Circuit Theory and Electronics Fundamentals

Engineering Physics

Lab 3: AC/DC Converter

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Contents

1 Introduction

In this work we reproduced an AC/DC converter both using a simulation and a theoretical model. The circuit consisted of a transformer which receives 230V of AC current and a frequency of 50Hz, an envelope detector and a voltage regulator. The circuit should produce a 12V DC output voltage.
For the *ngspice* simulation, we used one current controlled current source and a voltage controlled voltage source and to simulate the transformer. This is connected in series to the envelope detector, consisting of a full-wave bridge rectifier and a capacitor. In turn, this is connected in series to a voltage regulator consisting of diodes and a resistor. This circuit can be seen in Figure 1.

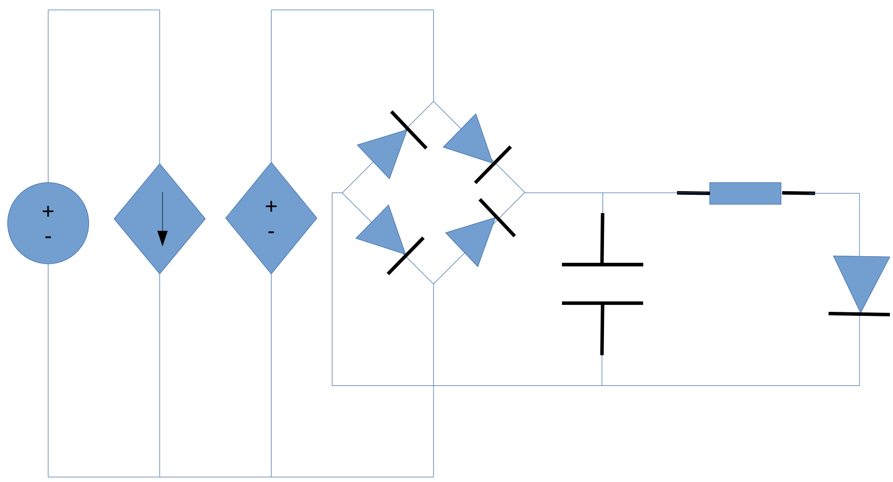

Figure 1: Simulation circuit

In theoretical analysis, the transformer was connected to the same envelope detector, where the diodes were approximated by voltage sources, like the diodes, two in each direction. This circuit can be seen in Figure 2, where the voltage source corresponds to the voltage obtained in the secondary winding of the transformer from *ngspice*. In the voltage regulator, seen in Figure 3, the same as in the simulation, the diodes were replaced with resistors.

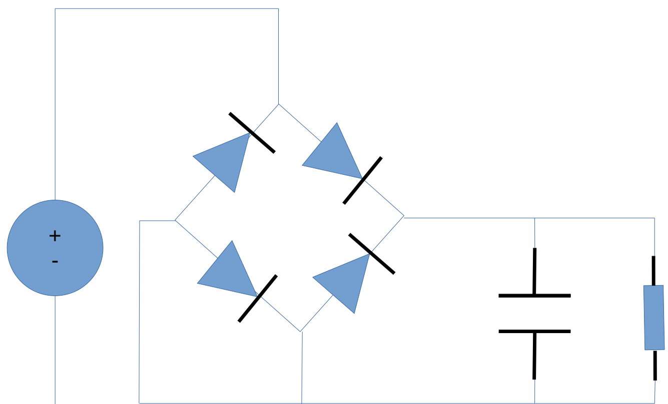

Figure 2: Theoretical envelope detector

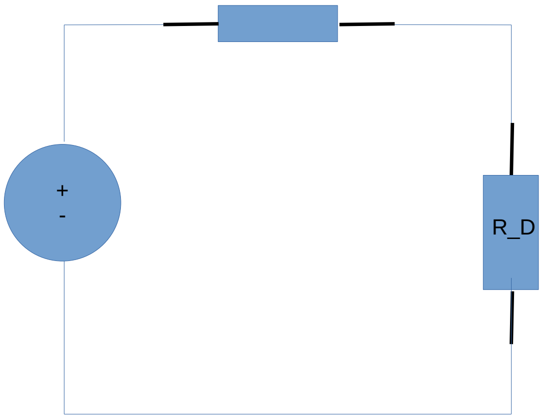

Figure 3: Theoretical voltage regulator

The comparison between the two methods can be seen in Section 4.

2 Simulation

To make this simulation, the model for all the diodes used was the default offered by *ngspice*. The input voltage in this circuit is

$$v_S = Acos(\omega t), \quad \omega = 2\pi f \tag{1}$$

with amplitude A=230V and frequency f=50Hz.

2.1 Transformer

From the transformer equation

$$I_T = nI_S \Leftrightarrow v_T = \frac{1}{n}v_S \Leftrightarrow v_T = \frac{230}{n}cos(\omega t) \tag{2}$$

where n is the ratio between the number of spires in the primary winding (S) and the secondary (T). The current controlled current source generates a current $I_T = nI_s$. We chose n so that the voltage generated by the voltage controlled voltage source, v_T would have amplitude close to 12V. In this case we chose it to be 20V, so we need n to be 11.5.

2.2 Envelope Detector

The envelope detector reduces the oscillation of the voltage wave and makes the signal totally positive. To make it, we used the default diode model of *ngspice*, where the ideality factor, η, is 1. We chose the resistor to have resistance $3k\Omega$ and the capacitor to have capacitance $3\mu F$.

2.3 Voltage Regulator

The voltage regulator further reduces the oscillations in the wave and is the final step in the converter. In order to do this, we connected to the resistor, in series, a number of diodes.

The optimal results were achieved when the number of diodes was 18, so this number of components was used. The plots resulting from this analysis can be seen in Figure 4.

3 Theoretical Analysis

To make this analysis, we used the voltage obtained in equation (1), as a source to mimic the voltage after passing through the transformer.

3.1 Envelope Detector

To make the envelope detector, we used a full-wave bridge rectifier, where the diodes were approximated by voltage sources of voltage $V_{ON} = 0.65$. The current would only pass through to the resistor and capacitor if $|V_S| \geq 2V_{ON}$, since there are two diodes polarized in each direction (if $V_S \geq 2V_{ON}$, it passes throught the forward-biased resistors and if $V_S \leq -2V_{ON}$, it passes through the backward biased ones). The rectified voltage through the resistor (and capacitor), v_B and

$$v_B(t) = \begin{cases} v_S(t) - 2V_{ON}, & if \quad v_S(t) \geq 2V_{ON} \\ -v_S(t) - 2V_{ON}, & if \quad v_S(t) \leq -2V_{ON} \\ 0, & if \quad |v_S(t)|<2V_{ON} \end{cases} \tag{3}$$

We chose the resistor to have resistance $R = 3k\Omega$ and the capacitor to have capacitance $C = 3\mu F$ as well.
To calculate the time where the diodes turn off, we used

$$t_{OFF} = \frac{1}{\omega} \arctan\left(\frac{1}{\omega RC}\right) \tag{4}$$

During the time where the diodes are off $V_S<2V_{ON}$, the capacitor discharges through the resistor and the voltage is

$$v_E(t) = (Acos(\omega t_{OFF}) - 2V_{ON})e^{-\frac{t-t_{OFF}}{RC}} \tag{5}$$

The output voltage after passing through this envelope, v_O, becomes

$$v_O(t) = \begin{cases} v_B(t), & if \quad t<t_{OFF} \\ v_E(t), & if \quad t>t_{OFF} \;\; and \;\; v_E(t)>v_B(t) \\ v_B(t), & if \quad t>t_{OFF} \;\; and v_E(t)<v_B(t) \end{cases} \tag{6}$$

This way the oscillations are reduced.

3.2 Voltage Regulator

To make the voltage regulator, the diodes were approximated using resistors. We used 18 diodes to be able to compare the results with the simulation. To calculate each resistance, we used

$$r_d = \frac{V_T}{I_s e^{\frac{V_D}{\eta V_T}}} \tag{7}$$

where $V_D = 12/18V$, ie the voltage divided by all the diodes. I_S is the reverse saturated current of the diodes and we used $I_S = 1pA$, and we used the same η as in the simulation: 1. V_T is the thermal voltage, used 25mV, the value for 25℃. The resistor in Figure 3, R_D corresponds to $18r_d$, since they are connected in series and the input voltage is the one resulting from the

envelope detector v_O.
The output voltage from this circuit is

$$v_o(t) = \frac{R_D}{R + R_D} v_O(t) \tag{8}$$

where R is the resistor from the envelope detector. This is only the AC part of the output. The total output of this converter then is

$$v_{OUT}(t) = 12 + v_o(t) \tag{9}$$

4 Results

4.1 Plots

The results obtained from the analysis in Section 2 can be seen in Figure 4.

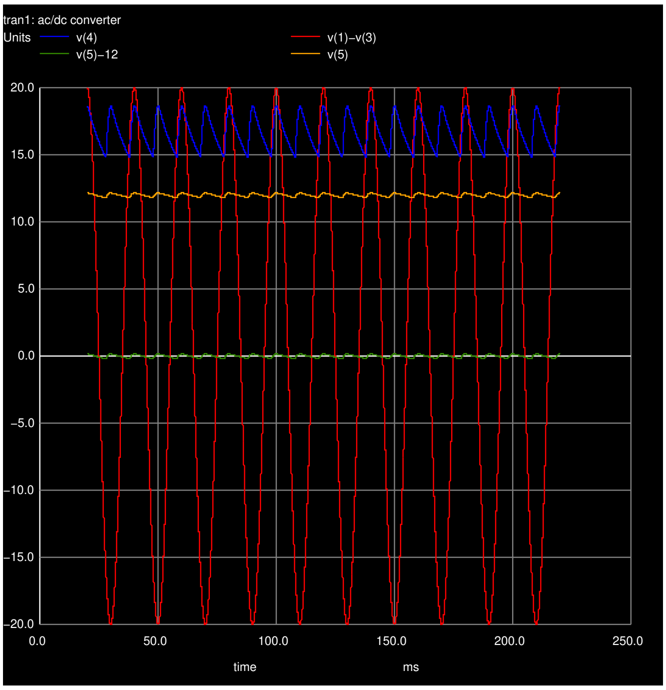

Figure 4: Voltage simulation plots over time: red - voltage in secondary winding; blue - envelope detector output voltage; yellow - voltage regulator output voltage; green - ripple

From Section 3 we obtained one period of the waves, seen in Figures 5 to 8.

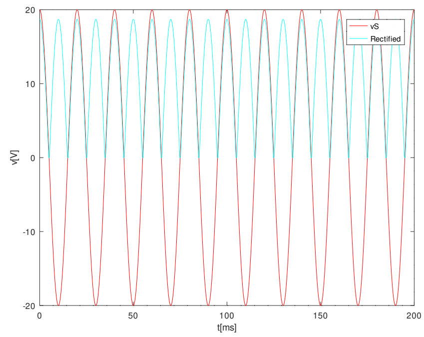

Figure 5: Voltage in the secondary winding (red) and voltage in rectifier (cyan) over time

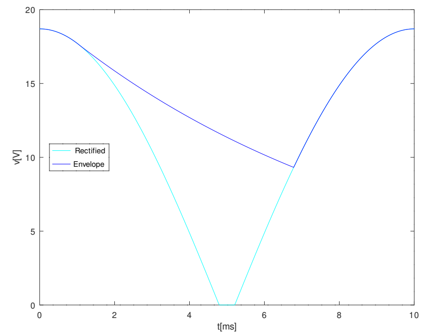

Figure 6: Envelope detector output voltage (blue) and voltage in rectifier (cyan) over one period

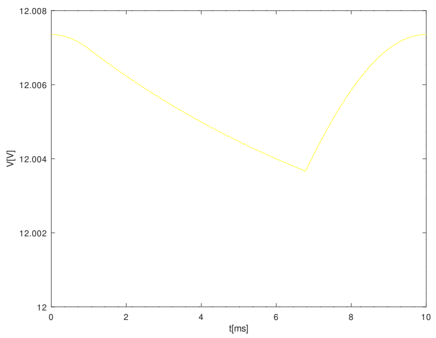

Figure 7: Voltage regulator output voltage over one period

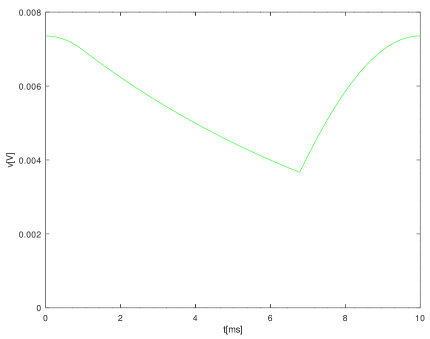

Figure 8: Ripple over one period

4.2 Merit

To calculate the merit we used the following equation:

$$M = \frac{1}{cost(ripple(v_O) + average(v_O - 12) + 10^{-6})} \tag{10}$$

The cost is the sum of the cost of the resistor (1 MU/kΩ), the capacitor (1 MU/μF) and the diodes (0.1 MU/diode). Our total cost is 8.2 MU.
The DC output level average was calculated using function average() in *ngspice* and function mean() in *octave*. The results were 11.99012V and 12.007V, respectively.
The ripple was calculated using functions max() and min() in both *ngspice* and *octave*. The results were 0.35752V and 0.00036995V, respectively.
The merit was only calculated for the *ngspice* simulation and the result was 0.3319.