Simulation and Validation of Power Losses in the Buck-Converter Model included in the SmartElectricDrives Library

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1 Abstract

In this work a buck converter model included in the simulation software tool - the SmartElectricDrives library - is verified. The main focus is put on the converter losses. For these purposes a buck converter test bench was designed and set up. The power losses where measured according a defined series of measurements. Conduction and switching losses are investigated in this paper and their impact on the converter behavior is analyzed. As a result of the implemented losses concept the user should be able to parameterize the converter without comprehensive knowledge about transient transistor effects and data sheet availability.

2 Introduction

DC-DC converters are used to convert the unregulated DC input into a controlled DC output at a desired voltage level. The input voltage can be provided by a DC voltage source (e.g. a battery) or the DC-bus of an AC-DC-converter. The DC-DC converters are widely used in regulated switched mode DC power supplies and in DC motor drive applications.

In this paper one DC-DC-converter, like those utilized in electric vehicles, is investigated. The measurements on an electric vehicle emphasize the role of the dc-dc converter on the automotive market. In the investigated vehicle there are utilized three DC-DC converters in total. Two of them are used for feeding the electrically excited DC motor and one of them for charging the board system battery.

For shortening the period of development and reducing costs, simulation is a crucial step in the continuous design process. For the simulation of the energy flow of an entire hybrid vehicle [5] [6], the losses of each component have to be taken into account. So the modeling of the power losses in DC-DC converter are relevant regarding the power balance of the whole system. Special software tools are necessary for this development process because the conventional simulation and calculation programs do not meet interdisciplinary and dynamic demands. In this contribution the Modelica [1] model of a DC-DC converter, taking the power dissipation into account, will be presented. Moreover the simulation results will be validated through measurements.

3 The Buck-Converter Model

3.1 The SmartElectricDrives Library

The SmartElectricDrives (SED) library [2] is written in Modelica and developed by arsenal research, with the focus on automotive applications. The SED library contains all basic machine types like asynchronous induction machines, permanent magnet synchronous machines, and direct current machines combined with various components needed for modern closed loop controlled drive systems like controllers and power electronic converters.

The most common DC-DC converters such as the chopper, the buck (step-down) converter, the boost (step-up) converter, the buck-boost converter and the full bridge are already included in the current version of the SED. The consideration of losses is planned to be implemented in the next release of the SED.

An important feature of the SED is that some components e.g. all the converter models are implemented at two different level of abstraction. The user can choose between power balance converters and ideal switching converters. In power balance converters the current flow is adjusted automatically due to the energy balance between the supply side and the load side considering switching and conduction losses. In switching converters the output voltage and the current flow is given by transistors switching states which are controlled by pulse width modulation. Power balance converters are designed for simulations in which switching effects do not have to be considered. Their big advantage is that simulations work much faster with these models since the calculation effort for the power balance equation is much smaller compared to processing a large number of switching events.

3.2 The Buck-Converter

The basic structure of a buck converter is shown in Figure 1. A buck converter produces an average output voltage v_{Load} less than the DC input voltage v_{Supply}. By varying the duty ratio

$$D = \frac{t_{on}}{T_S} \tag{1}$$

of the switch, v_{Load} can be controlled.

t_{on} …switch on duration

t_{off} …switch off duration

T_S …switching time period

L …inductance

C …capacitance

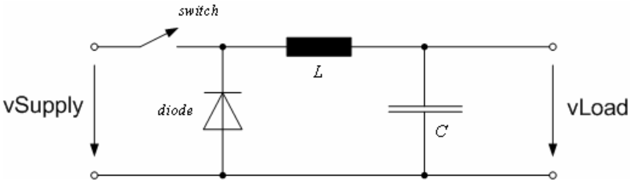

Figure 1: Basic structure of the buck-converter

The ideal output voltage v_{Load} of the buck converter without considering the conduction losses is:

$$vLoad = vSupply \cdot D \tag{2}$$

Normally, the switch is either an IGBT (Insulated-Gate Bipolar Transistor) or a MOSFET (Metal Oxide Semiconductor Field Effect Transistor).

3.3 The Losses in the Buck-Converter Model

The losses of the buck converter [3] [4] are mainly conduction losses and switching losses. Conduction losses occur when the converter current flows through the internal power electronic components and involves a voltage drop, reducing the output voltage. Switching losses arise during the switching of the transistor or diode. During ‘switching on’ the voltage drop decreases whereas the current rises, causing high losses. Contrarily, during ‘switching off’ the losses are causes by a rising voltage drop and a decrease of the current.

The conduction and switching losses are considered in both the power balance and the ideal switching converter model.

- Conduction losses of the ideal switching model are affected by forward state-on resistance and the forward threshold voltage of the transistor and the diode, respectively. The power balanced converter model uses a controlled voltage drop to take the conduction losses into account. The losses of the inductor are considered too, whereas the losses in the capacitor are neglected. A parameter estimation function supports the user in determining consistent parameters.
- Both the power balance and the switching converter model use a controlled current sink at the input terminal to take the switching losses into account. For calculating the actual switching losses, the nominal switching power dissipation with respect to the rated operation point has to be known.

4 Calculation of Converter Losses

4.1 Conduction Losses

For the calculation of conduction losses it is assumed that the inductor current flows continuously. In this case one converter switching period consists of two converter circuit states (Figure 2 and Figure 3).

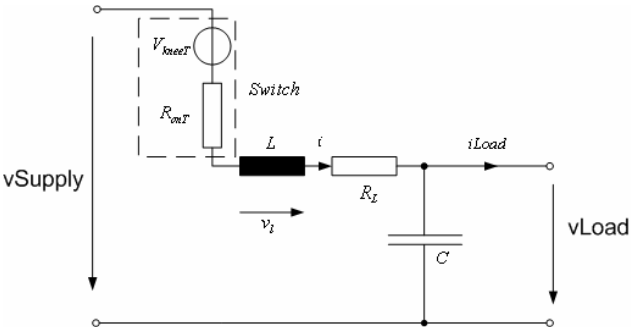

Figure 2: Buck-Converter circuit state: switch on

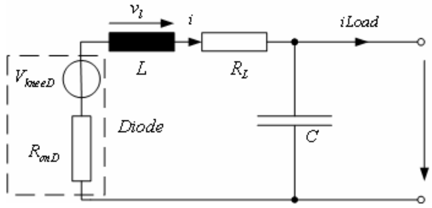

Figure 3 Buck-Converter circuit state: switch off

In steady state operation the waveform of voltages and currents repeat periodically. Therefore the integral of the inductor voltage v_l over one period, T_s, is zero:

$$\int_{0}^{Ts} v_l dt = \int_{0}^{t_{on}} v_l dt + \int_{t_{on}}^{t_{off}} v_l dt = 0 \tag{3}$$

According to the Kirchhoff's voltage laws applied to both converter circuit states (Figure 2 and Figure 3), (3) leads to:

$$\begin{aligned} &\left[vSupply - vLoad - V_{kneeT} - i \cdot (R_{onT} + R_L)\right] \cdot D = \\ &\left[vLoad + i \cdot (R_{onD} + R_L) + V_{kneeD})\right] \cdot (1 - D) \end{aligned} \tag{4}$$

From (3) we obtain the average voltage drop between ideal (2) and real output voltage:

$$\begin{aligned} &\Delta v = vSupply \cdot D - vLoad = \\ &\left[V_{kneeT} + i \cdot (R_{onT} + R_L)\right] \cdot D + \\ &\left[V_{kneeD} + i \cdot (R_{onD} + R_L))\right] \cdot (1 - D) \end{aligned} \tag{5}$$

The conduction losses of the power transistor

$$P_{C\_T} = \left[i^2 \cdot (R_{onT} + R_L) + V_{KneeT} \cdot i\right] \cdot D \tag{6}$$

and the diode

$$P_{C\_D} = \left[i^2 \cdot (R_{onD} + R_L) + V_{KneeD} \cdot i\right] \cdot (1 - D) \tag{7}$$

sum up to the total conduction losses:

$$P_C = P_{C\_T} + P_{C\_D} \tag{8}$$

Equation (6) and (7) prove that the model of the ideal switching power semiconductors inherently model the conduction losses. The voltage drop of the power balance model is based on (5).

v_l …inductor voltage

$vSupply$, $vLoad$ ….average supply voltage, average load voltage

R_{onT} , R_{onD} …state-on resistance of transistor/ diode

R_L …inductor resistance

V_{kneeT} , V_{kneeD} …forward threshold voltage of transistor/diode

i …average inductor current (equals average load current)

$iLoad$ …average load current

4.2 Switching Losses

Detailed modeling of the switching losses through switching events leads to a high numeric effort. Therefore the average of these losses according to (9)-(15) is taken into account in the SED buck-converter.

$$P_S = P_{S\_T} + P_{S\_D} \tag{9}$$

$$P_{S\_T} = P_S \cdot (1 - r_{S\_D}) \cdot \frac{i_T}{i_{T\_Nom}} \cdot \frac{v_{blocking\_T}}{v_{blocking\_T_{Nom}}} \cdot \frac{f}{f_{Nom}} \tag{10}$$

$$P_{S\_D} = P_S \cdot r_{S\_D} \cdot \frac{i_D}{i_{D\_Nom}} \cdot \frac{v_{blocking\_D}}{v_{blocking\_D_{Nom}}} \cdot \frac{f}{f_{Nom}} \tag{11}$$

The blocking voltages of the transistor and the diode are:

$$v_{blocking\_T} = vSupply + i_D \cdot R_{onD} + V_{kneeD} \tag{12}$$

$$v_{blocking\_D} = vSupply - i_T \cdot R_{onT} - V_{kneeT} \tag{13}$$

The nominal blocking voltages of the transistor and the diode are:

$$v_{blocking\_T_{Nom}} = VDC + i_{T\_Nom} \cdot R_{onD} + V_{kneeD} \tag{14}$$

$$v_{blocking\_D_{Nom}} = VDC - i_{D\_Nom} \cdot R_{onT} - V_{kneeT} \tag{15}$$

P_{S_T} , P_{S_D} …switching losses in transistor/ diode

P_S …sum of switching losses

r_{S_D} …ratio of switching losses in the diode

i_T , i_{T_Nom} …transistor current/ nominal transistor current

i_D , i_{D_Nom} …diode current, nominal diode current

$v_{reverse\_T}$ / $v_{reverse\_D}$ …blocking voltage of transistor/diode

$v_{reverse\_T_{Nom}}$ / $v_{reverse\_D_{Nom}}$ …nominal blocking voltage of transistor/ diode

VDC …nominal DC supply voltage

f , f_{Nom} …switching frequency/ nominal switching frequency

5 Measurement Setup

The measurement setup is shown in Figure 4.

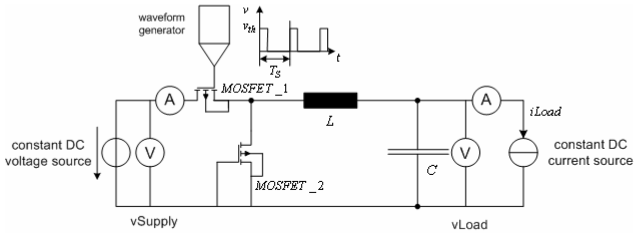

Figure 4 Measurement setup

Two power MOSFETs are used. One of them (MOSFET_1) is used as switch. The freewheeling diode of the other one (MOSFET_2) is used as buck diode. The converter is fed by a constant DC-voltage. A constant current source is used as the converter load. The switching MOSFET_1 is controlled by a waveform generator. The pulsewidth of the waveform generator is variable from 0 to 1 (0 means an open switch, whereas at duty cycle 1 the switch is closed all the period).

The parameters in Table 1 are obtained from the data sheet [7] of the used MOSFETs and measurements, respectively.

MOSFETs	$R_{onT} = 7m\Omega$ (data sheet)
	$R_{onD} = 3m\Omega$ (data sheet)
	$V_{kneeT} = 0V$ (data sheet)
	$V_{kneeD} = 0.8V$ (data sheet)
Inductor	$R_L = 2.9m\Omega$ (measured)
	$L = 4.57\mu H$ (measured)
Capacitor	$C = 1000\mu F$ (measured)

Table 1

The conducted measurements are summarized in the Table 2.

ID	V_{DC}	i_{Load}	f	duty cycle
M1	30 V	5 A	100kHz	0.2,..0.8 (step 0.1)
M2	30 V	10 A	100kHz	0.2,..0.8 (step 0.1)
M3	30 V	15 A	100kHz	0.2,..0.8 (step 0.1)
M4	30 V	20 A	100kHz	0.2,..0.8 (step 0.1)
M5	30 V	25 A	100kHz	0.2,..0.8 (step 0.1)
M6	30 V	30 A	100kHz	0.2,..0.8 (step 0.1)
M7	30 V	35 A	100kHz	0.2,..0.8 (step 0.1)
M8	30 V	40 A	100kHz	0.2,..0.8 (step 0.1)

Table 2

Figure 5 illustrates the obtained power losses versus duty cycle for measurement M5.

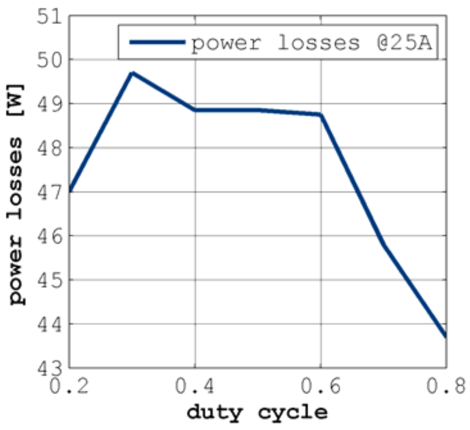

Figure 5: Power losses @25A

6 Simulation and Comparison with Measurement Results

6.1 Simulation

Figure 6 shows the simulation model of the buck converter. The operation conditions summarized in Table 1 are also applied to the simulations.

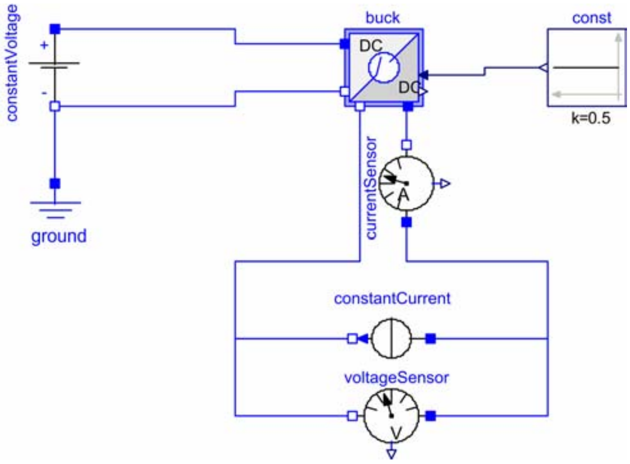

Figure 6: Simulation model of the buck converter

The measurement result of the total power losses at the nominal operating point (load current of 25 A; duty cycle of 0.5; switching frequency 100 kHz) is $P_l = 48.85W$. The conduction losses at the nominal operating point are calculated according to (6)-(8) $P_C = 14.93W$. The switching losses are calculated as the difference between total losses and conduction losses: $P_S = 33.92W$. The simulation reference values of switching losses in the nominal operating are defined by this calculated value. The simulation is fed by this value of switching losses. By changing the nominal operating point the value of the power dissipation is calculated by equations (9)-(15).

In Figure 7 the measured and the simulated power losses versus the duty cycle for measurements M2, M5 and M8 are compared.

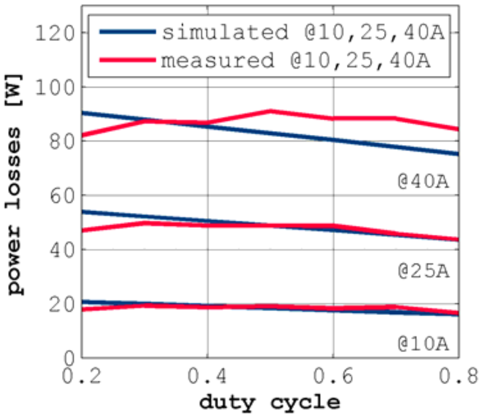

Figure 7: Comparison of measured and simulated power losses at different load currents

The output voltage is strongly dependent on the duty cycle, and almost independent of the load current. Figure 8 presents the load voltage versus duty cycle at three different load currents.

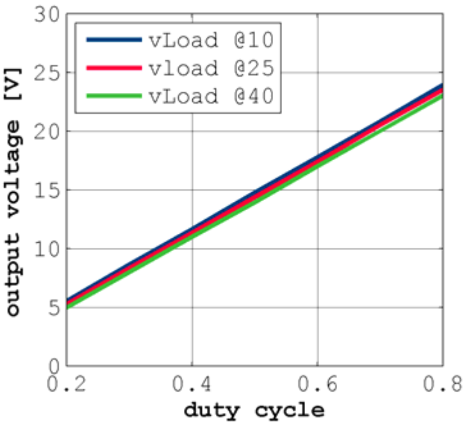

Figure 8: Measured output voltage at different load currents

The deviation of the simulated output voltage from the measurements results is less than 4 % (Figure 9).

Figure 9: Simulated voltage error at different duty cycles and load currents

6.2 Parameter Optimization

Temperature dependency and other physical effects lead to simulation results deviating from measurements. The measured losses in Figure 10 were linearly approximated, leading to the fitted parameters shown in Table 3.

MOSFETs	$R_{onT} = 13.8 m\Omega$
	$R_{onD} = 3 m\Omega$
	$V_{kneeT} = 0V$
	$V_{kneeD} = 0.5245V$

Table 3

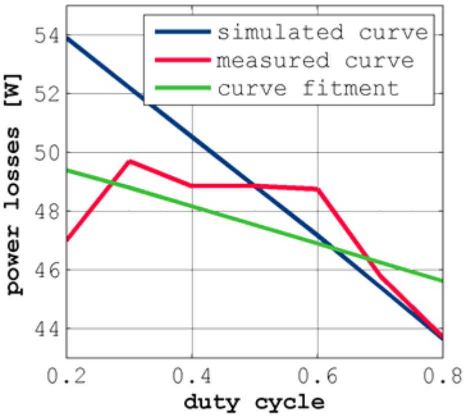

Figure 10: Power losses curve fitment

The change of the operation condition summarized in Table 1 is applied to the simulations.

Figure 11 illustrates the average errors (average error using parameter set from Table 1 and average error using parameter set from Table 3) of the simulated losses from the measurement results at different load currents. Average error means the averaged error value over the duty cycle at a specific load current.

Figure 11: Average errors

It is obvious that the simulation with the new parameter set delivers better results in a large range.

7 Conclusion

In many applications DC-DC power converters are employed in a variety of applications, including power supplies for computers, power systems and telecommunications equipment, as well as dc motor drives.

For the simulation of the energy flow of an entire hybrid vehicle, the losses of each component have to be taken into account. The consideration of losses in DC-DC converter simulations should be organized user-friendly. This means that without big knowledge of all converter elements parameter it should be possible to carry out significant simulation results for a large operating range. As the measuring and simulating results have already shown, this target is fulfilled by the in the SED implemented DC-DC buck converter. The conduction losses are defined by forward resistances and threshold voltages. These parameters can get by data sheets or by measurements. To consider the switching losses, the nominal switching power dissipation with respect to the rated operation point has to be known. An optimization in a sub-operating range is easy done by calculating new parameters from the linear approximated measured power losses curve and using this improved set of parameters in the simulation.

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