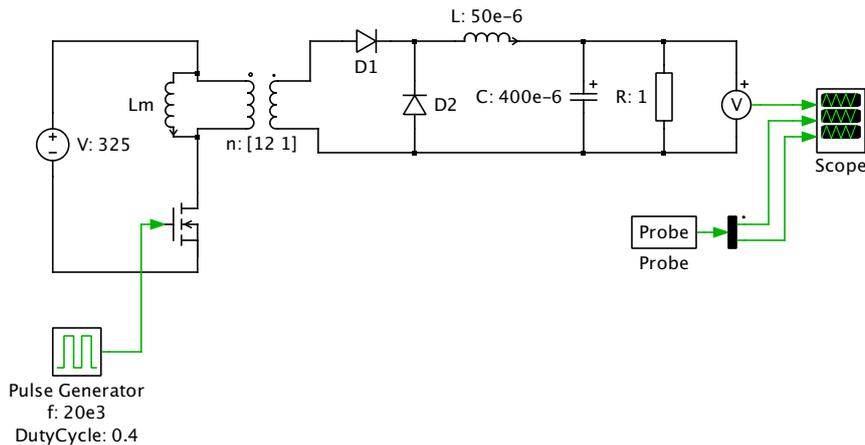
**Your Task:** To add this effect to your model, add a magnetizing inductance  $L_m$  in parallel with the primary winding of the ideal transformer, as shown in Fig. 3. Set  $L_m = 5$  mH and try to run the simulation again.



Why does PLECS abort with an error message? (Take a look at the conduction state of the semiconductors.)



When the MOSFET opens, there is no longer a path for the magnetizing inductance current to flow, thus forcing it to instantaneously jump to zero. This isn't possible in PLECS.



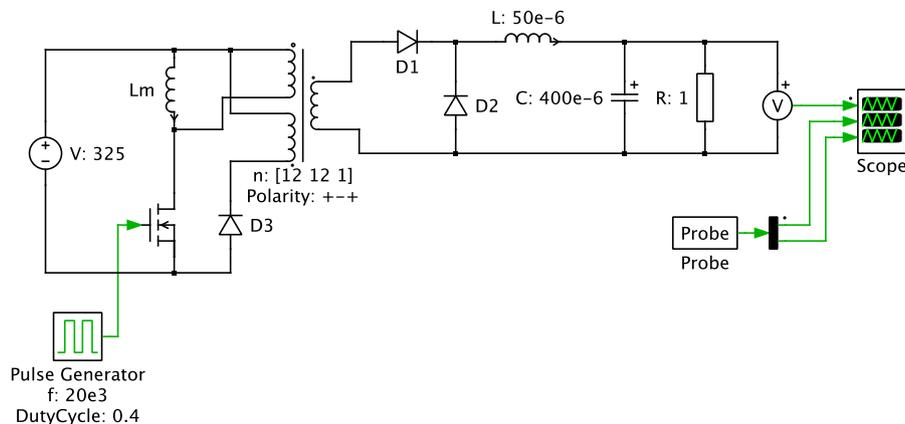
**Figure 3: Forward converter with transformer magnetizing inductance**



**Note:** If PLECS aborts with such an error message, there is usually something wrong with the circuit design. In reality, the MOSFET in off-state represents a very large resistance rather than an open circuit. You can model this with an additional resistor, e.g.  $R_{\text{off}} = 10 \text{ k}\Omega$ , connected in parallel to the MOSFET. If you display the voltage across the MOSFET now, you will observe a very high voltage when the MOSFET is turned off. It is this voltage that would destroy the MOSFET in reality.

## 3.2 Adding a demagnetizing winding

One approach that allows the transformer magnetic energy to be recovered uses a third demagnetizing winding as shown in Fig. 4. If the MOSFET switches off, the magnetizing current now has a return path through diode  $D_3$  and the tertiary winding.



**Figure 4: Practical forward converter with a tertiary demagnetizing winding**



**Your Task:** Add a third winding to the transformer and connect a diode according to Fig. 4. To do this, add an additional winding to the primary side by changing the number of windings to [2 1]. Set the number of turns on the additional winding to 12 and reverse its polarity by setting the polarity vector to +--+.



**Note:** In order to avoid transformer saturation the transformer must be totally demagnetized before the MOSFET starts to conduct. It is a common practice to have the same number of turns on the primary and the demagnetizing windings.



Add a Probe and Scope block to monitor the current through  $L_m$  and gradually increase the duty cycle of the pulse generator. What is the maximum duty cycle that can be reached before the transformer saturates?



50 %



At this stage, your model should be the same as the reference model:  
Forward\_Converter\_2.plecs.

## 4 Parasitic effects

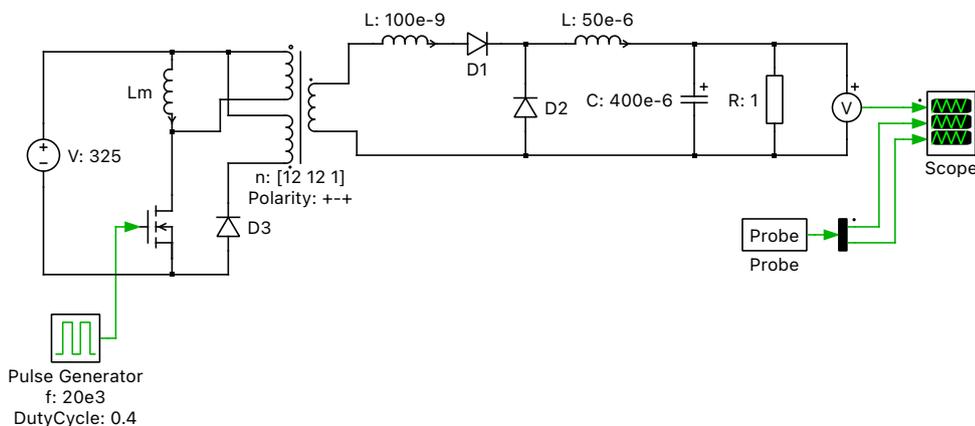
The output DC-DC stage of the converter now operates correctly with ideal components. The next stage of this modeling exercise is to add parasitic effects such as transformer leakage inductance and diode reverse recovery charge to investigate the effects of these non-idealities.

### 4.1 Transformer leakage inductance

The windings of a practical transformer are not completely coupled. All windings have a small leakage inductance that can be modeled as an inductor in series with the winding.



**Your Task:** Add a leakage inductance of  $L_1 = 100 \text{ nH}$  at the secondary side of the transformer as shown in Fig. 5.



**Figure 5: Forward converter with leakage inductance**



How does the leakage inductance influence the shape of the current through the diodes  $D_1$  and  $D_2$ ? If you cannot observe any difference, zoom into the commutation interval.



The diode current now rises over a short period of time rather than instantaneously.



Why is it not possible to connect leakage inductances in series with the primary and the demagnetizing windings?

- A** Again, by adding inductance in these paths, there would be no route for the inductive current to flow when the MOSFET is turned off.

## 4.2 Diode reverse recovery

In PLECS, power semiconductors are usually represented by static models consisting of an ideal switch, a forward voltage and an on-resistance. In some cases, however, it may be desirable to include dynamic effects during semiconductor turn-on and turn-off.

The reverse recovery effect of power diodes is probably the most important dynamic effect. It causes power dissipation and overvoltages that must be accounted for in the circuit design. The effect can be observed when a forward biased diode is rapidly turned off. It takes some time until the excess charge stored in the diode during conduction is removed. During this time the diode represents a short circuit instead of an open circuit, and a negative current can flow through the diode. The diode finally turns off when the charge has been removed by the flow of reverse current. PLECS uses a behavioral model presented in [2] to model reverse recovery.



**Your Task:** In the circuit from Section 4.1, replace the diodes  $D_1$  and  $D_2$  with the Diode with Reverse Recovery component,  $D_{rr}$ . For this exercise, you can use the default diode parameters. Additionally add a Probe and Scope block to observe the diode currents and voltages in order to reply to the question below.



**Note:** The reverse recovery diode model introduces stiff differential equations and will create an error or result in a long simulation time if you use the standard ode45 solver. In the **Simulation Parameters**, you will need to manually change the **Solver type** from the non-stiff **DOPRI** to the stiff **RADAU** for PLECS Standalone or **ode15s** for PLECS Blockset. However since PLECS version 4.5 a new variable-step solver **auto** has been added as default, where the solver switching from DOPRI to RADAU is automatically done if a model is found to become stiff during a simulation. By default the **Relative tolerance** setting is  $1e-3$ . Change the relative tolerance to  $1e-6$  and observe the effect on the simulation speed and the diode currents during a switching transition.



How large is the peak overcurrent value in diode  $D_{rr1}$  and the peak overvoltage in diode  $D_{rr2}$  in steady-state operation? Use the Cursors in the Scope to measure the peak overcurrent value.



$\sim 18$  A for  $D_{rr1}$  and  $\sim 30$  V for  $D_{rr2}$ .



At this stage, your model should be the same as the reference model: `Forward_Converter_3.plecs`.

## 5 Including the mains rectifier

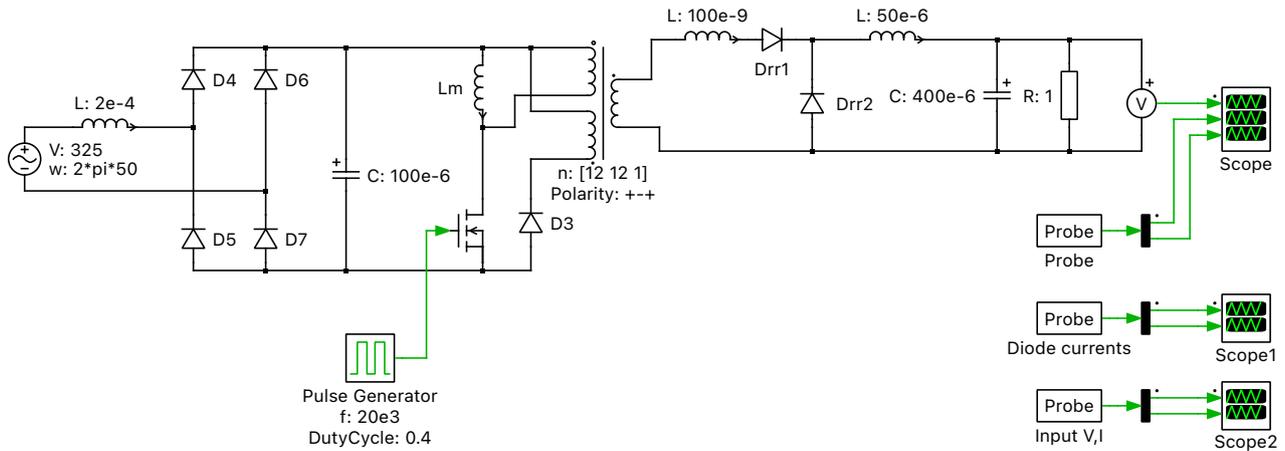
In the last part of this exercise, you will complete the converter model by replacing the DC voltage source with a mains rectifier stage.



**Your Task:** Add a 325 V (230 V<sub>rms</sub>), 50 Hz Voltage Source AC component in series with a 200  $\mu$ H inductor to model the single-phase mains. The input stage of the power supply consists of a diode rectifier with a DC filter capacitor. Model the input stage according to Fig. 6 and display the mains current and the DC link voltage using a Scope block. Adjust the simulation time span to 40 ms in order to simulate two full periods of mains supply.



At this stage, your model should be the same as the reference model:  
Forward\_Converter\_4.plecs.



**Figure 6: Circuit model for power supply including mains rectifier and forward converter**

## 6 Conclusion

This exercise has demonstrated a step by step approach for creating a detailed model of a two stage DC-DC converter starting with an idealized model of a forward converter. When the diode reverse recovery effect was added, the system became numerically stiff because the simulation model had time constants differing by several orders of magnitude. The time constant of the reverse recovery phenomenon is in the range of 10 ns and the time constant of the output filter is in the order of 1 ms. However, with the use of a stiff solver and appropriate tolerance settings, the converter could still be simulated with a fast speed.

In practice a control system would be added to regulate the output voltage. A voltage controller can easily be implemented using the control blocks in the PLECS component library, but this step is left for the user to explore.

## References

- [1] Ned Mohan, Tore M. Undeland, William P. Robbins, *Power Electronics – Converters, Applications and Design*, Third Edition, John Wiley & Sons, 2003
- [2] Alan Courtay, MAST Power Diode and Thyristor Models Including Automatic Parameter Extraction, SABER User Group Meeting Brighton, UK, September 1995

## Revision History:

Tutorial Version 1.0      First release

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