University of Colorado
Boulder

ECEA 5715 Power Electronics Capstone Project
Milestone 3

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1. Approach

Upload a screen shot of the LTspice circuit model of your closed-loop controlled converter. The screen shot should include only your circuit. It is not necessary to include the template header provided in milestone3.asc (simulation commands and parameters, control signals, battery and bus models, measurement commands).
Add a brief description of your final closed-loop converter design including:

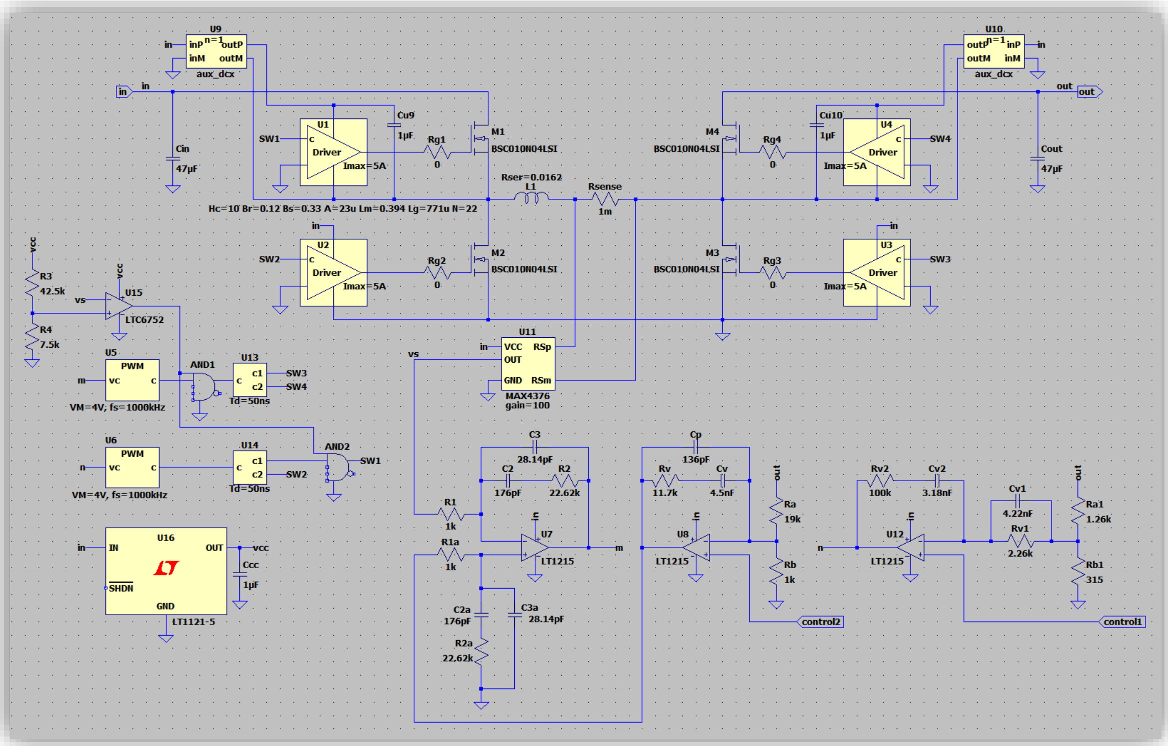

Figure 1. Final Schematic

1. A summary of the converter topology and the control techniques employed.

For the battery discharge portion, I changed the Topology from a single Voltage control source Non-inverting Buck Boost to a separated Buck/Boost dual voltage reference control type Converter. With this approach, the Max Inductor Current would be lower, we can redesign the Inductor with a smaller (lighter) core.

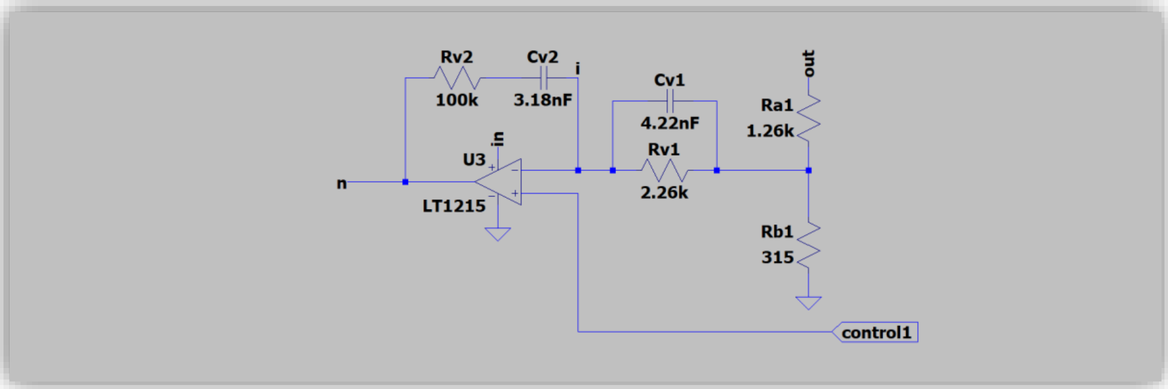

Figure 2. Voltage Mode Control PID Compensator

In Buck Mode, SW1 and SW2 would be used as synchronized Buck Converter with SW4 constantly Close and SW3 constantly Open. Voltage Mode with PID compensator is used for regulating the 5V output.

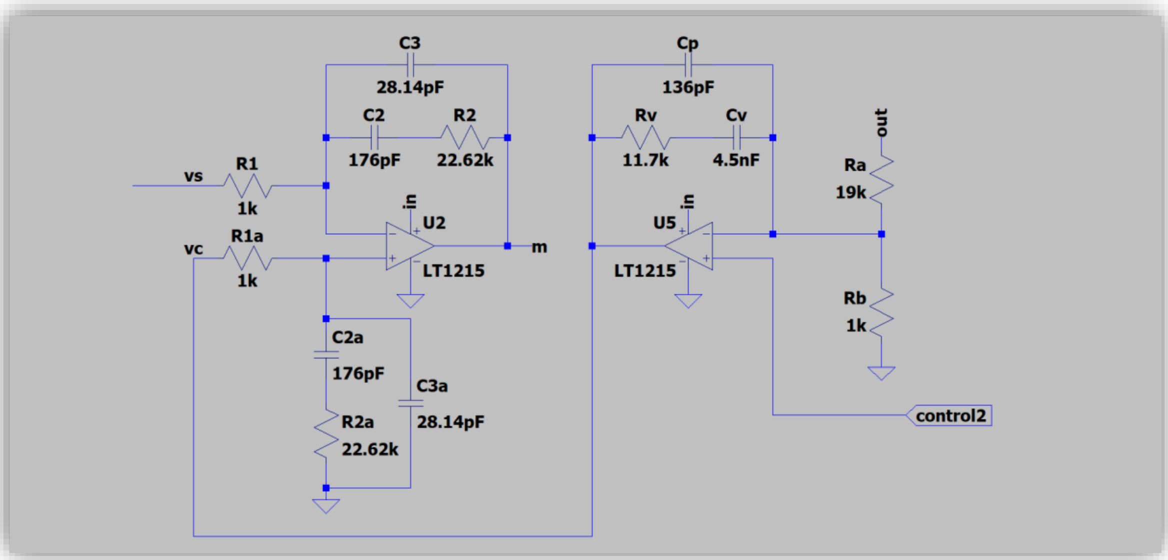

Figure 3. Averaged Current Mode Control PI Compensators

In Boost Mode, SW3 and SW4 would be used as synchronized Boost Converter with SW1 constantly Close and SW2 constantly Open. Average Current Mode with two loops with PI compensators are used for regulating the 20V output.

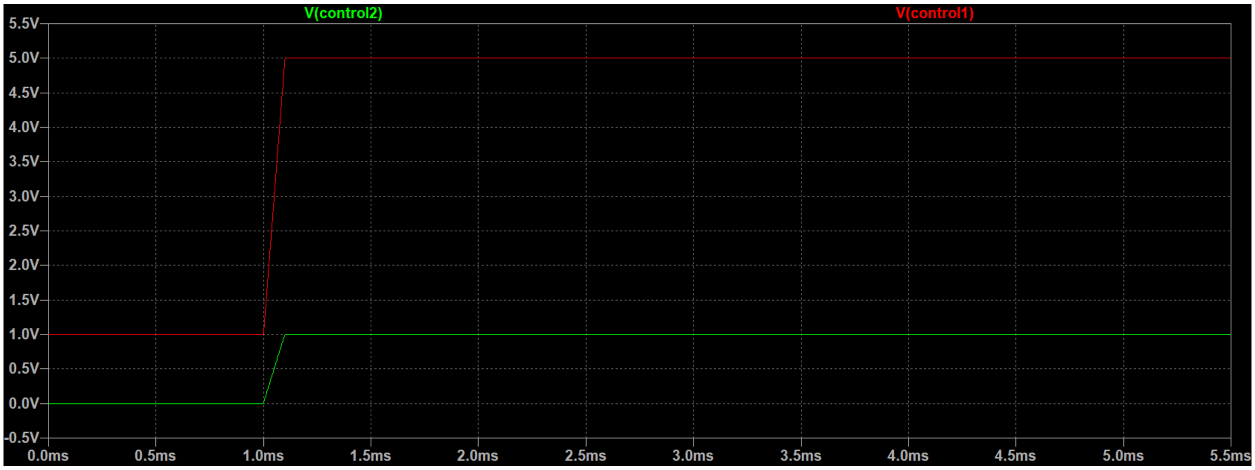

Figure 4. Voltage Control Reference

At Operating Point 1, Buck mode, Converter is dominated by V(control1) with reference to 1V; V(control2) is 0V which setting SW3 opened and SW4 closed.

At Operating Point 2, Boost mode, Converter is dominated by V(control2) with reference to 1V also; while V(control1) is 5V which making the converter to have high enough gain to saturate the output, making SW2 opened and SW1 closed (turning on 100% duty cycle).

When in reverse direction, SW3 and SW4 would be used as synchronized Buck Converter with SW1 constantly Close and SW2 constantly open. It would be desired to also use Rsense as current sensing with an additional current sensor for reverse direction, Average Current Control shall be used. Turning the converter as Constant Current Battery Charger.

2. A summary of how you implemented current limiting in your design.

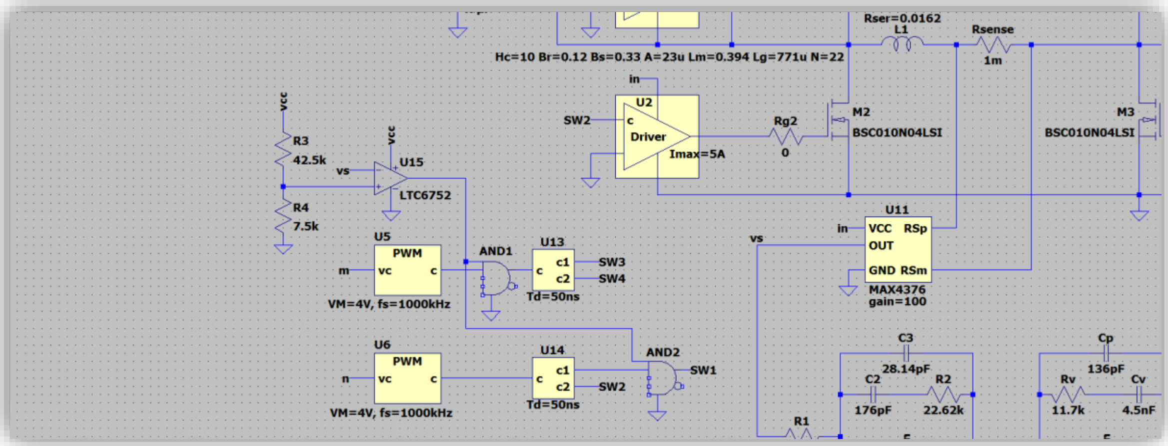

Figure 5. Inductor Current Limit Circuit

Since I chose Average Current Mode for Operating Point 2, which has disadvantage on limit transient current control when voltage reference changes drastically. Moving from 5V to 20V can have significant current spike which would cause the Inductor saturated, I implement a simple comparator and two AND gates as current limit circuit. Turn SW3 and SW1 off when an excess of current, SW2 and SW4 would be the Inductor Current path to deliver the current to the load. The converter acts as non-inverting Buck Boost at this instant until voltage output reaches steady state.

The limit is set to approximately 7.5A, The converter might take additional time to reach steady-state, but the Inductor would not saturate. With max Flux density of 0.29T (obtained from .meas) of whole simulation period.

Now thinking back, Peak Current Mode would be a better choice for this application.

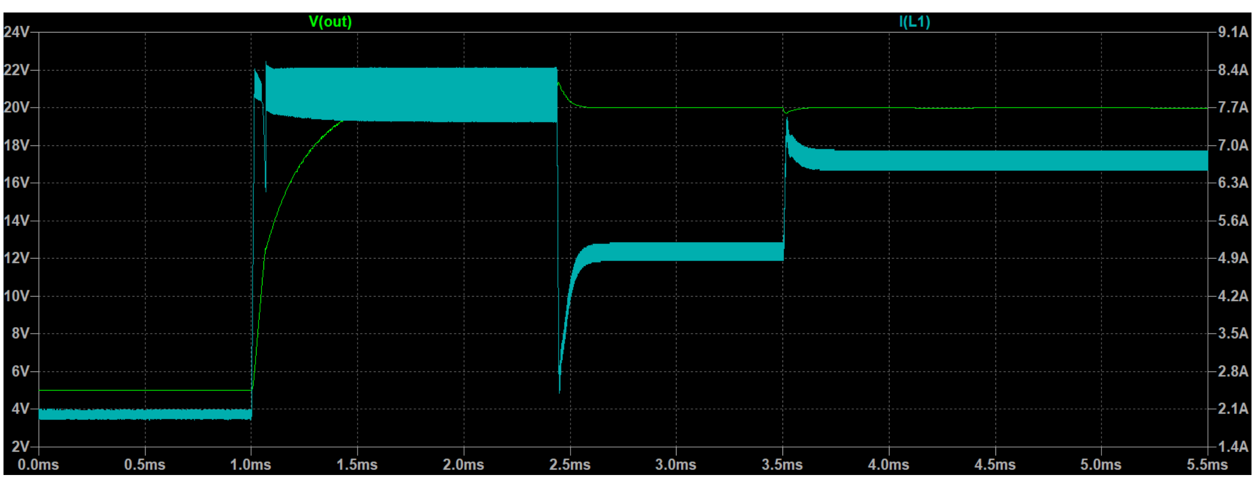

Figure 6. V(out), I(L1)

3. The magnetic cores used in the design and the total weight of the cores in grams.

I redesigned my Inductor because the change of Topology. Based on information and format of milestone 1.

Worst-case operating point for the inductor design: state Vbat, Vout, and Iout

Point 2, Vbat = 9.6V, Vout = 20V, Iout = 3A
Check IL comparison of each point in step 3 below.

DC value IL of the inductor current at the worst-case operating point: include equations used to calculate IL, and report IL value as a number with units.

$$I_L = \left(\frac{1}{D'}\right)\frac{V_{out}}{R} = \left(\frac{1}{1-0.5231}\right)\cdot 3 = \mathbf{6.2906A}$$

Switching Frequency = 1MHz (by choice)
Switching Period = 1/1MHz = 1µS
Maximum allowable Peak to Peak Current Ripple ≈ 5% (by choice)

$$V_L(t) = L\frac{dI_L(t)}{dt}$$

$$\Delta I_L = \frac{0.05 \times I_L}{2} = \frac{0.05 \times 6.2906}{2} = 158mA$$

Selected inductance L: include equations used to calculate L, and report inductance L as a number with units.

Minimum Desired Inductor Value that covers worst case scenario (neglect losses)

$$L = \frac{V_{in} D T_s}{2\Delta I_L} = \frac{9.6 \cdot 0.5231 \cdot 1\mu S}{2 \cdot 158 mA} = \mathbf{15.96\mu H}$$

For conservative purpose, we will use a common commercial value: $\mathbf{18\mu H}$
With Inductance chosen, recalculate ripple and ILmax.

	Vin	Direction	Vout	IL	Duty	L	ts	dIL(t)	ΔIL	ILmax
	V		V	A		H	s	A	A	A
Point 1	12.6	→	5	2.0000	0.3991	1.80E-05	1.00E-06	0.2794	0.1397	2.1397
	11.1		5	2.0000	0.453	1.80E-05	1.00E-06	0.2794	0.1397	2.1397
	9.6		5	2.0000	0.5238	1.80E-05	1.00E-06	0.2794	0.1397	2.1397
Point 2	12.6	→	20	4.7801	0.3724	1.80E-05	1.00E-06	0.2607	0.1303	4.9105
	11.1		20	5.4318	0.4477	1.80E-05	1.00E-06	0.2761	0.1380	5.5699
	9.6		20	6.2906	0.5231	1.80E-05	1.00E-06	0.2790	0.1395	6.4301
Point 3	20	←	12.6	4.7356	0.6335	1.80E-05	1.00E-06	0.7039	0.3519	5.0875
	20		11.1	5.3677	0.5589	1.80E-05	1.00E-06	0.6210	0.3105	5.6782
	20		9.6	6.1915	0.4845	1.80E-05	1.00E-06	0.5383	0.2692	6.4607

Required Kg: include equations used to calculated Kg, and report the value as a number with units.

Inductance at zero current = 18uH
Imax = 6.4301A, (we will round it to 7A)
Bmax = 0.25T
DC winding resistance R = 20mΩ (by choice)
Fill factor Ku = 0.6

$$K_g \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u} = \frac{(1.724 \cdot 10^{-6})(18 \cdot 10^{-6})^2 (7)^2}{(0.25)^2 (0.02)(0.6)} 10^8 = \mathbf{3.6 \times 10^{-3} cm^5}$$

Selected core size: justify how you selected the core size, and report the selected core size. You must use cores in the magnetics design tables of standard cores provided in the course (file “AppendixD.pdf”).

Core type (A) (mm)	Geometrical constant K_g (cm^5)	Geometrical constant K_{gfe} (cm^x)	Cross-sectional area A_c (cm^2)	Bobbin winding area W_A (cm^2)	Mean length per turn MLT (cm)	Magnetic path length ℓ_m (cm)	Core weight (g)
EE12	$0.731 \cdot 10^{-3}$	$0.458 \cdot 10^{-3}$	0.14	0.085	2.28	2.7	2.34
EE16	$2.02 \cdot 10^{-3}$	$0.842 \cdot 10^{-3}$	0.19	0.190	3.40	3.45	3.29
EE19	$4.07 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	0.23	0.284	3.69	3.94	4.83

Selected air gap lg: include equations used to calculate lg and report the value of lg as a number with units.

$$l_g = \frac{\mu_0 L I_{max}^2}{B_{max}^2 A_c} 10^4 = \frac{(4 \cdot \pi \cdot 10^{-7})(18 \cdot 10^{-6})(7)^2}{(0.25)^2(0.23)} 10^4 = \boldsymbol{7.71 \cdot 10^{-4} m}$$

Selected number of turns n and wire gauge AWG: include equations used to select n and AWG and report the values as numbers.

$$n = \frac{L I_{max}}{B_{max} A_c} 10^4 = \frac{(18 \cdot 10^{-6})(7)}{(0.25)(0.23)} 10^4 = 21.913 \approx \boldsymbol{22\ turns}$$

$$A_w \leq \frac{K_u W_A}{n} = \frac{(0.6)(0.284)}{22} = 0.00775 cm^2$$

AWG#	Bare area, 10^{-3} cm^2	Resistance, 10^{-6} Ω/cm	Diameter, cm
15	16.51	104.3	0.153
16	13.07	131.8	0.137
17	10.39	165.8	0.122
18	8.228	209.5	0.109
19	6.531	263.9	0.0948

#19 AWG

$$R_{dc} = \frac{\rho n MLT}{A_w} = \frac{(1.724 \cdot 10^{-6})(22)(3.69)}{(0.006531)} = \boldsymbol{16.2 m\Omega}$$

Predicted Bmax in steady-state operation at the worst-case operating point: include equations used to calculate Bmax, and report the value found as a number with units. Does the inductor saturate at the worst-case operating point?

$$BscaleL1 = \frac{\mu_0 n}{l_g} = \frac{(4 \cdot \pi \cdot 10^{-7})(22)}{(7.71 \cdot 10^{-4})} = 0.0342$$

```
.param BscaleL1=0.0342
```

$$B = \frac{\mu_0 n I}{l_g} = \frac{(4 \cdot \pi \cdot 10^{-7})(22)(7)}{(7.71 \cdot 10^{-4})} = \mathbf{0.2396T}$$

Report the total weight of the cores used in the design as a number in grams. The weights of all standard cores are listed in the magnetics design tables. Include only the weight of the ferrite, not the copper or other parts of the inductors.

The weight of EE19 is **4.83g.**

The SpiceLine for the Inductor (Final Choice) should be:

```
Hc=10 Br=0.12 Bs=0.33 A=23u Lm=0.394 Lg=771u N=22
Rser=0.0162
```

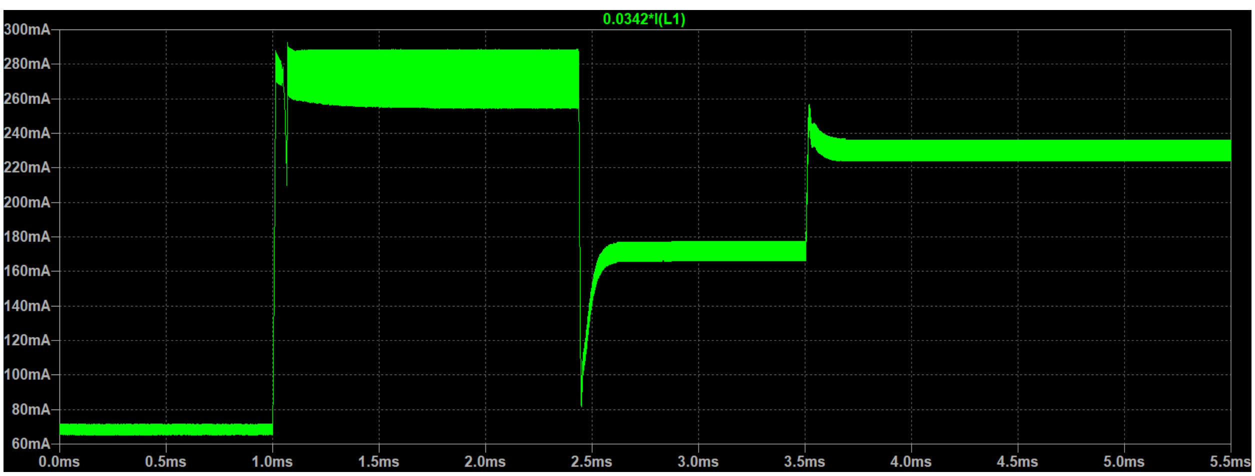

Figure 7. Flux Density

The Inductor Flux Density peaks at 0.29T which is lower than our threshold (0.33T).

4. The sum of all power stage capacitances used in the design in microfarads.

Cin	Cout	Cu9	Cu10	Ccc	Ctotal
47uF	47uF	1uF	1uF	1uF	**97uF**

2. Simulation

Place your Milestone 1 LTspice files into a dedicated folder. Make sure all simulations run correctly using the files in that folder. Remove all .raw files, but include all files necessary to run the required simulations (all .sch. .asy, .lib files). Create a .zip file of the folder and upload this .zip file.
The folder must include a single schematic (.sch) file that contains the template header from milestone3.sch and the circuit model of your closed-loop controlled converter. Note that the template header milestone3.sch ignores simulation results for the first Tskip = 0.5 ms. This is to allow any converter capacitors to be initially charged from the battery before the converter commences normal operation including current limiting. The template header tests your converter prototype at three operating points, in this order:

1. USB output 5V at 2A, Vbatt = 12.6V, steady-state operation expected at time=t1-Tskip
2. USB output 20V at 2.25A, Vbatt = 9.6V, steady-state operation expected at time=t2-Tskip
3. USB output 20V at 3A, Vbatt = 9.6V, steady-state operation expected at time=Tend-Tskip

In addition, the template tests the converter under a step load transient from 2.25A to 3A at at time=t2 for the output USB output voltage equal to 20V.
In the template header you should adjust the parameters **t1**, **t2**, and **Tend** as necessary so that the template measurements of the steady-state operating points and the step-load transient are made correctly. Your simulation should use the control signal parameters **Vref1 5V**, **Vref1 20V**, (and **Vref2 5V**, **Vref2 20V** if the second control signal source is used), to set the reference(s) for your control loop(s) as necessary to reach the steady-state operating points defined above, and you should adjust these parameters as well. Also define the switching period parameter **Ts** so that the template produces accurate measurements.

```
vout_5v: AVG(v(out))=4.99571 FROM 0.00099 TO 0.001
vout_20v: AVG(v(out))=19.9927 FROM 0.005489 TO 0.005499
vin_ripple_20v: PP(v(in))=0.0014286 FROM 0.005489 TO 0.005499
vout_ripple_20v: PP(v(out))=0.0357265 FROM 0.005489 TO 0.005499
pin_20v: AVG(-v(in)*i(vbatt))=64.243 FROM 0.005489 TO 0.005499
pout_20v: AVG(v(out)*i(rload))=59.6579 FROM 0.005489 TO 0.005499
eff_20v: 100*pout_20v/pin_20v=92.8629
vout_20_min: MIN(v(out))=19.6664 FROM 0.0035 TO 0.0055
bmaxl1_20v: MAX(0.0342 *i(l1))=0.292935 FROM 0 TO 0.005499
```