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# Application Note

**AN-PSM-11**

## Switched and Averaged PSPICE Models

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N e v e r s t o p t h i n k i n g

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# Contents

# 1 Preliminary remarks

The simulations described in this document were carried out with *PSpice V8.0 Version V2.0*.

## 1.1 Description of the converter symbols

All the symbols used in the converter circuits have the same structure.

**Inputs**

ue: Connection for the input voltage.
d1: Input of the averaged pulse control factor $d_1$ for controlling the converter. CAUTION: This input is not restricted to values between 0 and 1. Meaningless pulse control factors (e.g. $d_1 = -0.5$) can therefore be specified. (Limiting occurs in the pulse-width modulator).

**Outputs**

ua: Connection(s) for the output voltage(s).
Ud: Drain connection of the external switching transistor.
d3: Output for display of the operating mode and length of the interval $d_3T_S$ (inductor current $i_L = 0$). $d_3 = 0$ means the converter is operating continuously. For example, $d_3 = 0.3$ means the converter is operating discontinuously and the time duration of the interval is $d_3T_S = 0.3 * T_S$ ($T_S$ is the switching period).
dis: Output which describes the slope of the switch current in the interval $d_1T_S$. This quantity is necessary for current loop operation. In the case of a “single-inductor-converter”, dis is equal to the slope of the inductor current $i_L$ in the interval $d_1T_S$. In the case of a converter with several inductors, however, it is a weighted linear combination of the inductor currents.
iL: Output for the averaged inductor current. In the case of a converter with one inductor it is the mean value of the current through this inductor. This quantity is important for current loop operation.
eta: Output which indicates the efficiency of the circuit. CAUTION: The output supplies meaningful values only in the steady-state condition and with DC analysis. Moreover, it serves only as a point of reference, as, of course, the switching losses of the real converter are not taken into account.

With all models, variable parameters are represented in the symbol and can be edited by double-clicking. The variable values can be either figures (e.g. L = 50uH) or parameter values (e.g. L ={L1}). For latter, the parameter values must be defined in the circuit by a PARAM block.

Every averaged model has a **null** parameter. This parameter serves as a convergence aid. PSPICE experiences difficulties if an expression in an EVALUE source in IF commands is to become zero. Example:

E3 IF (V(dss)-Dmin>0, V(dss),Dmin)

It makes sense here to replace the 0 by a very small value (1*u* = $10^{-6}$; 1*m* = $10^{-3}$).

$$-1m \leq null \leq 1m$$

It is by no means certain that a value with a large magnitude is always favorable. It is possible that a circuit with null=100u does not converge, but does with null=10u.

Unfortunately a little experimentation is unavoidable.

The control inputs and outputs are each referred to the ground of input $U_e$. In the case of the circuits with electrical isolation, the outputs can be connected in any way, i.e. also connected in series. They must have only one, albeit very high-resistance path to the primary ground.

## 1.2 General notes

Both converters are intended for operation with pulse-width modulators with integrated switching transistors. The test circuits are identical for both. The TDA1683x is used for driving the flyback converter with one output (1004i_LIN) and the TDA16822 for the converter with two outputs (1005i_LIN). Both are Infineon products. The averaged circuit will be presented first, then the averaged model derived from it. A simulation in the time domain follows in order to demonstrate the accuracy of the model. It compares the transient responses when a pulse-width modulator with current loop is used. The curves show the comparison of the inductor current $i_L$ and the output voltage $u_a$ of the switched and the averaged circuits.

| Quantity | Switched model | Averaged model |
|---|---|---|
| $i_L$ | I(L1) | V(iL) |
| $u_a$ | V(uazt) | V(ua) |

The table shows the assignment of the quantities used to the models.

The curve V(d3) of the averaged model shows the temporal response of the length of $d_3$. This quantity can assume a value between zero and one. V(d3) = 0 means that the interval $d_3T_s$ = 0, i.e. the converter operates continuously. V(d3) = 1 means that the inductor current is always zero. This can be the case, for instance, if the controller in a converter with feedback disconnects as a consequence of an excessive output voltage (actual value).
The transformer ratios V1 and V2 in the case of the converter with two outputs represent the ratio of the number of primary turns w1 to the respective secondary winding w2 and w3:

V1 = w1 / w2 V2 = w1 / w3

The diode forward voltage drops can be arbitrarily chosen in the case of the averaged models (including zero, for instance). In order that the results from the switched model agree with those of the averaged model during the comparison simulation in the time domain, the diode forward voltage drops must in each case be assumed as $u_d$ = 0.8V, since the forward voltage of the SPICE diode is preset at approximately 0.8V. The differences compared to the switched model depend very strongly on the chosen time increment and the ripple of the inductor current. The larger the two are chosen, the greater the differences become.

The subsequent simulations can be performed only with the averaged model, since only with that is SPICE able to calculate operating points which differ from zero. The first simulation shows an analysis of the DC operating points. It can be seen how the efficiency *h* = *V(eta)* and the length of the interval $d_3$ = V(*d*3) change when the control voltage is increased from 0 to 4V.

The second diagram shows the comparison of the output voltage $u_a$ = V(*ua*) with the theoretical value V(uas). This value is calculated in the simulation by an EVALUE source. Since no internal resistances are taken into account in this calculation, the deviations naturally become greater as the load current increases.
The last simulation shows the characteristic in the frequency domain. In each case the response characteristic of pulse control factor $d_1$ to the output voltage $u_a$, i.e. $u_a/d_1$, is shown in Bode diagrams. The upper diagram shows the amplitude response

$$A = 20\log\sqrt{\mathrm{Re}^2 + \mathrm{Im}^2}$$

and the lower the phase response

$$j = \arctan\frac{\mathrm{Im}}{\mathrm{Re}}$$

with

$$\frac{u_a}{u_d} = F(jw) = \mathrm{Re}(jw) + j\,\mathrm{Im}(jw)$$

In the process the load resistor $R_a$ is varied logarithmically with three values per decade. It can be readily seen that at a certain resistance value the converter changes from continuous to discontinuous operating mode.
SPICE calculates the operating point before every frequency response analysis. Six operating point calculations (DC analyses) are therefore performed for each run. The results of these calculations are available in the SPICE output file.

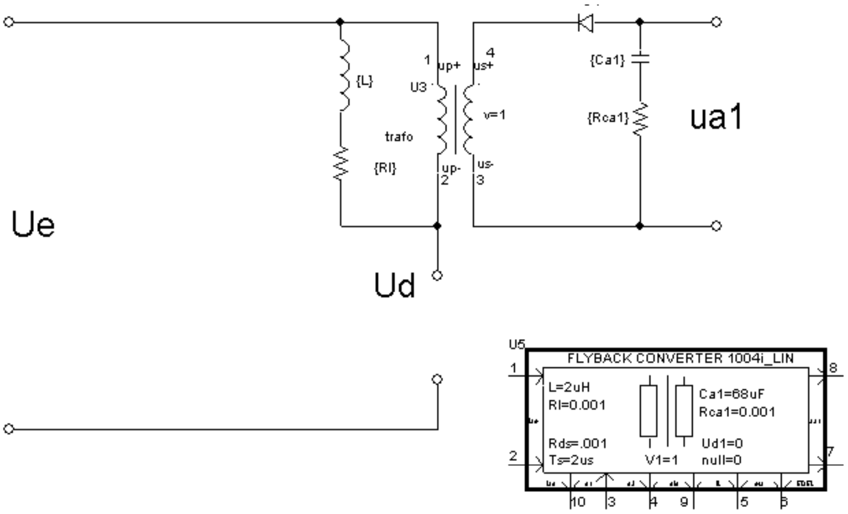
Example of a SPICE output file:

**Operating points from the frequency response analysis of converter 1004i fq**

```
**** SMALL SIGNAL BIAS SOLUTION     PARAM RA = 10
******************************************************************************
NODE    VOLTAGE    NODE    VOLTAGE     NODE    VOLTAGE    NODE    VOLTAGE
( d1)     .0662   ( d3) 126.1E-18    ( FB)    2.0000    ( iL)       .6688
( Tj)   23.0000   ( ua)    6.2452    ( Ud)    99.9550   ( ue)   100.0000
(dis) 1.000E+06 ( eta)     .8804    ( Vcc)   20.0000   (X U1.3)   -.0450

**** SMALL SIGNAL BIAS SOLUTION     PARAM RA = 21.544
******************************************************************************
NODE    VOLTAGE    NODE    VOLTAGE     NODE    VOLTAGE    NODE    VOLTAGE
( d1)     .0976   ( d3)   0.0000     ( FB)    2.0000     ( iL)    .5121
( Tj)   23.0000   ( ua)   9.9567     ( Ud)   99.9500     ( ue) 100.0000
(dis)1.000E+06   ( eta)    .9208    ( Vcc)   20.0000   (X U1.3)  -.0505

**** SMALL SIGNAL BIAS SOLUTION     PARAM RA = 100
******************************************************************************
NODE    VOLTAGE    NODE    VOLTAGE     NODE    VOLTAGE    NODE    VOLTAGE
( d1)     .1003   ( d3)     .4605    ( FB)    2.0000    ( iL)     .4987
( Tj)   23.0000   ( ua)   21.9080    ( Ud)   99.9500    ( ue) 100.0000
(dis)1.000E+06   ( eta)    .9599    ( Vcc)   20.0000   (X U1.3) -.0505

**** SMALL SIGNAL BIAS SOLUTION     PARAM RA = 215.44
******************************************************************************
NODE    VOLTAGE    NODE    VOLTAGE     NODE    VOLTAGE    NODE    VOLTAGE
( d1)    .1003    ( d3)     .5988    ( FB)    2.0000    ( iL)     .4987
( Tj) 23.0000     ( ua)   32.3400    ( Ud)   99.9500    ( ue) 100.0000
(dis)1.000E+06 ( eta)      .9709    ( Vcc)   20.0000   (X U1.3) -.0505

**** SMALL SIGNAL BIAS SOLUTION     PARAM RA = 464.16
******************************************************************************
NODE    VOLTAGE    NODE    VOLTAGE     NODE    VOLTAGE    NODE    VOLTAGE
( d1)    .1003    ( d3)     .6939    ( FB)    2.0000    ( iL)     .4987
( Tj) 23.0000     ( ua)   47.6540    ( Ud)   99.9500    ( ue) 100.0000
(dis)1.000E+06 ( eta)      .9785    ( Vcc)   20.0000   (X U1.3) -.0505

**** SMALL SIGNAL BIAS SOLUTION     PARAM RA = 1.0000E+03
******************************************************************************
NODE    VOLTAGE    NODE    VOLTAGE     NODE    VOLTAGE    NODE    VOLTAGE
( d1)    .1003    ( d3)     .7591    ( FB)    2.0000    ( iL)     .4987
( Tj) 23.0000     ( ua)   70.1330    ( Ud)   99.9500    ( ue) 100.0000
(dis)1.000E+06 ( eta)      .9837    ( Vcc)   20.0000   (X U1.3) -.0505
```

# 2 Flyback converter with electrical isolation, 1 output

## 2.1 Averaged circuit



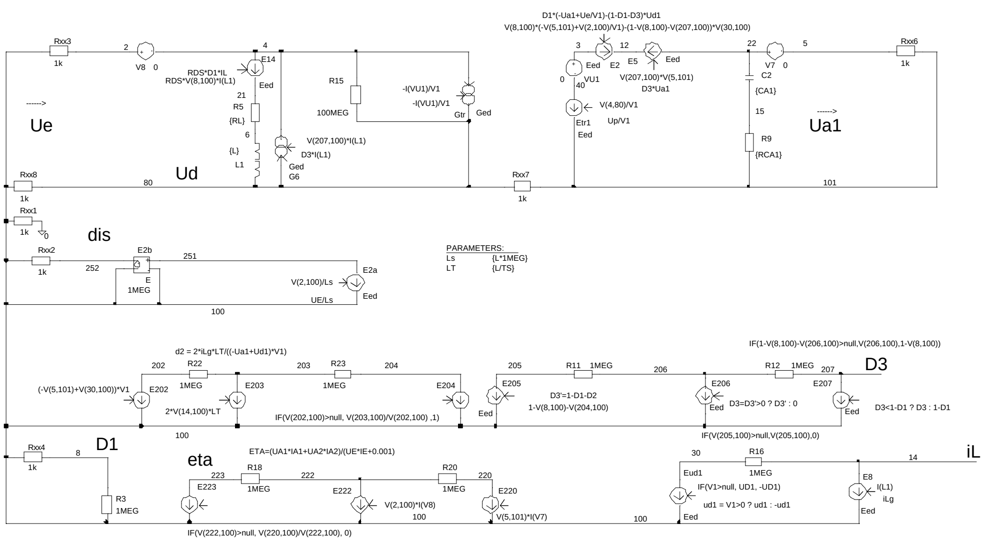

Ts: Cycle time

Ud1: Forward voltage of D1

Rds: Forward resistance of S1
Although no switch is integrated, the parameter Rds is required in order to determine the damping in the converter.

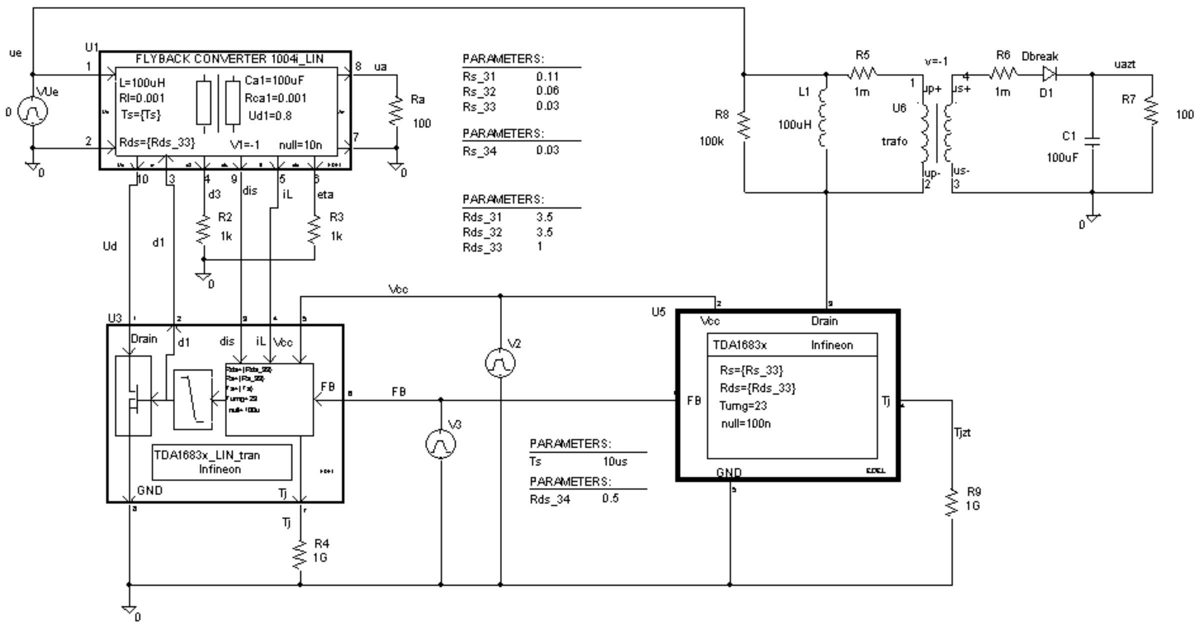
(File: 1004i_sch.sch)

## 2.2 Averaged model

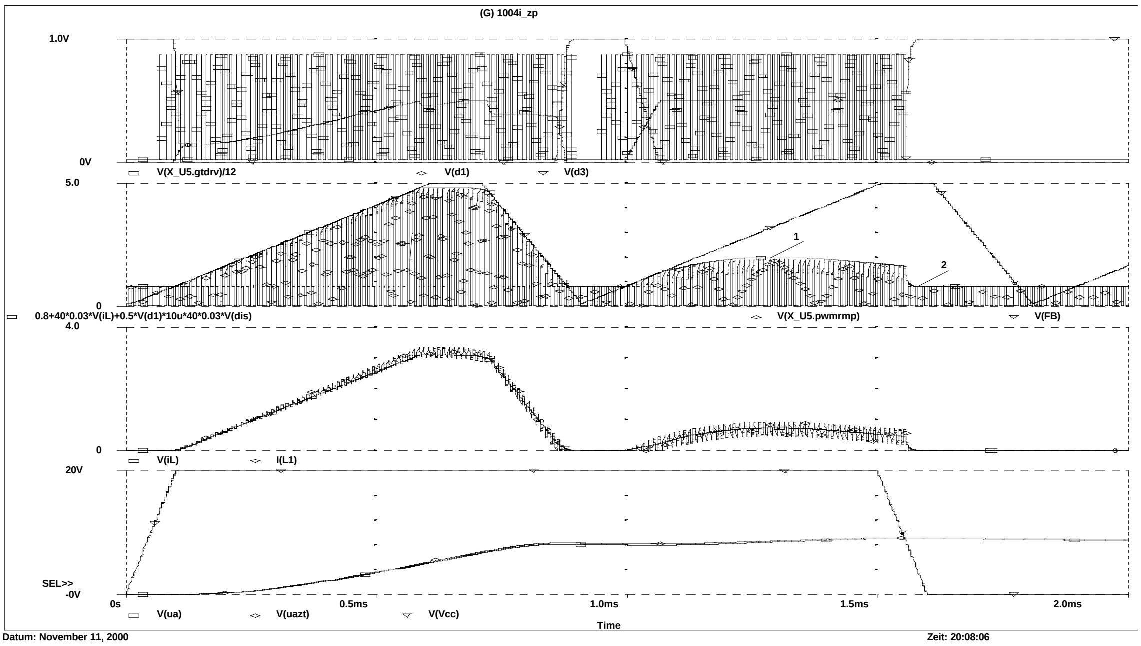



(File: 1004i_md.sch)

## 2.3 Time-domain characteristic with current loop



(File: 1004i_zp.sch)



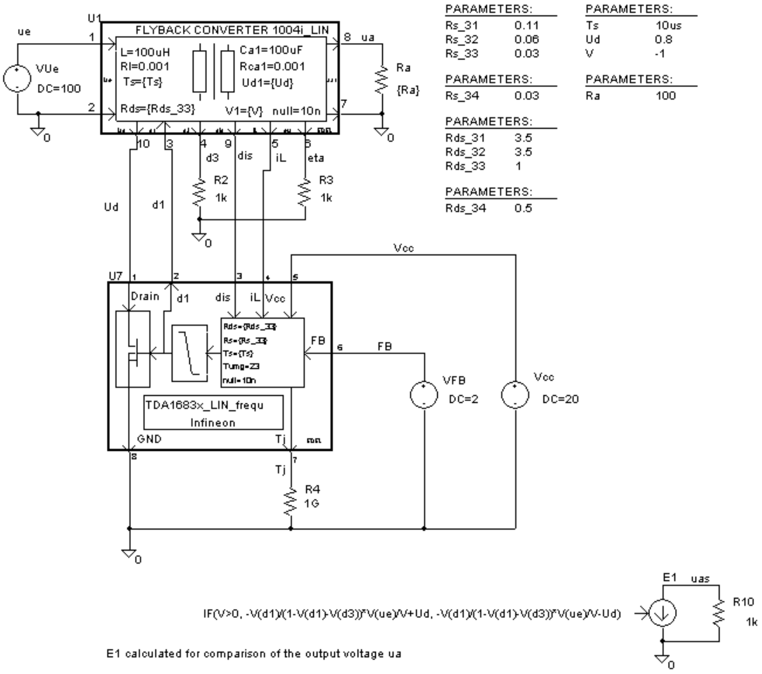
Switch-on characteristic with sawtooth controller voltage V(FB).The second curve shows the comparison of the inductor peak current $i_{Ls}$ in the switched model with the calculation in the averaged model:

$i_{Ls}$ ~ mean value of $i_L$ + half current rise dis * Ts.

$$i_{Ls} = 0.8 + 40R_s i_L + 1/2 d_1 T_s 40 R_s dis$$

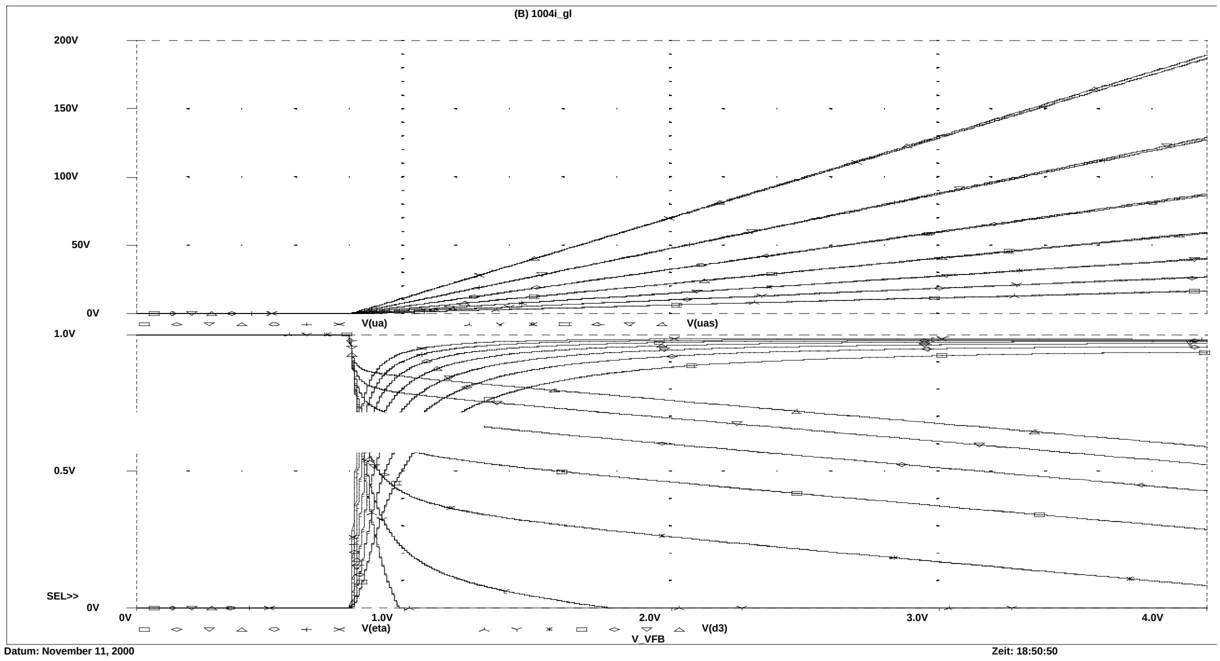
At marking 1 the current is limited by the maximum pulse control factor $D_{max}$ = 0.5. At marking 2 the PWM is switched off by the drop in the supply voltage Vcc.

## 2.4 DC operating points



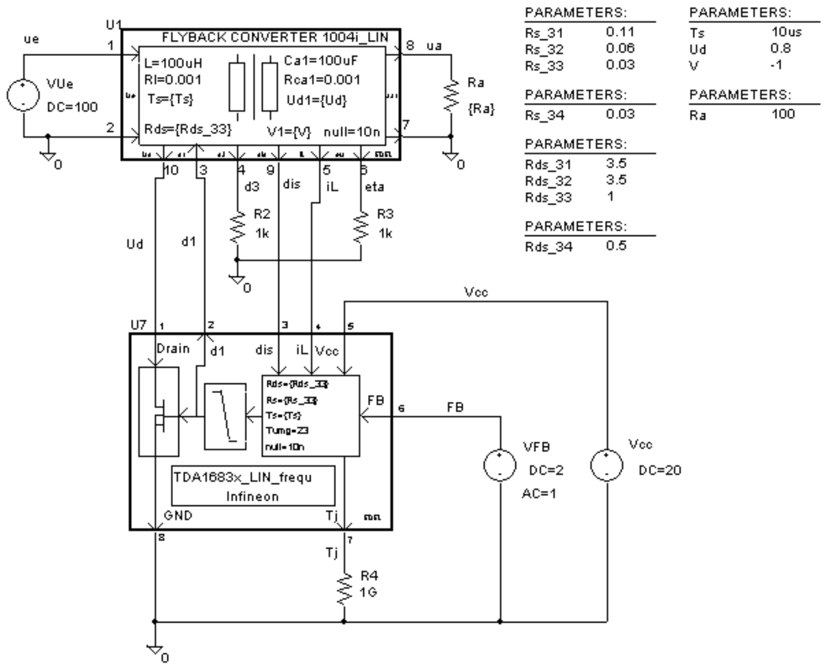

E1 calculated for comparison of the output voltage ua

(File:1004i_gl.sch)

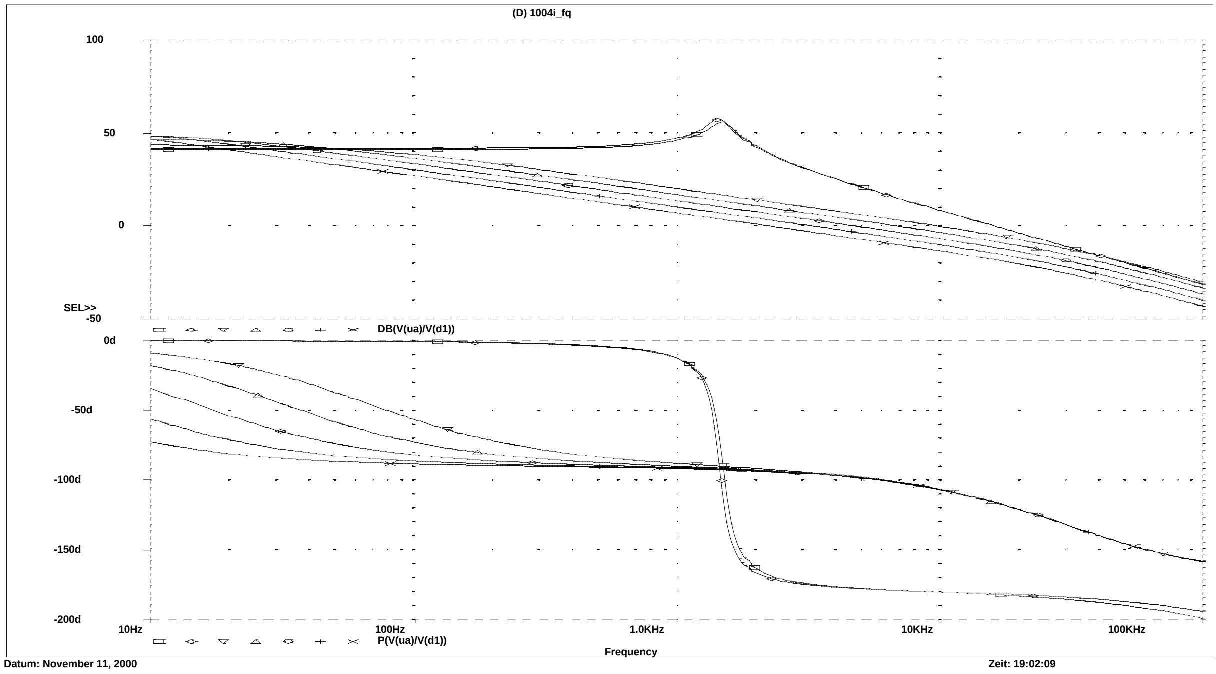



Logarithmic variation of $R_a$ from 10Ω ... 1kΩ with 3 values per decade, with $U_e$ = 100V and $U_{d1}$ = 0.8V. The TDA 1683x is switched on only after *V(FB)* ≥ 0.8V.

## 2.5 Frequency-domain characteristic



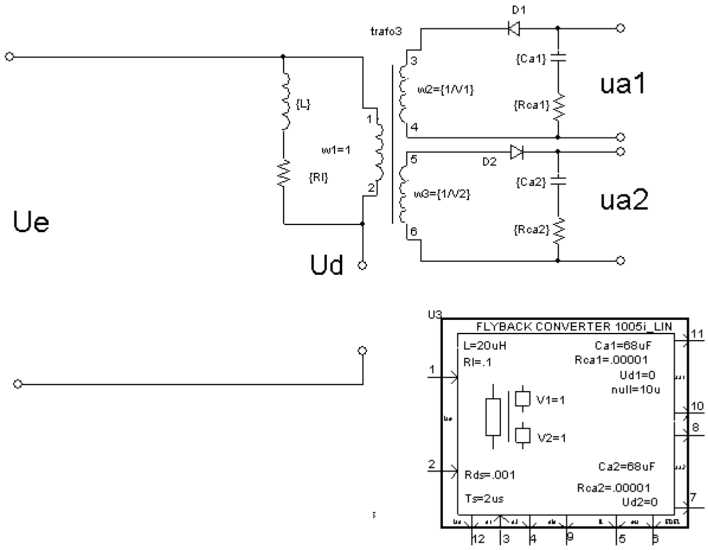

(File:1004i_fq.sch)




Response characteristic of $u_a/d_1$. Variation of Ra from 10Ω ... 1kΩ with 3 values per decade.

# 3 Flyback converter with electrical isolation, 2 outputs

## 3.1 Averaged circuit



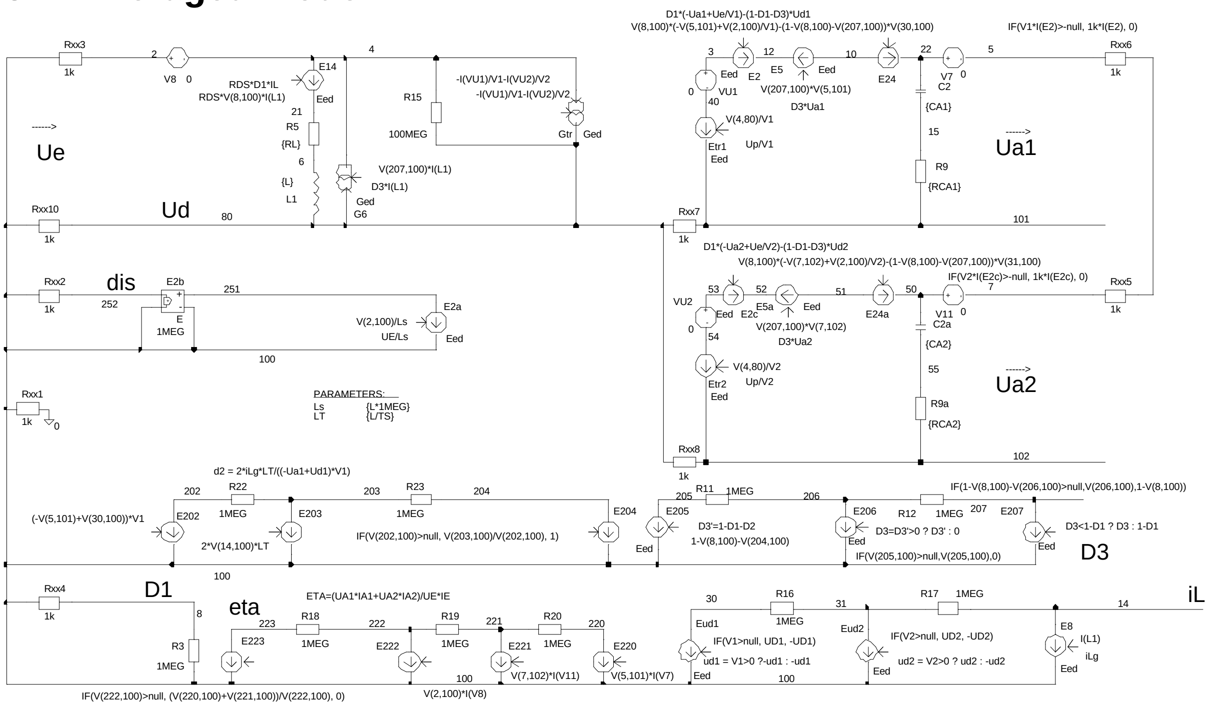

Ts: Elementary period

Ud1: Forward voltage of D1
Ud2: Forward voltage of D2

Rds: Forward resistance of S1
Although no switch is integrated, the parameter Rds is required in order to determine the attenuation in the converter.

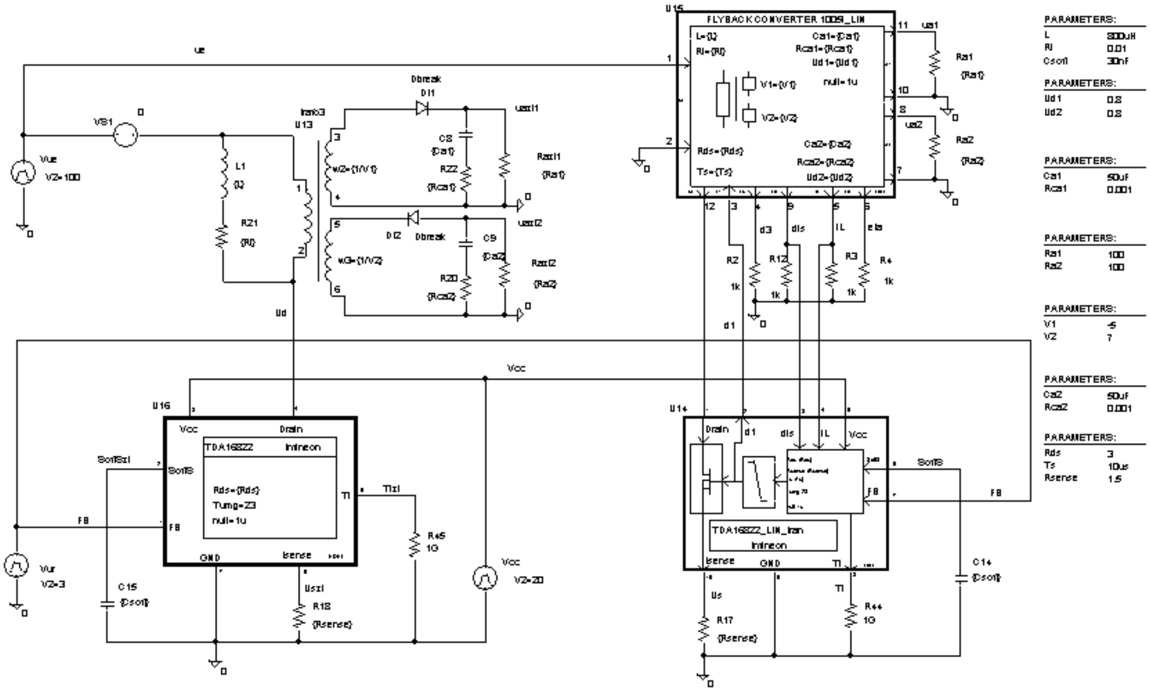
(File: 1005i_sch.sch)

## 3.2 Averaged model

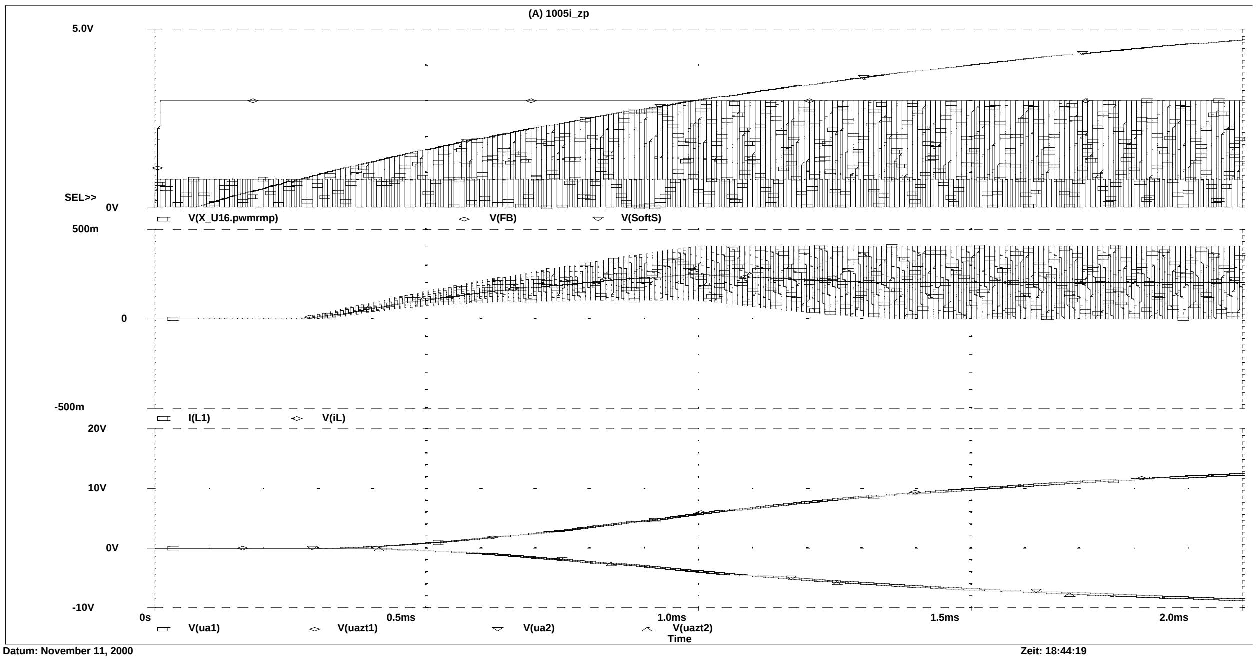



(File: 1005i_md.sch)

## 3.3 Time-domain characteristic with current loop

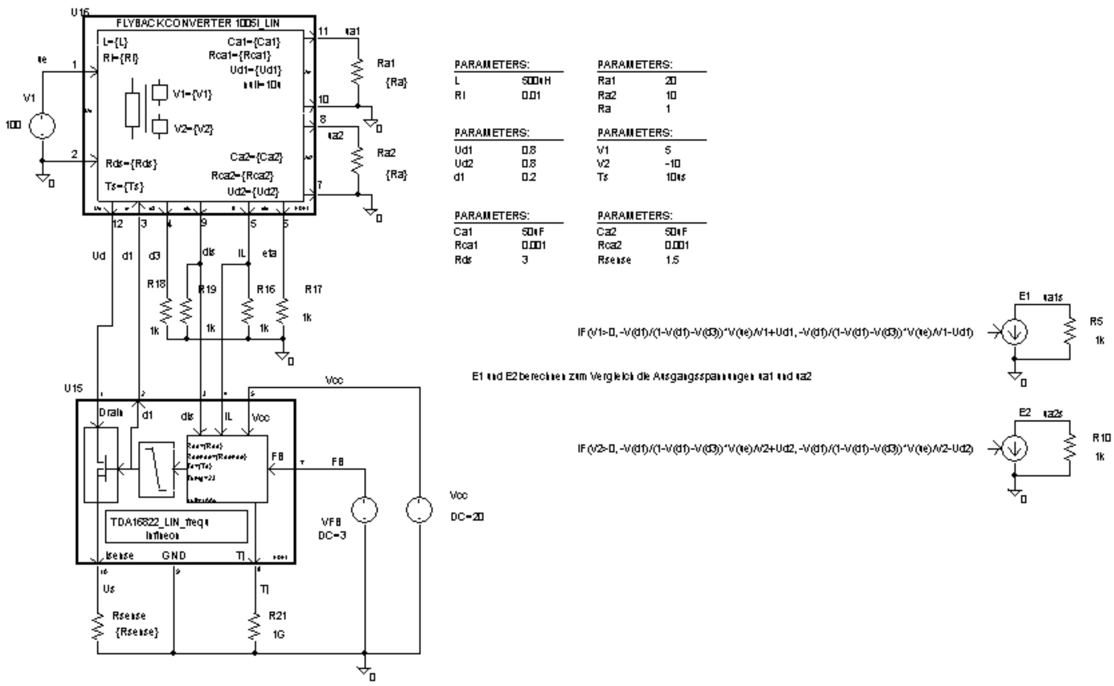



(File: 1005i_zp.sch)



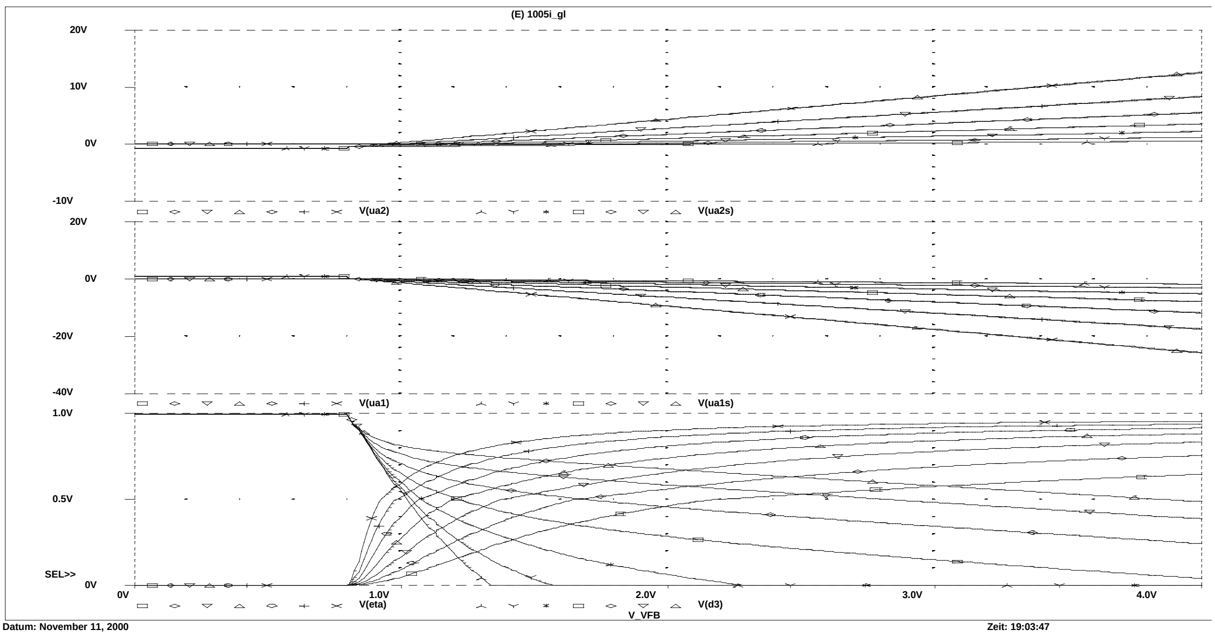

Switch-on characteristic with current loop for a step change of the control voltage *V(FB)* from *V(FB) = 0 to V(FB) = 3V*. The top curve shows how the inductor peak current is limited, first by the soft-start voltage and then by the controller voltage V(FB).

## 3.4 DC operating points



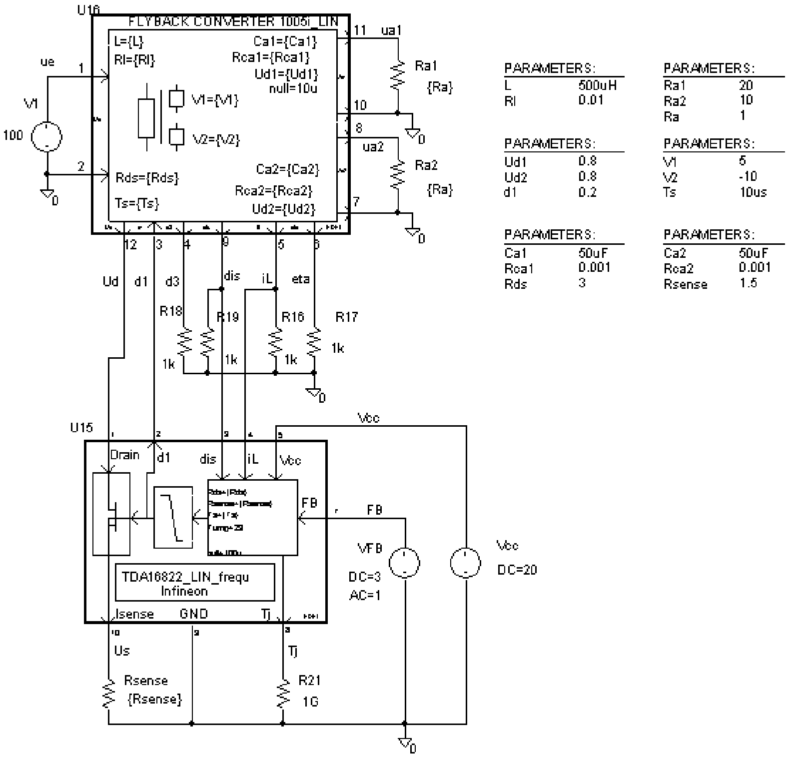
Calculate E1 and E2 for comparison of the output voltages ua1 and ua2

(File: 1005i_gl.sch)

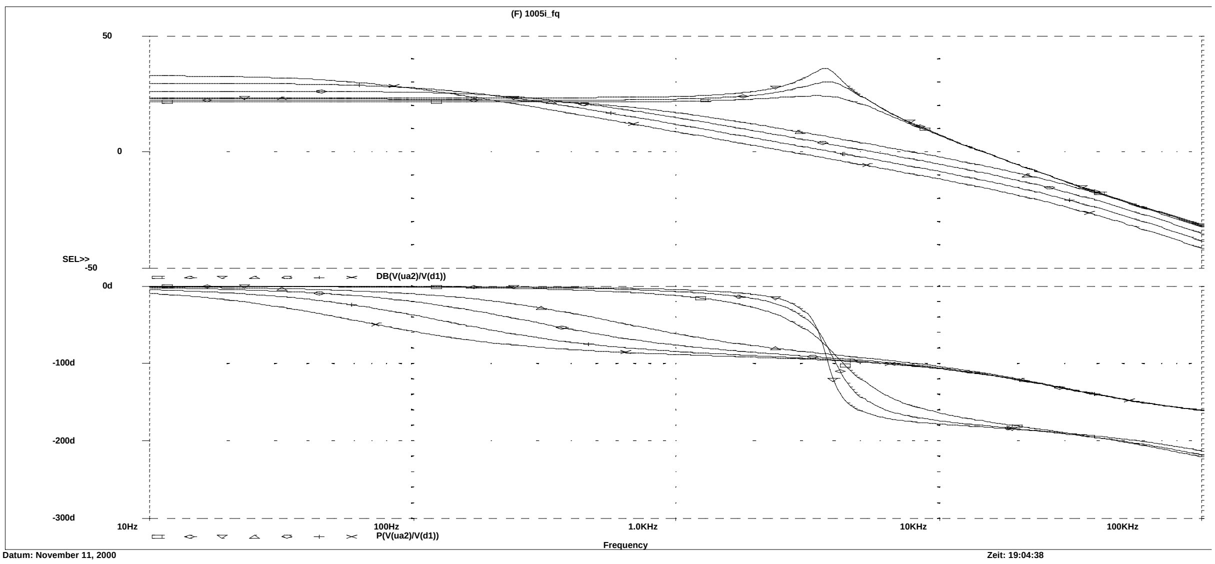


Logarithmic variation of $R_a$ from 1Ω ... 100Ω with 3 values per decade, with $U_e$ = 100V and $U_{d1}$ = $U_{d2}$ = 0.8V. The TDA 16822 is switched on only after *V(FB)* ≥ 0.8V.

## 3.5 Frequency-domain characteristic




(File: 1005i_fq.sch)




Response characteristic of $u_{a2}/d_1$. Variation of $R_a$ from 1Ω ... 100Ω with 3 values per decade. The phase response begins at 0 because the transformer ratio V2 is negative.

# A Convergence aids

As SPICE was originally developed for simulation of integrated circuits, it makes sense to adapt the OPTIONS to the needs and conditions of switched mode power supplies. Experience shows that the following extreme values are adequate:

| | |
|---|---|
| Minimum voltage of interest in the circuit: | $U_{min} = 1\ mV$. |
| Minimum current of interest in the circuit: | $I_{min} = 1\ mA$. |
| Greatest resistance in the circuit: | $R_{max} = 100M\Omega$. |

If the preset relative tolerance (RELTOL) of 0.001 is retained, the following is obtained for the **transient analysis:**

RELTOL = 0.001 (preset)
VNTOL=RELTOL*$U_{min}$ ⇒ VNTOL = 1 uV (preset)
ABSTOL = RELTOL *$I_{min}$ ⇒ ABSTOL = 1uA

In addition, it is advantageous to increase the number of iterations per time increment in the transient analysis;

ITL4 = 40 ... 100.

In the **DC analysis**, i.e. to determine the operating point, SPICE automatically connects a very small conductance in parallel with the switching components. This conductance should be adapted to the circuit:

GMIN = 1/$R_{max}$ ⇒ GMIN = 0.01u

In addition, the number of iterations for determining the operating point should be increased:

ITL1 = 500

This results in the following changes to the OPTIONS:

**ABSTOL = 1uA**
**GMIN = 0.01u**
**ITL1 = 500**
**ITL4 = 40**

# B Notes on the subcircuits

## B.1 Activation

All subcircuits are located in the infineon library which can be found in the subdirectory *..\lib*. The library consists of two files:

Infineon1.slb
Infineon1.lib

In order to link the library, the following needs to be entered into SCHEMATICS before the first simulation is carried out:

*File / Edit Library / File / Open... / infineon1.slb / Save*

The circuits in SCHEMATICS can be called with *the commands Draw / Get New Part / Browse / infineon.slb.*

The subcircuit description is located in ...*\lib\infineon1.lib*. You therefore have to make this library known in SCHEMATICS:

*Analysis / Library and Include Files... / infineon.lib / Add Library**

The circuits contained in directory *...\SMPS_examples* are executable only under PSPICE version 7.1 or higher.

In order to use the subcircuits, the grid size must be set in SCHEMATICS:

*Options / Display Options / Grid Size 00.05in or Grid Size 01.25 mm*

## B.2 Adapting the averaged models

The averaged models (files *_mod.sch) of the subcircuits can be customized. To this end, the netlist must be regenerated following the modification:

*Analysis / Create Netlist*

This netlist can now be opened with the PSPICE text editor:

*Analysis / Examine Netlist*

All resistors beginning with Rxx must now be removed. This is done most easily with the *Search* command of the editor. Finally, the netlist must be copied into the subcircuit in infineon.lib.

**Information**

For information on simulation-related issues, please check out the INFINEON simulation web page: www.infineon.com/simulate or email to: simulate@infineon.com. For information on technology, delivery terms and conditions and prices of INFINEON devices please contact your nearest Infineon Technologies Office in Germany or our Infineon Technologies Representatives worldwide (see address list).

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