DC VOLTAGE REGULATION

Power Electronics Assignment 2
DT021A/3
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1. Linear DC voltage regulator

1.1. The positive linear voltage regulator

1.1.1. Calculation of the Resistor values

Calculating resistor values for R2 and R3 to achieve output DC voltage of 15V when supplying 24V into the regulator circuit as shown in figure 1.

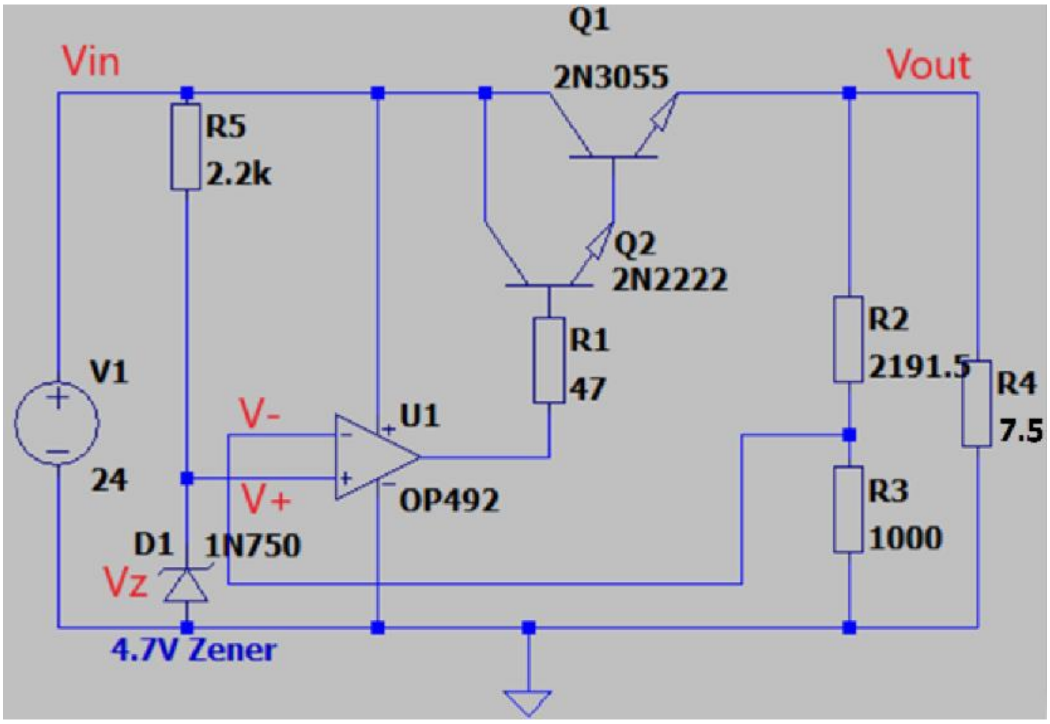

Figure 1 - Circuit diagram of the linear voltage regulators

Due to the close loop configuration of the amplifier, the voltage at the inverting and non-inverting terminals are equal. Therefore:

$$V+ = V- = V_Z$$

V- can also be represented as

$$\frac{R2}{R1 + R2} * V_o$$

$$\therefore \; V_o = V_Z * \left(1 + \frac{R1}{R2}\right)$$

Where V_o = 15v and V_Z = 4.7v and rearranging the equation to find the values for the resistor and assuming R2 is 1k ohms.

$$R1 = \left(\frac{V_o}{V_Z} - 1\right) * R2$$

$$R1 = \left(\frac{15}{4.7} - 1\right) * 1000$$

$$\boldsymbol{R2 = 1000\ \Omega}$$

$$\boldsymbol{R1 = 2191\ \Omega}$$

$$RL = \frac{V_o}{I_o}$$

$$\boldsymbol{RL = \frac{15}{2} = 7.5\ \Omega}$$

These calculated resistor values are used in the circuit to achieve 15 volts output as shown in figure 1. The simulation of the circuit shows the saturation peek at 15V in figure 2.

Figure 2 – Graph shows the supplied voltage 24v and constant output voltage of 15v produced by the circuit

1.1.2. Calculations for line regulations

Calculating the line regulation for a 10% drop in the input voltage

$$\mathbf{24 * 10\% = 2.4}\boldsymbol{v}$$

$$\boldsymbol{Vin}\ (\mathbf{10\%}\ \boldsymbol{drop}) = \mathbf{24 - 2.4 = 21.6}\boldsymbol{v}$$

Vo increases to 15v when Vin changes from 0v – 21.6v. The circuit keeps the output voltage constant.

$$\frac{\Delta V_o}{\Delta V_{in}}\ (\%)$$

$$= \frac{\frac{V_{o2} - V_{o1}}{V_o}}{V_{in2} - V_{in1}} * 100 = \frac{\frac{15-0}{15}}{21.6-0} * 100$$

$$\boldsymbol{Line\ Regulation}\ \% = \mathbf{4.16\%}$$

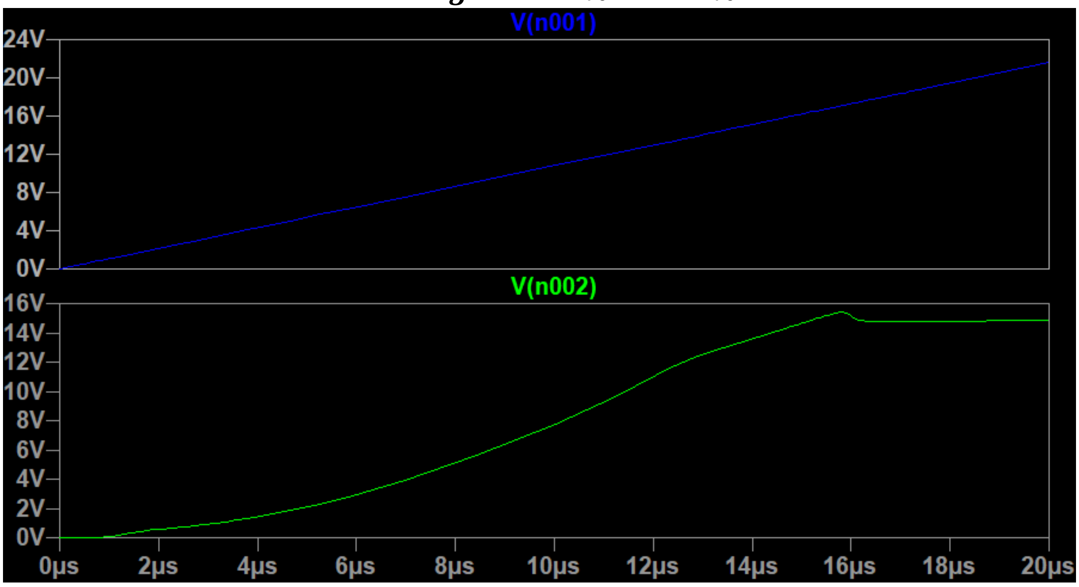

Figure 3 – Simulations graphs shows the supplied signal of 21.6v in the circuit produces the constant output signal of 15v

1.1.3. Calculations for load regulations

$$Load\ Regulations = \frac{V_{out\ (noload)} - V_{out\ (fullload)}}{V_{out\ (half\ load)}} * 100\%$$

$$Load\ Regulations = \frac{0 - 15}{1 * (7.5 * 2)} * 100\%$$

1.1.4. The efficiency at full load current

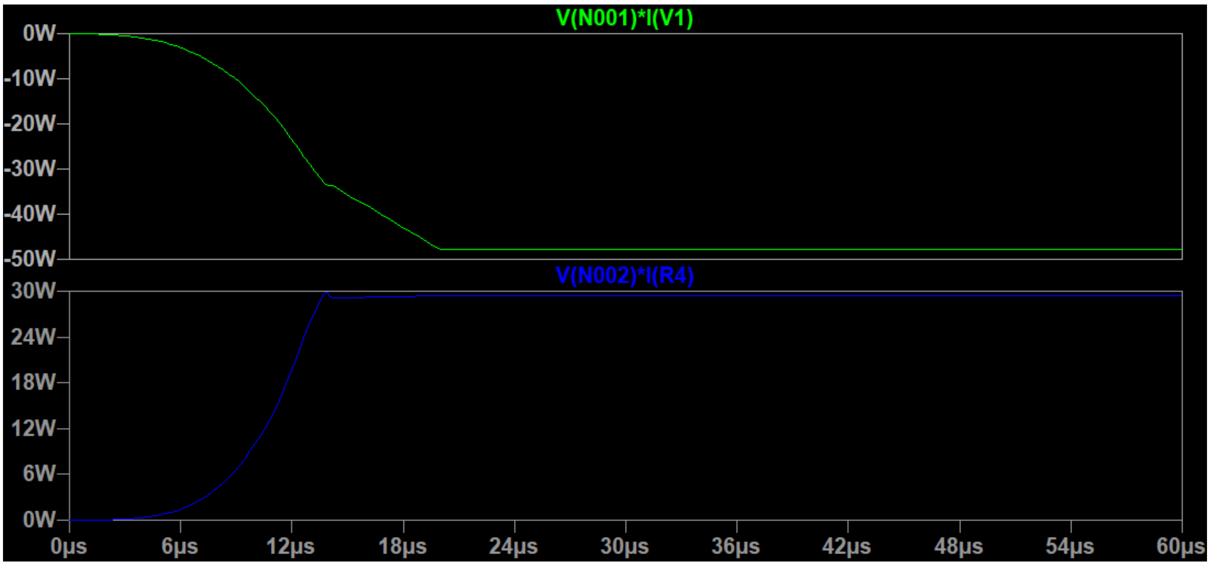

Figure 4 - Power dissipation in the input and the load

$$Efficiency\ = output\ power/\ input\ power\ (\%)$$

$$Efficiency\ = \frac{29.4W}{47.8W} * 100$$

$$Efficiency\ = \mathbf{61.5}\%$$

The 18.4W of power is loosed in the circuit because the transistor consumes most of the power. After all, it is conducting all of the time, so it has current and voltage across the transistor simultaneously which produces power loss and it just behaves like a resistor. Some of the power is also loosed in the Zener diode and Op-amp, which is not efficient.

1.2. The step-down switching regulator

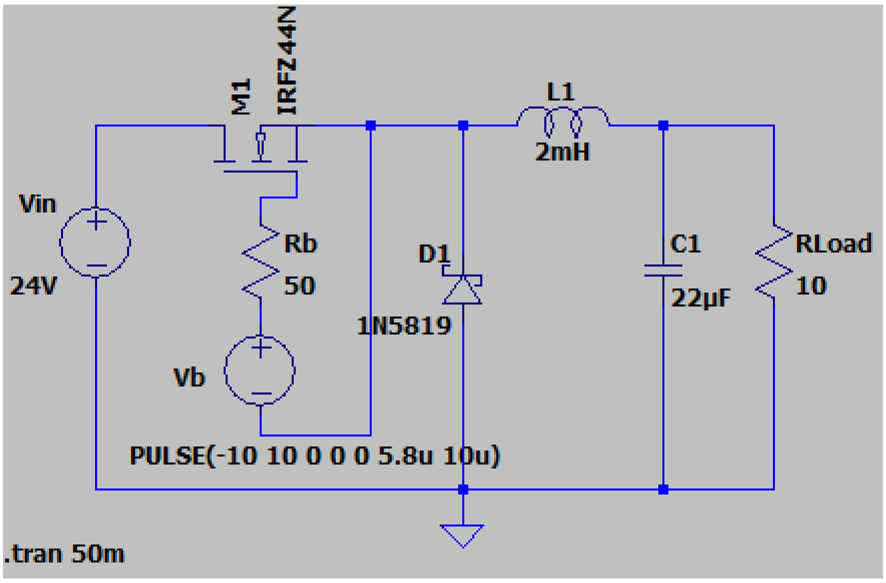

Figure 5 - Circuit diagram of the step-down switching regulator

1.2.1. Calculation of the pulse high width

Finding the formula for output voltage and controlling a suitable high pulse width time for Vg to achieve 14v at the output.

$$\Delta I_{Loff} = -\Delta I_{Lon}$$
$$-T_{off}\frac{V_{out}}{L} = -(V_{in} - V_{out})\frac{T_{off}}{L}$$
$$T_{off}\frac{V_{out}}{L} = (V_{in} - V_{out})\frac{T_{off}}{L}$$
$$T_{off}\,V_{out} = (V_{in} - V_{out})T_{on}$$
$$(T_{on} + T_{off})V_{out} = V_{in}T_{on}$$
$$V_{out} = V_{in}T_{on}\,(T_{on} + T_{off})$$

$$\boldsymbol{Period} = T = T_{on} + T_{off}$$

$$\boldsymbol{DutyCycle} = D = \frac{T_{on}}{T}$$

$$V_{out} = V_{in}\frac{DT}{T}$$
$$\boldsymbol{V_{out}} = DV_{in}$$

We know, $V_{in} = 24v$, $V_{out} = 14v$, $T = $ 10us and Ton can be calculated accordingly

$$T_{on} = \frac{V_{out}\,T}{V_{in}}$$

$$T_{on} = \frac{14 * 10 * 10^{-6}}{24}$$

$$\boldsymbol{T_{on} = 5.833\ us}$$

The graph in figure 6 produces 14.5v output when setting the pulse high width to 5.822 μs.

Figure 6 - Resultant output voltage of the step-down switch regulator

1.2.2. Calculations for L1 and C1

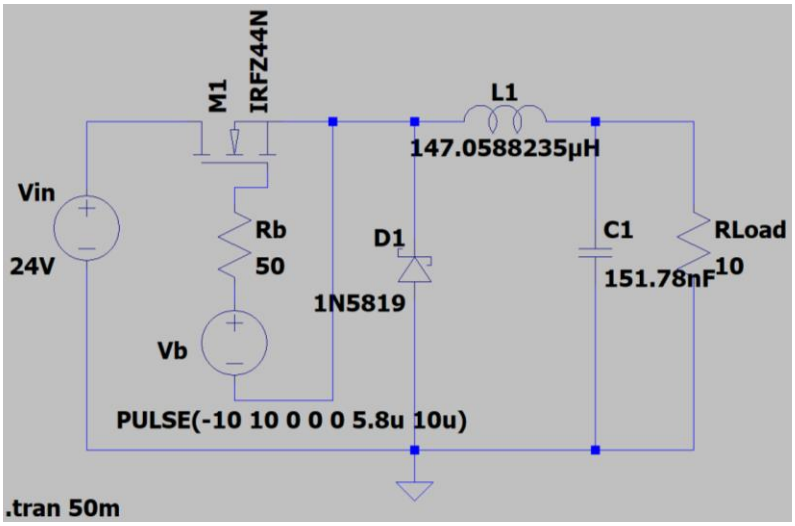

Figure 7 - Circuit diagram of the DC step down voltage regulator with C1 and L1 values

To find Inductor value:

$$\text{Duty D} = \frac{V_o}{V_i} = \frac{14}{24} = 0.5$$

$$T_{on} = 5.833\ \mu s$$

$$V_L = L\frac{\Delta I_L}{\Delta T} = L\frac{1 \times (I_{peak} - I_{avg})}{T_{on}}$$

$$V_L = L\frac{1}{T_{on}}$$

$$L = V_L\frac{T_{on}}{I_{Load}}$$

$$V_L = V_i - V_o$$

$$V_L = 24 - 14 = 10V$$

Therefore

$$L = 10\frac{0.5 * 10 * 10^{-6}}{1 * 1.7 * 20\%}$$
$$\boldsymbol{L = 147.058\,\mu H}$$

To find capacitor value:

$$\Delta V_o = \Delta\frac{Q}{C}$$
$$\Delta Q = \frac{1}{2}\left(\frac{T}{2}\right) * \frac{\Delta I_L}{2}$$
$$C = \frac{\Delta Q}{\Delta V_o}$$
$$C = \frac{10 * 10^{-6} * 1.7 * 20\%}{8 * (14 * 20\%)}$$
$$\boldsymbol{C = 151.78nF}$$

1.2.3. Comparison of inductor current and load voltage

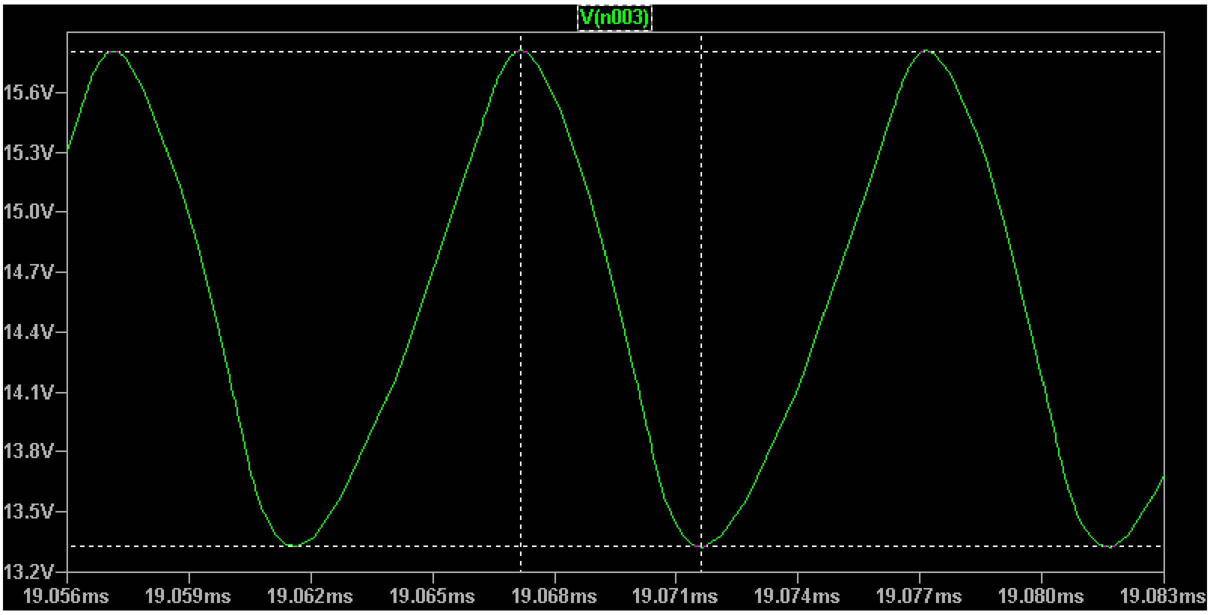

Figure 8 - Load voltage response of the ripple voltage

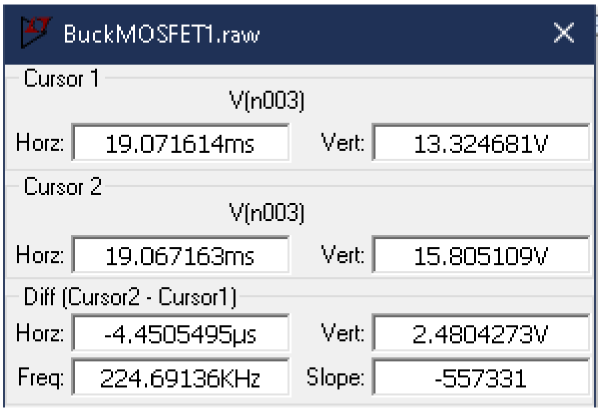

Figure 9 - Cursor shows the voltage ripple waveform of the load at 2.48V peek to peek

$$Measured\ ripple\ voltage: 2.48V$$

$$Calculated\ ripple\ voltage: 14\ *\ 20\%\ =\ 2.8V$$

$$Error\ = \frac{2.48}{2.8} * 100 =\ 88.57\% - 100\% =\ 11.42\%$$

This step-down converter performs better than the linear regulator as it produces less error and is efficient.

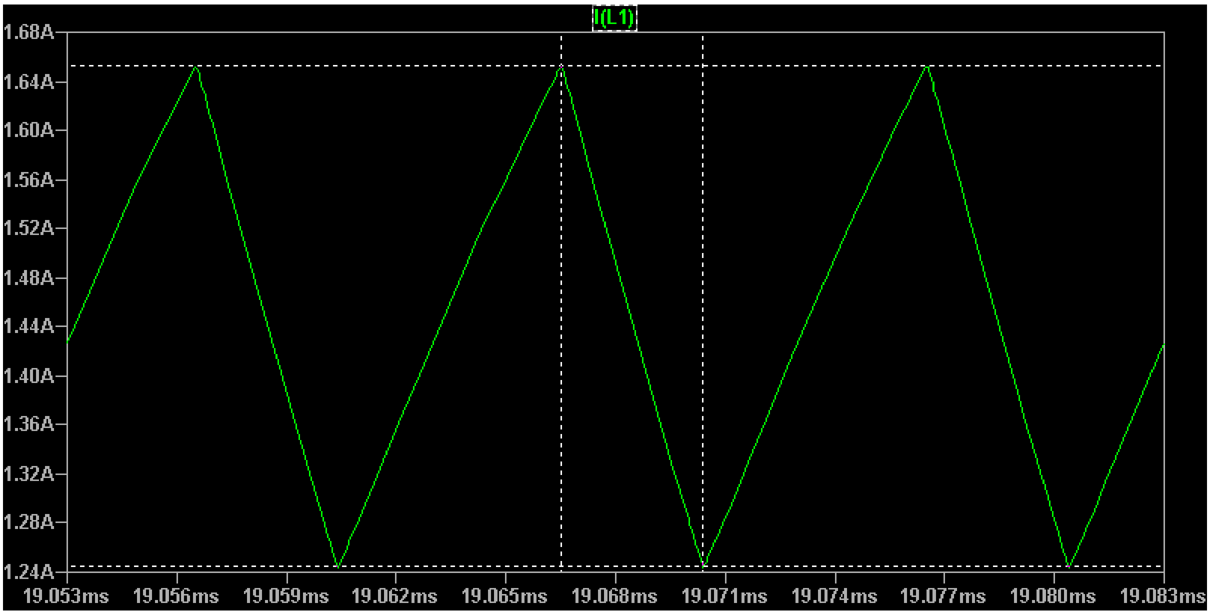

Figure 10 - Screenshot of the inductor current

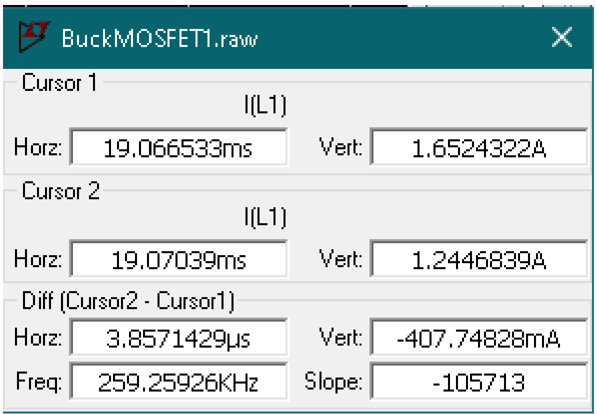

Figure 11 - Cursor shows the current ripple waveform of the inductor current at 407mA peek to peek

$$Measured\ ripple\ current: 407mA$$

$$Calculated\ ripple\ current: 1.7\ *\ 20\%\ =\ 340mA$$

$$Error\ = \frac{340}{407} * 100 =\ 88.53\% - 100\% =\ 11.47\%$$

1.2.4. The efficiency of the circuit

Calculated Power efficiency = $\frac{1.7*14}{1.7*24} = \frac{23.8}{40.8} * 100$ = 60%

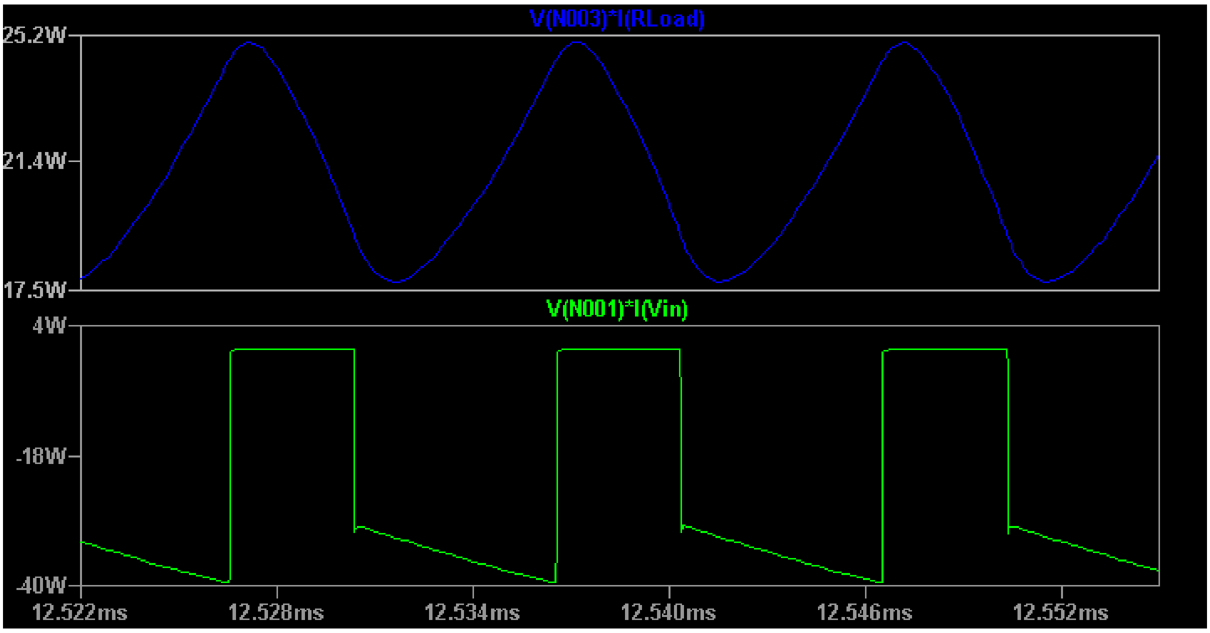

Figure 12 - Output power over the input power

2. Buck-Buck-Boost switching DC supply

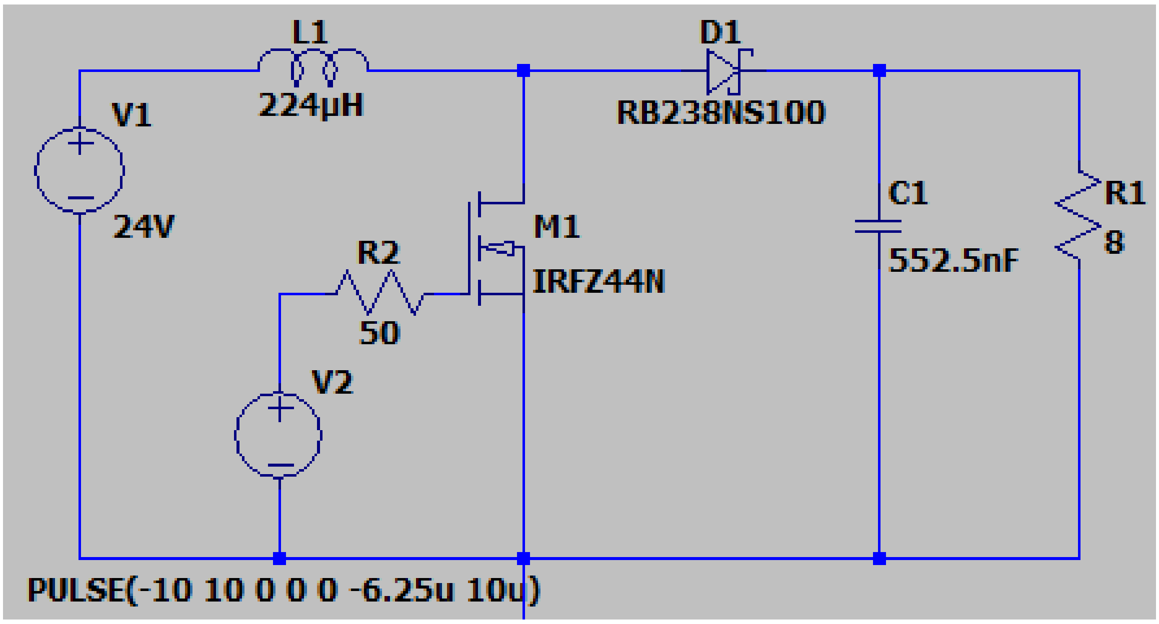

Figure 13 - Circuit diagram of the Buck-boost convertor

$$V_L = L\frac{\Delta I_L}{dt}$$

$$V_L \approx L\frac{\Delta I_L}{\Delta t}$$

$$V_L = L\frac{\Delta I_{off}}{T_{off}}$$
$$V_{in} = (V_L + V_{out})$$
$$V_L = L\frac{\Delta I_{off}}{T_{off}} + V_{out}$$
$$V_{in} = +V_{out} - L\frac{\Delta I_{off}}{T_{off}}$$
$$V_{out} = +V_{in} - L\frac{\Delta I_{off}}{T_{off}}$$
$$\Delta I_{off} = -\Delta I_{Lon}$$
$$V_{out} = +V_{in} + L\frac{\Delta I_{on}}{T_{off}}$$
$$V_{out} = +V_{in} + L\frac{V_{in}T_{on}}{L}\frac{1}{T_{off}}$$
$$V_{out} = V_{in} + V_{in}\frac{T_{on}}{T_{off}}$$
$$V_{out} = V_{in} + V_{in}\frac{DT}{(1-D)T}$$
$$V_{out} = V_{in} + V_{in}\frac{D}{(1-D)}$$
$$V_{out} = V_{in} + V_{in}\left(1 + \frac{D}{(1-D)}\right)$$
$$V_{out} = V_{in} + V_{in}\frac{(1-D)+D}{(1-D)}$$
$$\boldsymbol{V_{out} = \frac{V_{in}}{(1-D)}}$$
$$\boldsymbol{D = -\frac{V_{in}}{V_{out}} + 1}$$
$$\boldsymbol{D = -\frac{-15}{24} + 1}$$
$$\boldsymbol{D = 1.625}$$

Inductor:

$$L = (V_{in})(1-D)\frac{T_{on}}{2I_{Load}}$$

$$L = (-15)(1-1.625)\frac{1.625 * 10 * 10^{-6}}{2 * (1.7 * 20\%)}$$

$$L = 224\, uH$$

Capacitor:

$$\Delta V_c = \frac{I_{Load}T_{on}}{C}$$
$$10 = \frac{(1.7 * 20\%)(1.635 * 10 * 10^{-6})}{C}$$
$$C = \frac{(1.7 * 20\%)(1.635 * 10 * 10^{-6})}{10}$$
$$C = 552.5\, nF$$

$$RL = \frac{V_o}{I_o}$$

$$\boldsymbol{RL} = \frac{\mathbf{-15}}{\mathbf{1.7}} = \mathbf{-8.8}\ \boldsymbol{\Omega}$$

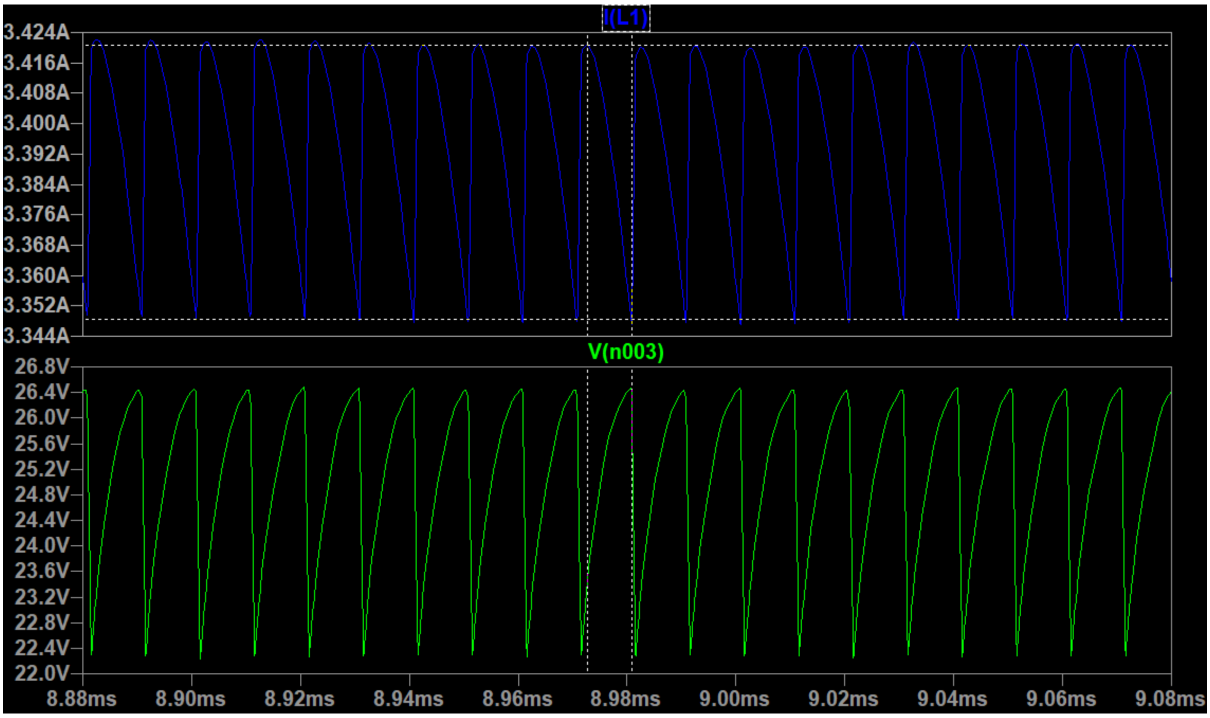

Figure 14 - Voltage ripple and Current ripple