Power supply project

1. Introduction

A power supply is an electrical device that supplies electric power to an electrical load. The primary function of a power supply is to convert electric current from a source to the correct voltage, current, and frequency to power to load. As a result, power supplies are sometimes referred to as electric power converters. The main components of a DC power supply are the transformer, the rectifier, the filter and the regulator.

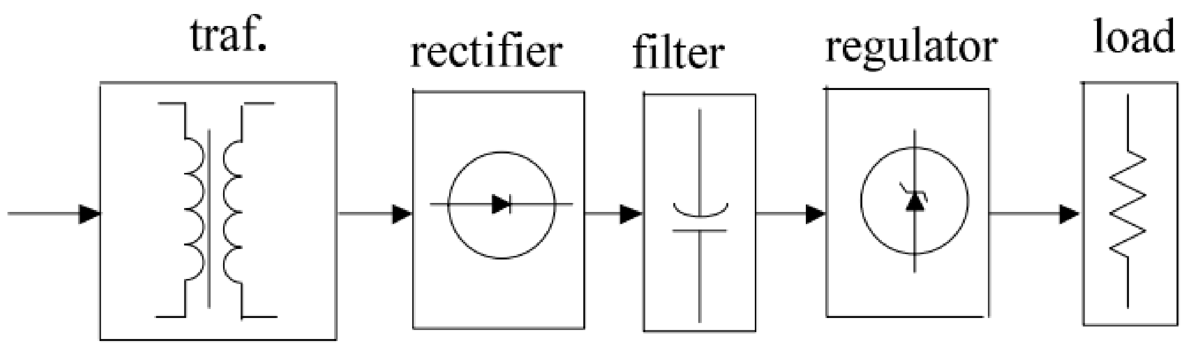

Figure 1: The block schematic of a power supply

1.2 The transformer

A transformer is a passive component that transfers electrical energy from one electrical circuit to another circuit, or multiple circuits. The main role of the transformer is to achieve a certain voltage value to obtain the wanted signal at the output of the circuit. Another role of the transformer is that of galvanic isolation. A varying current in any one coil of the transformer produces a varying magnetic flux in the transformer’s core, which induces a varying electromotive force across any other coil wound around the same core. Electric energy can be transferred between separate coils without a metallic connection between the two circuits.

1.3 Choosing the transformer

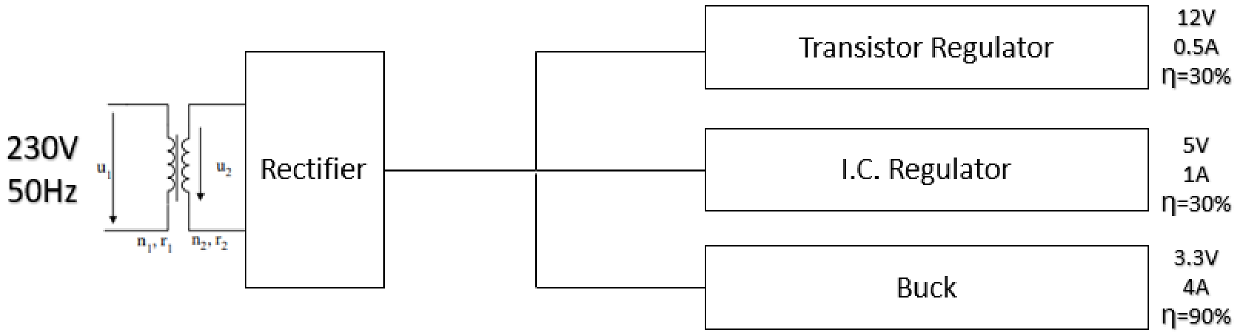

Figure 2: The block schematic of the project

In order to be able to choose the transformer we have to know the total power at the output of the rectifier using the next formula:

$$\eta = \frac{P_{out}}{P_{in}}$$

- The power at the input of the transistor regulator: 20W
- The power at the input of the I.C. regulator: 16.66W
- The power at the input of the Buck: 14.66W

Adding these results, we will get the total power at the output of the rectifier, which is 51.32W.

In order to find the voltage in the secondary, we will assume that the voltage drop on the rectifier's load is

16V. Considering the loses on the rectifier's diodes, we'll assume that the voltage on secondary is the one on the load plus the voltage on diodes and capacitor. That will give us a total voltage of approximatively 18V.

Parameter	**Value**
Primary voltage	230VAC
Secondary voltage	6-12-18-24V
Nominal power	150VA
Nominal frequency	50/60Hz
Secondary current	6.25A
Price	320 RON

2. Designing the rectifier

For my project I have chosen a full-wave diode bridge rectifier with capacitive filter. It is an arrangement of four diodes in a bridge circuit configuration that provides the same polarity of the output for either polarity of the input. The rectifier has a maximum efficiency of 80%. The schematic is showed in the figure below:

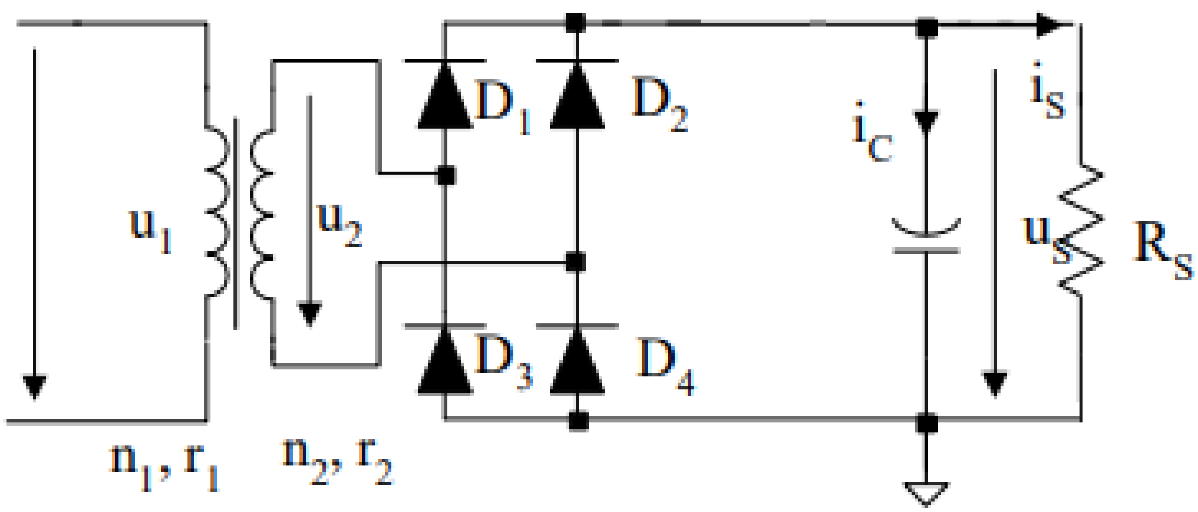

Figure 3: The schematic of the circuit

During the positive half-cycle of the voltage supply D1 and D4 conduct current in series, while D2 and D3 are reversed biased. During the negative half-cycle of the voltage supply D2 and D3 conduct current while D1 and D4 are reversed biased. Because two diodes are active on each half-cycle, the amplitude of the output signal will be smaller than that of the input signal with $2 * V_D$, which is around 1.4V. In the most cases the waveform obtained for the output voltage of a rectifier without capacitive filter is not appropriate for supplying electronic devices, because the ripple component of this voltage is too large and create too much noise. In such a case, the output voltage would vary from zero to maximum, this is why the capacitor is placed in parallel with the load, to reduce the voltage ripple.

2.1 Dimensioning

Known values:

- P_{output} = 51.32W
- Primary voltage = 230V
- f = 50Hz
- Output voltage ripple = 500mV
- Minimum efficiency = 70%

We choose the voltage at the circuit's load 16V, taking into consideration the loses on the regulator. Knowing the output power and the load voltage, we can find the current through the load:

$$I_S = \frac{P_{output}}{U_S} = \frac{51.32}{16} = 3.2A$$

By knowing the load current and voltage, we can find the value of the load:

$$R_S = \frac{U_S}{I_S} = \frac{16}{3.2} = 5\Omega$$

Using the next formula, we can find the maximum current through a diode:

$$I_{Dmax} = \frac{I_S * \pi}{2} = 5.024A$$

Knowing the ripple and the load current we can compute the value of the capacitance:

$$C = \frac{I_S}{\Delta U_S * f} = 64mF$$

From the next formula, knowing the minimum efficiency, I extracted the input resistance of the circuit:

$$\eta = \frac{8}{\pi^2} * \frac{1}{1 + \frac{R_I}{R_S}} \geq 70\% => R_I = 0.8\Omega$$

RI represents the input resistance of the circuit and it's expressed as follows:

$$R_I = 2 * R_D + R_T$$

Where RD is the resistance of a diode and RT is the resistance of the transformer. The maximum reverse voltage of a diode is equal to the voltage in secondary. This one can be computed using the following expression:

$$U_2 = U_S + \frac{\pi}{2 * \omega * C} * I_S = 16.125V$$

To this value I added the voltage drop on two diodes, because two are active on each cycle. After this I obtained an input value for the circuit about 18V.

2.2 Choosing the components

- For the capacitor I have chosen an aluminum electrolytic capacitor with the capacitance of 64mF and a rated current of 50VDC from Mouser Electronics
- For the diode I have chosen a Schottky diode with the forward current of 6A and the maximum reverse voltage or 20V

2.3 The simulation

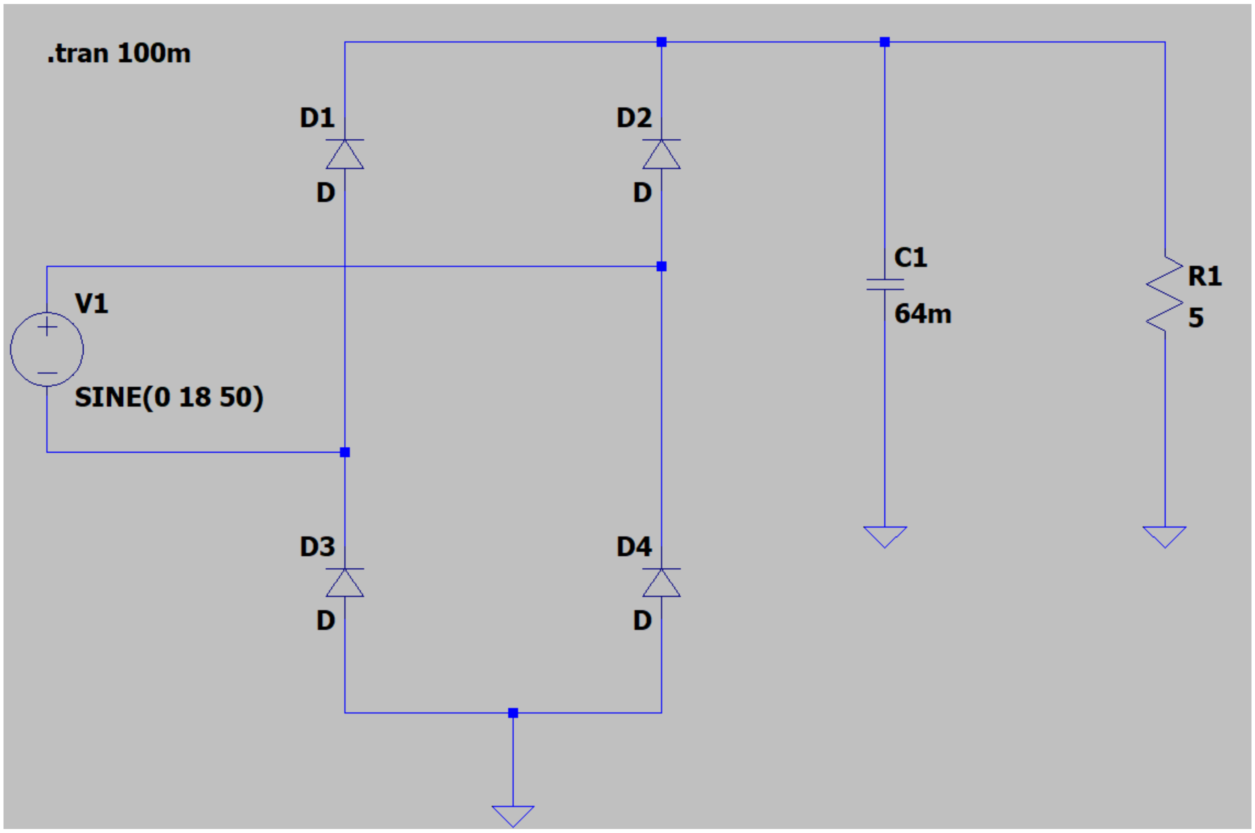

Figure 4: The circuit in LTspice

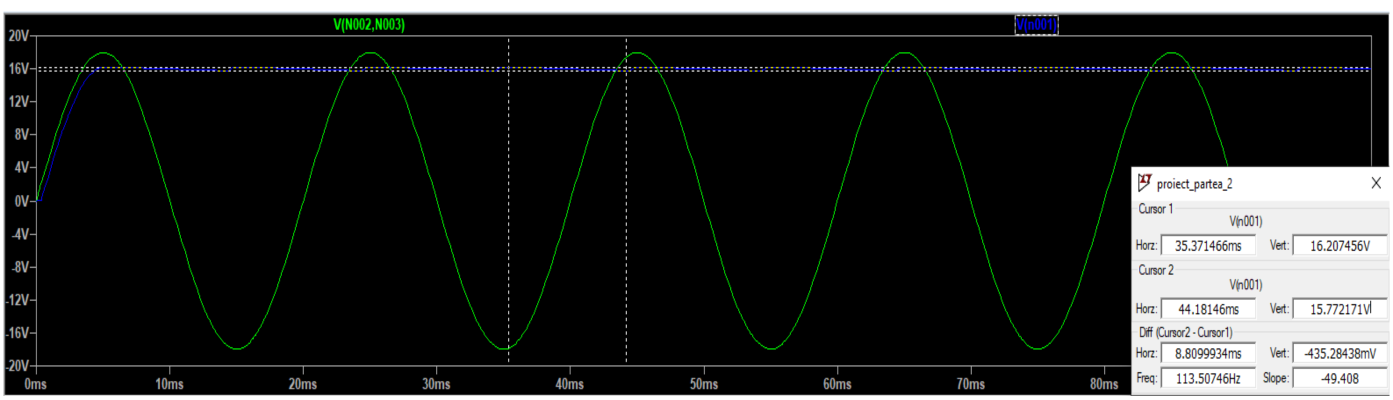

Figure 5: The input and the output voltages

3. Transistor series voltage regulator

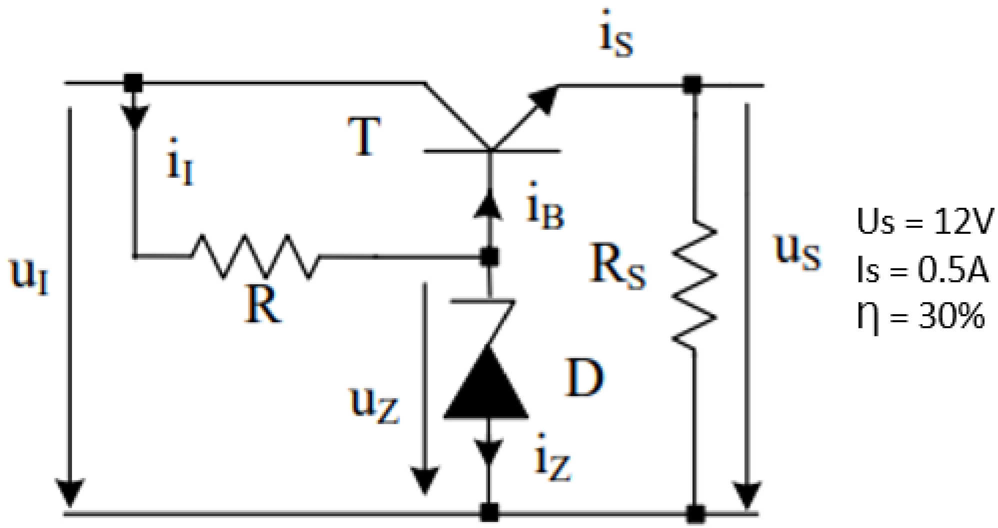

Figure 6: The schematic of the circuit

The circuit above represents a transistor series voltage regulator. The transistor is connected in an emitter follower configuration. This means that the transistor behaves as a variable resistance. If a variation at the output occurs, let's say that the output voltage increases, the emitter-base voltage of the transistor will decrease, which will cause the current in the base of the transistor to decrease too. This means that the transistor will conduct less, so the performance of the transistor is reduced. This will maintain the voltage at the output at a constant level.

3.1 Dimensioning

Known parameters:

- $U_S = 12V$
- $I_S = 0.5A$
- $\eta = 30\%$
- $P_{out} = 6W$
- $P_{in} = 20W$
- $U_I = 16V$

Knowing the voltage on the load and the current through it, the load itself can be calculated:

$$R_S = \frac{U_S}{I_S} = \frac{12V}{0.5A} = 24\Omega$$

The voltage on the Zener diode can be computed using the next formula, assuming that the base-emitter voltage of the transistor is approximatively 0.6V, and assuming that we are going to use a Darlington configuration:

$$U_Z = U_S + 2 * U_{vb} = 12V + 1.2V = 13.2V$$

Now, we are going to assume a Zener current of 10mA and a current amplification factor for the transistor of 1000. Knowing the output current and the amplification factor, we can compute the current in the base of the transistor:

$$i_B = \frac{i_S}{\beta} = \frac{0.5A}{1000} = 0.5mA$$

Knowing the Zener current and the base current of the transistor, we can compute the current that passes through the resistor:

$$i_I = i_B + i_Z = 10mA + 0.5mA = 10.5mA$$

Now, we can compute the value of the resistance that finds itself in the base of the transistor:

$$R = \frac{U_I - U_Z}{i_I} = \frac{16 - 13.2}{10.5mA} = \frac{2.8}{10.5mA} = 266\Omega$$

3.2 Choosing the components

- For the diode I have chosen a Zener diode with the Zener voltage of 13.2V and the Zener current of 10mA
- For the transistor I have chosen a Darlington Transistors with the current amplification factor of 1000, the maximum collector-emitter voltage of 60V and the maximum collector current of 1A
- For the resistance I have chosen a SMD resistor with the resistance of 267Ω

3.3 Simulation

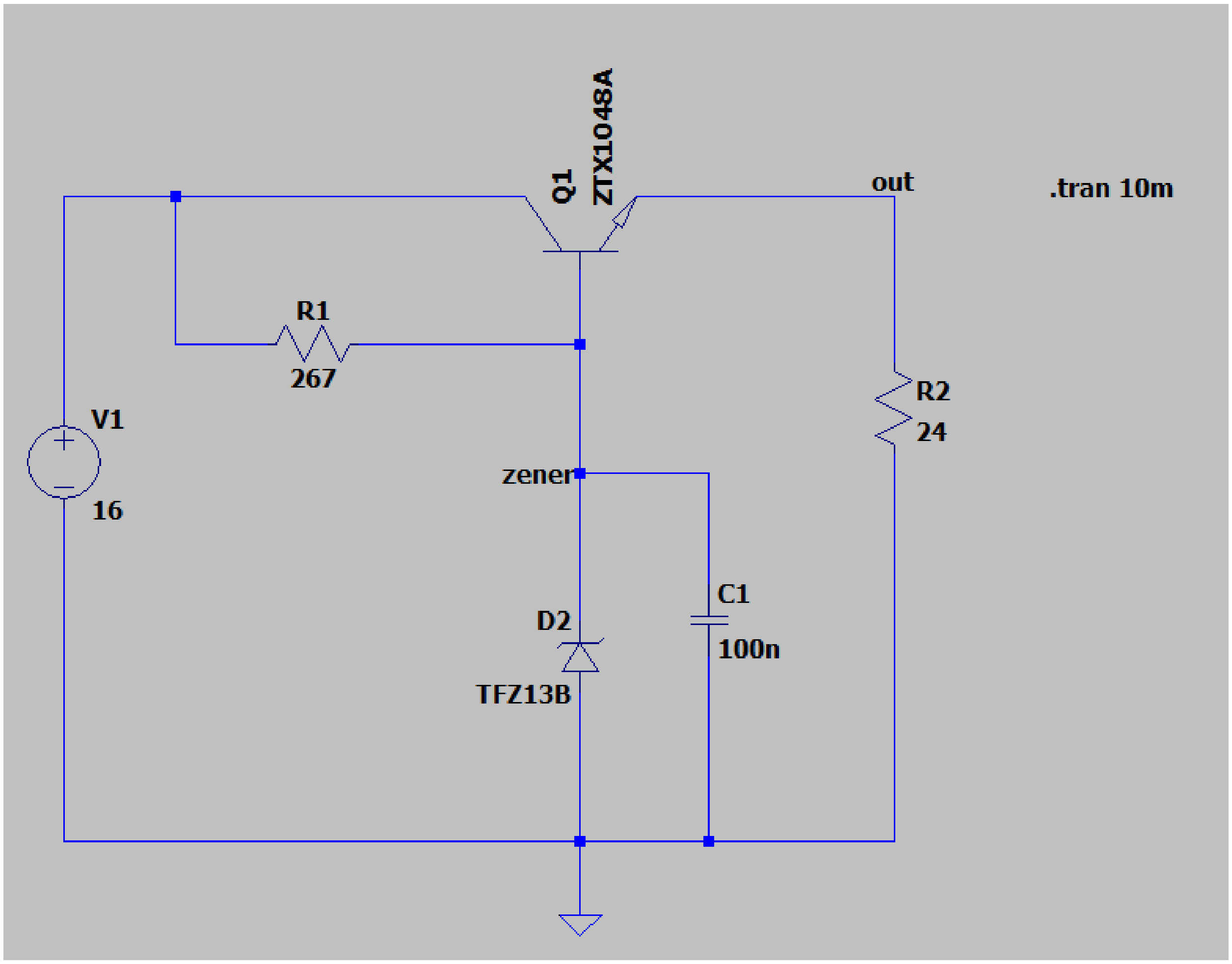

Figure 7: The circuit in LTspice

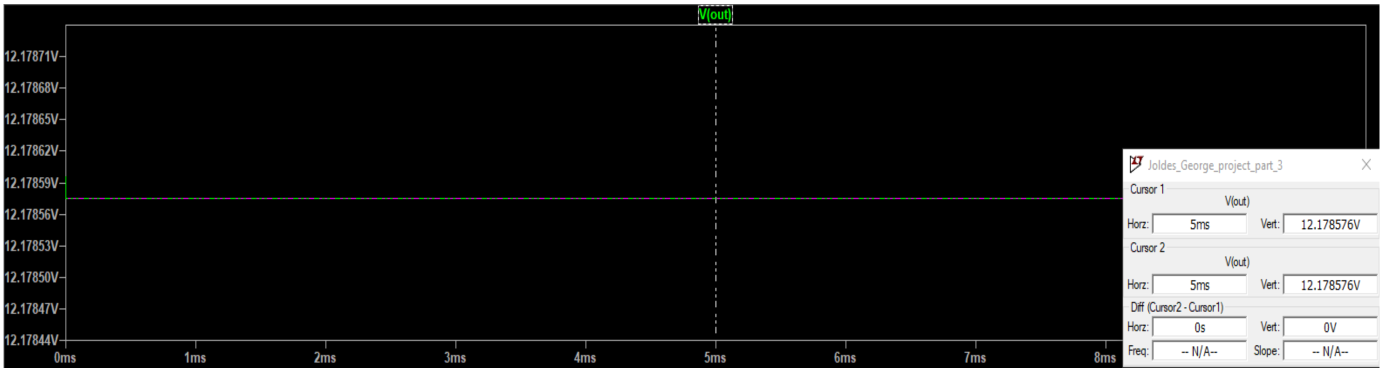

Figure 8: The output voltage

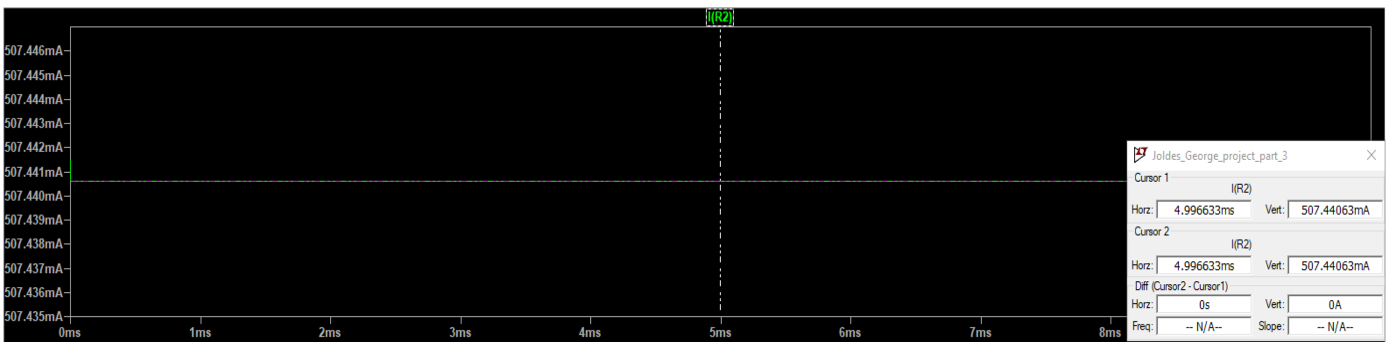

Figure 9: The output current

4. Integrated circuit voltage regulator

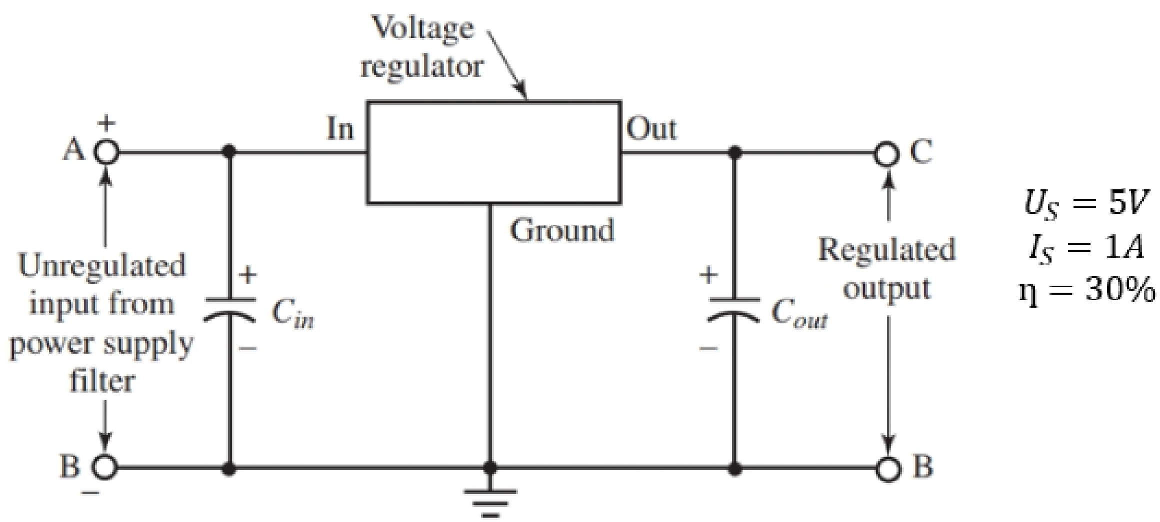

Figure 10: The schematic of the circuit

For the project I have chosen the LM7805 voltage regulator. This series of fixed-voltage (µA7800) integrated-circuit voltage regulators is designed for a wide range of applications. These applications include on-card regulation for elimination of noise and distribution problems associated with single-point regulation. Each of these regulators can deliver up to 1.5 A of output current. The internal current-limiting and thermal-shutdown features of these regulators essentially make them immune to overload. In addition to use as fixed-voltage regulators, these devices can be used with external components to obtain adjustable output voltages and currents, and also can be used as the power-pass element in precision regulators.

4.1 Dimensioning

Known parameters:

- $U_S = 5V$
- $I_S = 1A$
- $\eta = 30\%$
- $U_I = 16V$
- $P_{out} = 5W$
- $P_{in} = 16.66W$

Knowing the power that enters the circuit and the voltage at the input, the input current can be computed:

$$I_{in} = \frac{P_{in}}{U_S} = \frac{16.66W}{16V} = 1.04A$$

Knowing the desired parameters at the output of the circuit, the load resistance can be computed:

$$R_S = \frac{U_S}{I_S} = \frac{5V}{1A} = 5\Omega$$

4.2 Choosing the components

- The IC: for the integrated circuit, I have chosen the LM7805 from TME which costs 6.42 RON each.
- The capacitors: for the capacitors I have chosen 2 1uF capacitors, one for the input of the IC and the other one for the output from TME which costs 0.22720 RON each for a minimum order of 100 pieces.

4.3 The simulation

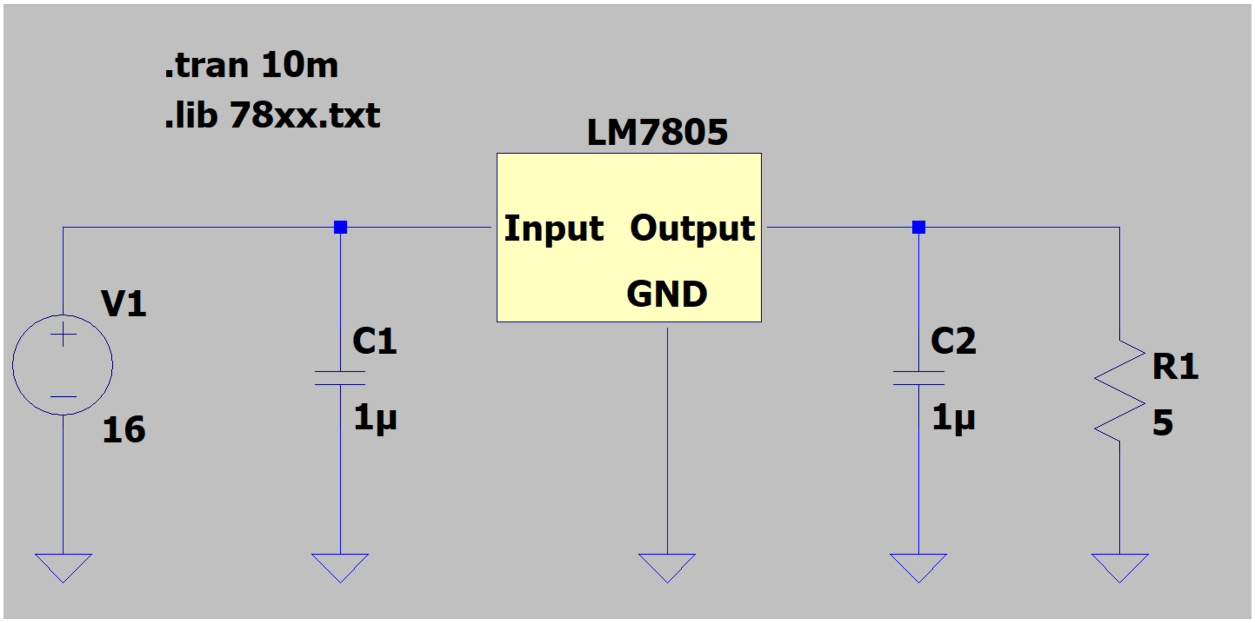

Figure 11: The circuit in LTspice

In the next figure the voltage at the output of the circuit is shown:

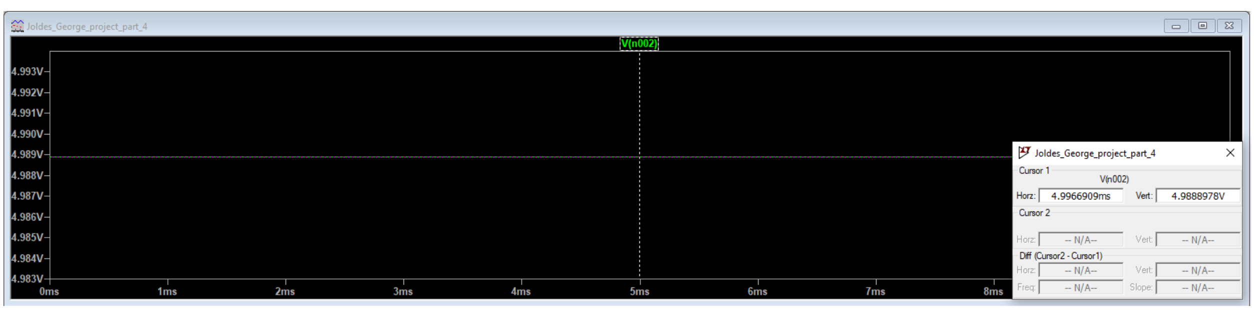

Figure 12: The output voltage

Its value is 4.98V in the simulation, which is close enough to the 5V desired. In the figure below the current through the load is shown:

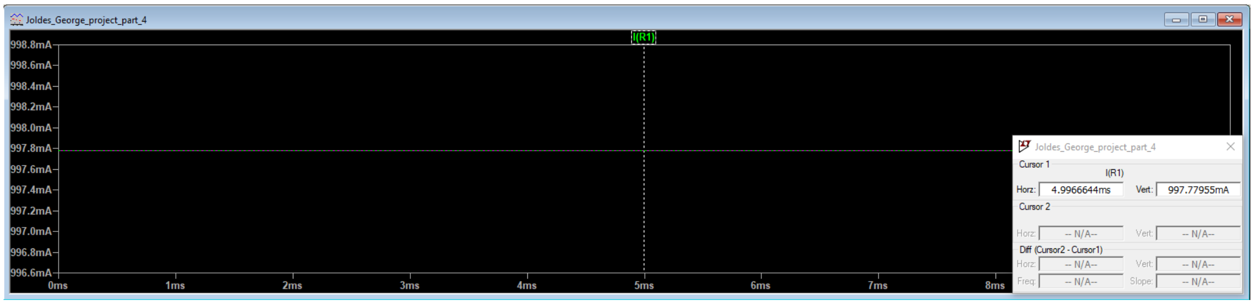

Figure 13: The output current

Its value is 997mA. The desired value is 1A. The simulation result is satisfying. It can be observed that the circuit meets the requirements. Below it is also shown the power dissipated by the load:

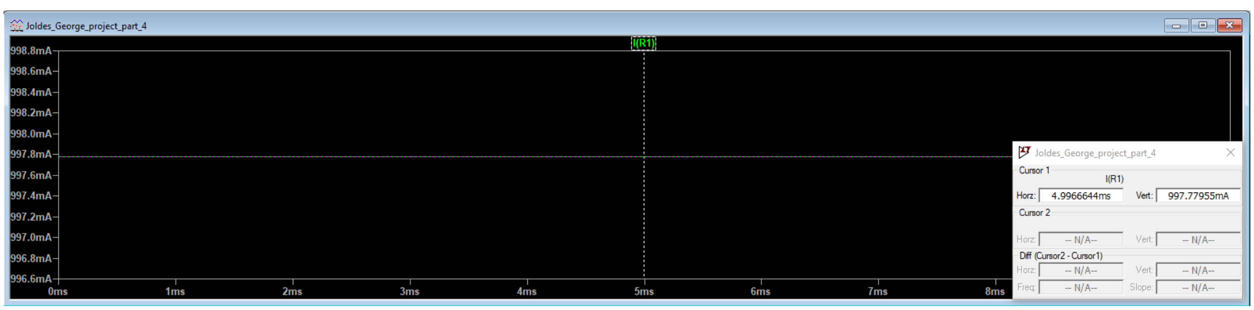

Figure 14: The output power

5. The step down (buck) DC-DC converter

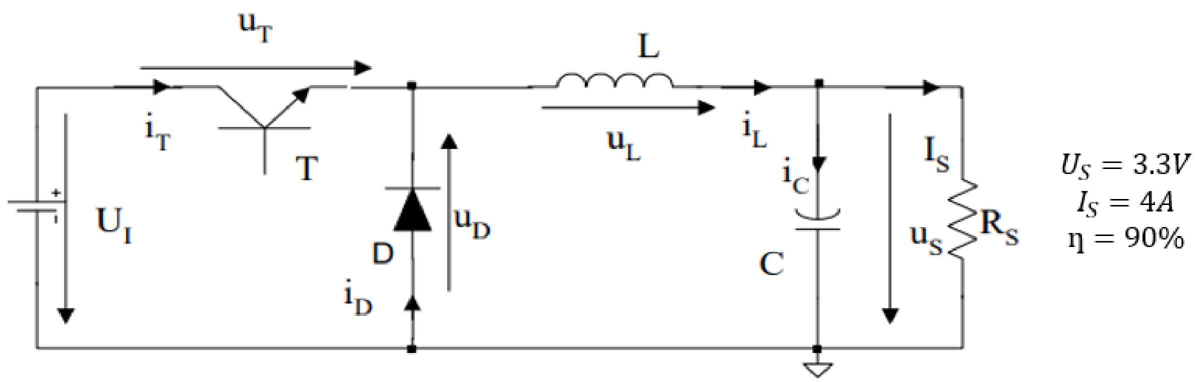

Figure 15: The schematic of the circuit

The buck converter generates at the output a voltage which is smaller than the one at the input, but it can increase the current. When the transistor is open, through the inductor flows the load current and the capacitor current. Assuming that the average value of the capacitor current in steady state is 0, the average value of the inductor is equal to the load current. When the transistor is blocked, because of the energy stored in the inductor, the diode assures a discharging path for the current in the inductor. There can be distinguished two operation modes: CCM (Continuous Conduction Mode) and DCM (Discontinuous Conduction Mode). In CCM is assumed that the current through the inductor is always greater than 0. In CCM the output voltage depends only on the input voltage and the duty cycle. If the load current drops to a minimum value I_{SL}, then the minimum current of the inductor can drop to 0. This current represents the limit through the CCM and DCM.

5.1 Dimensioning

The known parameters:

- $U_S = 3.3V$
- $I_{Smax} = 4A$
- $I_{Smin} = 100mA = 0.1A$
- $\eta = 90\%$
- $P_{in} = 14.66W$
- $P_{out} = 13.2W$
- $\Delta U_S = 20mV = 0.02V$
- $f_S = 100KHz => T = \frac{1}{f_S} = 10\mu s$
- $U_I = 16V$
- $\Delta U_I = 500mV = 0.5V$

Assuming that the output voltage is constant, one can compute the minimum and maximum value of the load by taking into account only the variation of the load current:

$$U_S = ct.$$

$$R_{Smax} = \frac{U_S}{I_{Smin}} = 33\Omega$$

$$R_{Smin} = \frac{U_S}{I_{Smax}} = 0.825\Omega$$

When the input voltage varies between U_{Imin} and U_{Imax}, the duty cycle will vary between δ_{max} and δ_{min}:

$$U_{Imax} = U_I + \frac{\Delta U_I}{2} = 16.25V$$

$$U_{Imin} = U_I - \frac{\Delta U_I}{2} = 15.75V$$

$$\delta_{max} = \frac{U_S}{U_{Imin}} = 0.21 = 21\%$$

$$\delta_{min} = \frac{U_S}{U_{Imax}} = 0.2 = 20\%$$

Knowing the minimum value of the load, we can consider that value as being the limit between CCM and DCM:

$$I_{SL} = I_{Smin} = 0.1A$$

Knowing the minimum value of the output current, the value of the inductor can be found:

$$L_{min} = \frac{U_I * T}{2 * I_{Sl}} * \delta * (1 - \delta) = \frac{U_S * T}{2 * I_{SL}} * \left(1 - \frac{U_S}{U_I}\right)$$

One can determine the minimum inductance required to avoid the discontinuous conduction for a certain limit value of the load current I_{SL}:

$$L_{min} = \frac{U_{Imax} * T}{2 * I_{Sl}} * \delta_{min} * (1 - \delta_{min})$$
$$= \frac{U_S * T}{2 * I_{SL}} * \left(1 - \frac{U_S}{U_{Imax}}\right) = 132\mu H$$

The period is made up of the time when the transistor is ON (T_C) and the time when the transistor is OFF (T_B):

$$T = T_C + T_B$$

$$\delta = \frac{T_C}{T}$$

$$T_C = \delta * T$$

$$T_{Cmax} = \delta_{max} * T = 2.1\mu s$$

$$T_{Cmin} = \delta_{min} * T = 2\mu s$$

$$T_B = T - T_C$$

$$T_{Bmax} = T - T_{Cmin} = 8\mu s$$

$$T_{Bmin} = T - T_{Cmax} = 7.9\mu s$$

During the time when the transistor is ON, the voltage on the inductor is equal to:

$$U_L = U_I - U_S = L * \frac{\Delta I_L}{T_C} = L * \frac{I_{Lmax} - I_{Lmin}}{T_C} = 12.7V$$

$$U_{Lmax} = U_{Imax} - U_S = 12.95V$$

$$U_{Lmin} = U_{Imin} - U_S = 12.45V$$

When the transistor is OFF, the voltage on the inductor is equal to:

$$U_L = -U_S = -L * \frac{\Delta I_L}{T_B} = -L * \frac{I_{Lmax} - I_{Lmin}}{T_B} = -3.3V$$

The minimum and maximum value of the current through the inductor can also be computed:

$$\begin{aligned} I_{Lmax} &= I_S + \frac{\Delta I_L}{2} = I_S + \frac{U_S * T}{2 * L} * (1 - \delta) \\ &= I_S + \frac{U_S * T}{2 * L} * \left(1 - \frac{U_S}{U_I}\right) = 4.1A \end{aligned}$$

$$\begin{aligned} I_{Lmin} &= I_S - \frac{\Delta I_L}{2} = I_S - \frac{U_S * T}{2 * L} * (1 - \delta) \\ &= I_S - \frac{U_S * T}{2 * L} * \left(1 - \frac{U_S}{U_I}\right) = 0.01A \end{aligned}$$

For the transistor, we consider the maximum voltage as being the maximum input voltage:

$$U_{Tmax} = U_{Imax} = 16.25V$$

The maximum current through the transistor is the maximum output through the inductor:

$$I_{Tmax} = I_{Lmax} = 4.1A$$

The ideal switches do not dissipate power because, when the switch is closed the current through it is 0 and when the switch is open the voltage across it is 0.

For the diode, the maximum values for the current and for the voltage are the same as for the transistor. Being considered an ideal switch, the power dissipated by it is also 0. One can also compute the average value of the current through the it:

$$I_{Dmedmax} = I_S * (1 - \delta_{min}) = 3.2A$$

We consider that our capacitor has enough capacitance in order to maintain at the output a constant voltage. In reality, the output voltage has a small ripple. In order to choose the capacitor, we start from the maximum admitted variation of the output voltage:

$$C \geq \frac{1}{8} * \frac{\left(1 - \frac{U_S}{U_I}\right) * U_I * T^2}{L * \Delta U_S} = 60\mu F$$

The RMS value of the current through the capacitor is:

$$I_{Cef} \approx \frac{I_{SL}}{\sqrt{3}} = 0.06A$$

The input current can also be computed:

$$I_I = \frac{P_{in}}{U_I} = 0.91A$$

5.2 Choosing the components

The inductor

- Power Inductor from Mouser
- 150µH±10%
- 13.07 RON
- SMD termination style
- Maximum DC current 4.3A
- Maximum DC resistance 43mΩ

The capacitor

- Aluminum Electrolytic Capacitor from Mouser
- 220µF±20%
- 15.79 RON
- SMD termination style
- DC Voltage Rating 35VDC
- ESR 17mΩ
- Ripple Current 2.8A

The diode

- Schottky Rectifier from Mouser
- 4.42 RON

- SMD termination style
- Forward Voltage 440mV
- Repetitive Reverse Voltage 20V
- Forward Current 10A

The transistor

- MOSFET from Mouser
- 3.64 RON
- Drain-Source Breakdown Voltage 20V
- Continuous Drain Current 5A
- Drain-Source Resistance 30mΩ
- Rise Time 25ns
- Fall Time 100ns

5.3 Remaking the computations

The output voltage has to be recomputed, taking into consideration the forward voltage of the diode and the internal resistance of the inductance:

$$U_{Rp} = R_p * \Delta I_L = 0.17V$$

$$U_S{}^* = U_S + U_F + U_{Rp} = 3.9V$$

Knowing the output voltage, the new value of the minimum inductance has to be computed:

$$L_{min} = \frac{U_{Imax} * T}{2 * I_{Sl}} * \delta_{min} * (1 - \delta_{min})$$
$$= \frac{U_S * T}{2 * I_{SL}} * \left(1 - \frac{U_S}{U_{Imax}}\right) = 148\mu H$$

The minimum and maximum values for the load must be computed again as well:

$$R_{Smax} = \frac{U_S}{I_{Smin}} = 39\Omega$$

$$R_{Smin} = \frac{U_S}{I_{Smax}} = 0.98\Omega$$

For the new values of the output voltage, we will compute again the minimum and maximum values of the duty cycle:

$$\delta_{max} = \frac{U_S}{U_{Imin}} = 0.25 = 25\%$$

$$\delta_{min} = \frac{U_S}{U_{Imax}} = 0.24 = 24\%$$

For the new value of the inductance, the computation for the capacitor has to be remade:

$$C \geq \frac{1}{8} * \frac{\left(1 - \frac{U_S}{U_I}\right) * U_I * T^2}{L * \Delta U_S} = 50\mu F$$

The maximum average current through the diode is:

$$I_{Dmedmax} = I_S * (1 - \delta_{min}) = 3.04A$$

Further, I am going to compute the power loses of the transistor. For this I will need the drain-source resistance of the transistor $r_{DSon} = 30m\Omega$ and the rise and fall time of the transistor $t_r = 25ns$, $t_f = 100ns$. First, we are going to compute the conduction loses:

$$P_{cond} = {I_{Tmax}}^2 * r_{DSon} * \delta_{max} = 0.12W$$

The switching loses are described by the following equation:

$$P_{sw} = f_{sw} * I_{Tmax} * U_{Tmax} * t_{on} = 0.8W$$

So, the total dissipated power by the transistor is:

$$P_{tot} = P_{cond} + P_{sw} \approx 1W$$

For the diode, the dissipated power can be computed knowing the diode's forward voltage $V_F = 0.44V$:

$$P_D = I_{Dmax} * V_F * (1 - \delta_{min}) \approx 1.34W$$

Further, we are going to compute the maximum and minimum values of the capacitance. We assume a variation of the output current of $\Delta I_S = 2A$, and that the control circuit responds to this with a duty cycle variation to a minimum value of $\delta_m = 0.01$. Then, the response time is given by the following relation:

$$t_r = -\frac{\Delta I_S * L}{U_S * \left(\frac{\delta_m}{\delta} - 1\right)} = 77\mu s$$

For the next computations, we will assume $U_{Strmax} = 0.1 * U_S$ and the parasitic resistance of the capacitor $R_C = 17m\Omega$. The value of the capacitance belongs to the next interval:

$$\frac{t_r}{R_C} \geq C \geq \frac{\Delta I_S * t_r}{2 * U_{Strmax} - \Delta I_S * R_C}$$

$$4520\mu F \geq C \geq 205\mu F$$

5.4 Simulation

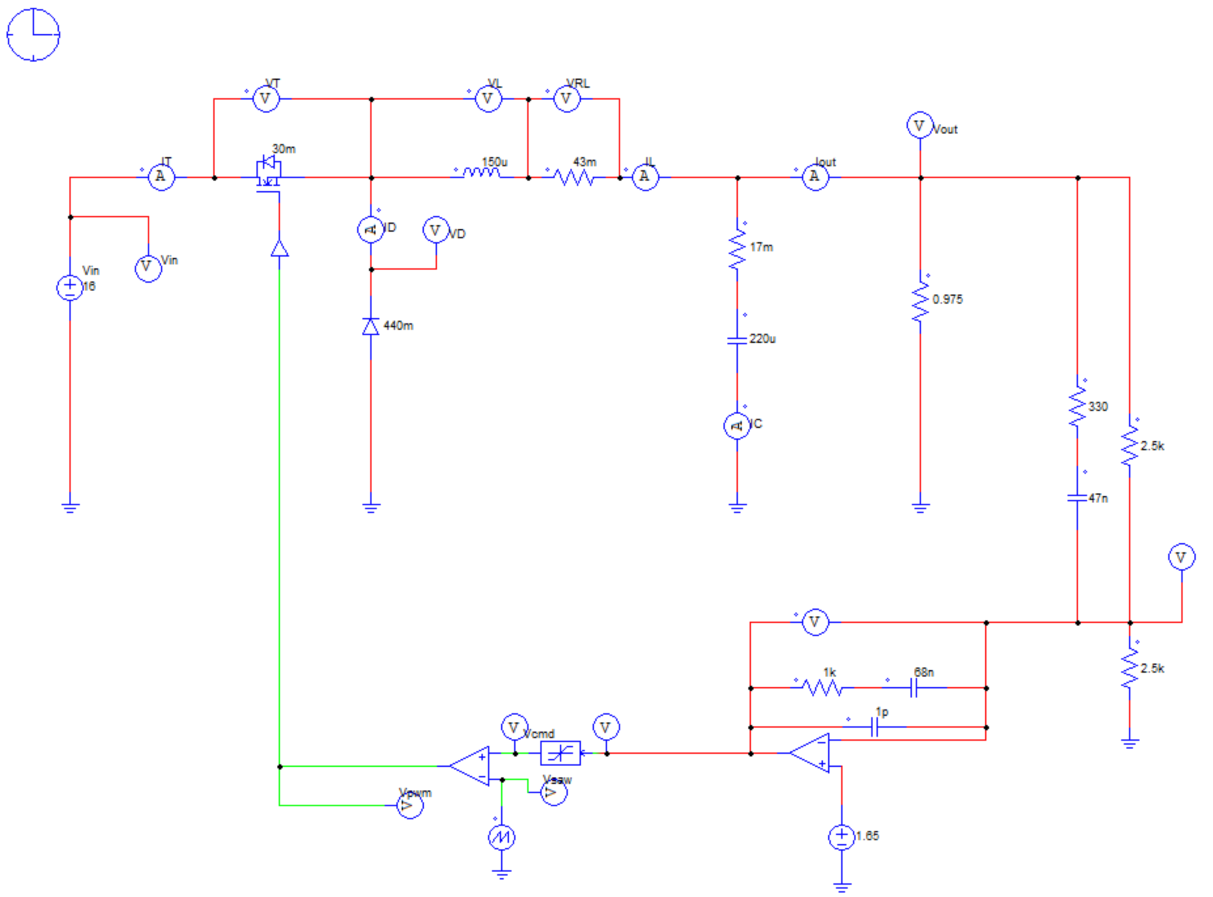

Figure 16: The circuit in PSIM

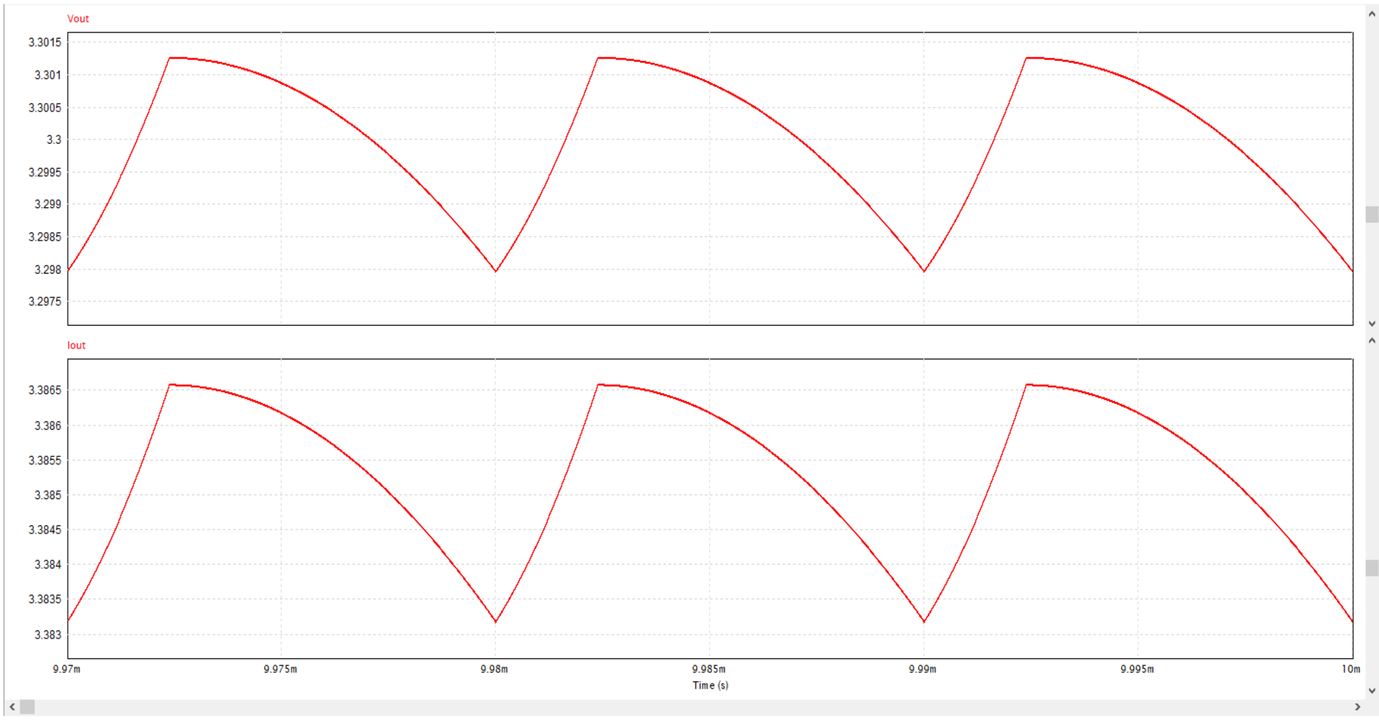

Figure 17: The output voltage and current