LELEC2660 - Project - Report 3
Losses, heating and design of the heatsinks

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1 Introduction

This report takes place in the design an AC-DC converter made of a **full-bridge single phase diode rectifier** and a **flyback converter** placed in series as shown in Figure 3.

More precisely we will in this third report compute the losses, the heating and design the heatsinks if necessary and the diode in the secondary.

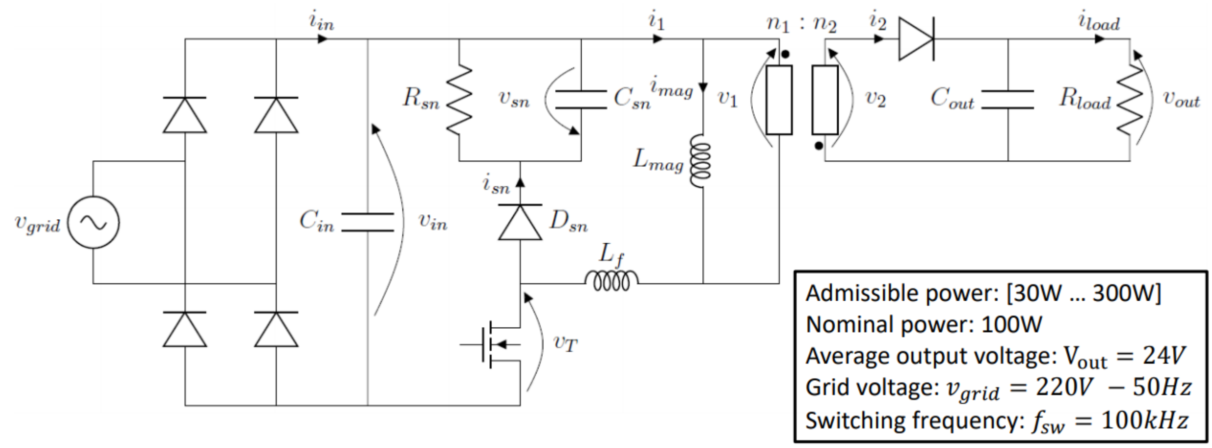

Figure 1: full circuit

2 Choice of the diode in the secondary

3 arguments will lead the choice of the diode in the secondary:

- It must support the current the average current $i_{2,avg} = i_{load}$
- It must support $i_{2,RMS} = 15.54A$
- It must support the reverse voltage applied

2.1 Average Current $i_{2,avg}$

In the worst case we have that this current is equal to

$$i_{2,avg} = \frac{P_{load,max}}{V_{out}} = 12.5A$$

2.2 Reverse Voltage V_R on the diode

The reverse voltage can be expressed as

$$V_R = V_2 - V_{out}$$

When the transistor is blocking, this expression can be rewriten

$$V_R = \frac{-n_2}{n_1} V_{in} - V_{out} \tag{1}$$

The maximum reverse value to tolerate is then equal to

$$V_{R,max} \approx -70[V]$$

2.3 Choice based on available datasheets

Based on the provided datasheets, we choose to use the diode **STTH3002** that match all the conditions:

- The maximum reverse voltage is about 300 [V].
- The maximum Average forward current is about 30 [A]
- The maximum RMS forward current is about 50 [A]

3 choice of the diode rectifier

To choose the diode rectifier we have to check three elements:

- It should support the average current. The average current through one diode is half the current $i_{in,avg}$ so:

  $$i_{rectifier,diode,avg} = i_{in,avg} = i_{1,avg} = \frac{P_{load}}{V_{in}}$$

  We take the biggest possible average current that the diode should support thus at $P_{load,max}$ so the diode should support an average current of $i_{rectifier,diode,avg} = 0.5$ A
- It should support the maximum peak current already calculated in rapport 2 $I_{peak} = 17.917$ A
- It should support the maximum reverse voltage applied when not conducting which is $V_{reverse} = -V_{grid} \approx -310$ V.

Looking at the datasheets, Bridge 1 and Bridge 2 seems to respect this constraints but bridge 2 has a limit average current of only 2A at 25 degrees Celsius and it decreases very quickly under 1A if the temperature increases (fig 1 on the datasheet of Bridge 3). We decide to take Bridge 1 because it has a higher peak current limit.

4 Losses Computation

The sources of losses we will consider in in this report are

- Dissipated power in the snubber circuit
- Losses in the transformer
- Losses in the transitor
- Losses in the diode
- Losses in the diode rectifier

4.1 snubber losses

The losses in the snuber circuit is due to the current flowing through resistance R_{sn} and we have from "rapport 2 equation (20)":

$$\frac{V_{sn}^2}{R_{sn}} = V_{sn} \frac{L_f \cdot i_{mag,max}^2}{2 \cdot T_{sw} \cdot (V_{sn} - \frac{n1}{n2} V_{out})} \tag{2}$$

<=>

$$\frac{V_{sn}}{R_{sn}} = \frac{L_f \cdot i_{mag,max}^2}{2 \cdot T_{sw} \cdot (V_{sn} - \frac{n1}{n2} V_{out})} \tag{3}$$

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$$2 \cdot T_{sw} \cdot V_{sn}^2 - V_{sn} \cdot 2 \cdot T_{sw} \cdot \cdot \frac{n1}{n2} V_{out} - R_{sn} \cdot L_f \cdot i_{mag,max}^2 = 0 \tag{4}$$

This above equation is a second order equation with unknow V_{sn}, keeping the positive solution whe have:

$$V_{sn} = \frac{2 \cdot T_{sw} \cdot \frac{n1}{n2} V_{out} + \sqrt{(2 \cdot T_{sw} \cdot \frac{n1}{n2} V_{out})^2 + 8 T_{sw} R_{sn} L_f i_{mag,max}^2}}{4 T_{sw}} \tag{5}$$

(Note: the above expression of V_{sn} was already given in "rapport 2" but there was an error in rapport 2, the expressions are not exactly the same)

In the above equation $i_{mag,max} = i_{mag,peak} = \frac{P_{load}}{\theta \cdot V_{in}} + \frac{V_{in} \cdot \theta \cdot T}{2 \cdot L_{mag}}$ from "rapport 1", so V_{sn} depends on the load and thus so does P_{sn}, using the above equations and R_{sn} calculated at previous report we obtain:

$$P_{sn} = \frac{V_{sn,max}^2}{R_{sn}} = \frac{L_f i_{mag,max}^2}{2 T_{sw}} \frac{\alpha}{\alpha - 1} \tag{6}$$

By applying this above equation for different value of P_{load} and thus different corresponding value of $i_{mag,max}$ we obtain the following table:

	P_{load}	P_{sn}
$P_{load,min}$	30W	0.6W
$P_{load,nominale}$	100W	2.87W
$P_{load,max}$	300W	18.65W

Table 1: Snubber circuit power

4.2 Losses in the Transformer

There are 2 types of losses in the transformer :

1. **Core Losses** : Applying a varying magnetic field to the core products 2 types of core losses : the Eddy's current due to the non zero-conductivity of the core and the Hysteresis losses due to the perturbation on the B-H curve.

2. **Copper Losses** : The term used to describe the energy dissipated by resistances in the wire used to wind the coil.

4.2.1 Core Losses

Seeing the data-sheet of the used core we get the graph of the total core losses in function of the applied magnetic field.
The magnetic field can be found using the lens's law :

$$\frac{v_1}{n_1} = A_{eff} \frac{dB}{dt}$$

From what we get for a half period of oscillation (taking all the numerical values from the previous reports):

$$\hat{B} = \frac{\Delta B}{2} = \frac{V_{in} \theta T_{sw}}{2 n_1 A_e} = 16.7[mT] \tag{7}$$

We get on the Figure 2 by extrapolating the curve at $100[kHz]$ for lower magnetic field amplitudes that $P_{core}/m^3 \approx 3[kW/m^3]$.
We can thus find the total power lost in the core by multipliyng this value by the effective volume of the transformer (the value 22700 mm^3 is available in the datasheet). We finally get

$$P_{core} = 0.0681[kW]$$

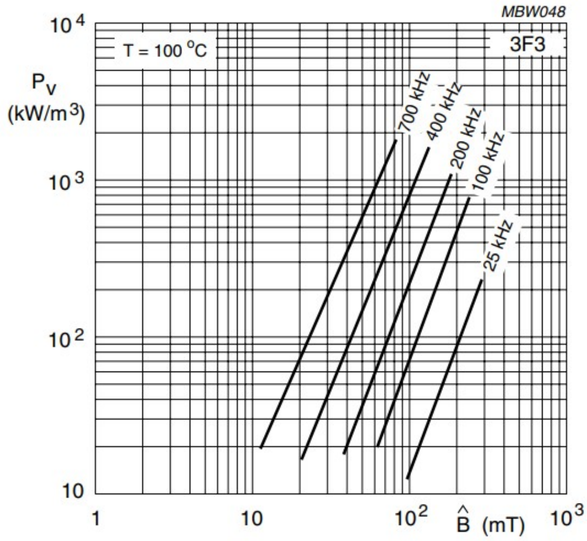

Figure 2: Core Losses

4.2.2 Copper Losses

The expression of the copper losses is as followed :

$$P_{copper} = I_{1,RMS}^2 R_1 + I_{2,RMS}^2 R_2 \tag{8}$$

With R_1 and R_2 the resistors of the winding at the primary and secondary, that can be expressed as

$$R_i = \frac{\rho l_i}{s_i}$$

With ρ the resistivity f the wire ($\approx 17e-9[\Omega/m]$), l_i the length of the winding i that we will consider here as equal to $l \cdot n_i$, with l the average length of turn,and s_i the cross section surface of the used cable.
From report 1 we have :
$s_1 = \frac{S_1}{n_1} = \frac{45.667\ 10^{-6}}{135} = 3.38\ 10^{-7}[m^2]$
$s_2 = \frac{S_2}{n_2} = \frac{62.145\ 10^{-7}}{20} = 3.12\ 10^{-6}[m^2]$
$l = 78.5[mm]$
We see a huge difference for the section of the winding in the primary and secondary due to the difference of current that each stage has to load.
We get for the resistors:

- $R_1 = 533[m\Omega]$
- $R_2 = 8.55[m\Omega]$

We then get

	P_{Copper}
$P_{load,min}$	0.046W
$P_{load,nominale}$	0.4W
$P_{load,max}$	3.59 kW

4.3 Losses in the Transistor

There are 2 types of losses in the transistor :

1. **Conduction Losses** : In the previous report we took for granted that the transistor acts as a perfect switch. We can take the conduction losses into account by putting a resistor in parallel of the transistor. The conduction losses correspond to the Joule effect in this resistor.
2. **Commutation Losses** : each time the transistor switch of one state to the other there are losses.

4.3.1 Conduction Losses

We can compute the conduction losses based on the model previously introduced of the resistor shunted with the transistor such that

$$P_{cond} = R_{ds,on}\, i^2_{1,RMS} \tag{9}$$

With $R_{ds,on}$ the resistor between the drain and the source of the the transistor when its passing. We find in the datasheet its maximum value being equal to 165 $[m\Omega]$
We then get :

	P_{cond}
$P_{load,min}$	32mW
$P_{load,nominale}$	94mW
$P_{load,max}$	0.28W

4.3.2 Commutation Losses

We know that the energy dissipated in the transistor when it turns on (Assuming we neglect Q_{rr}, the reverse recovery charge due to the non-ideal diode between the source and the drain of the transistor)

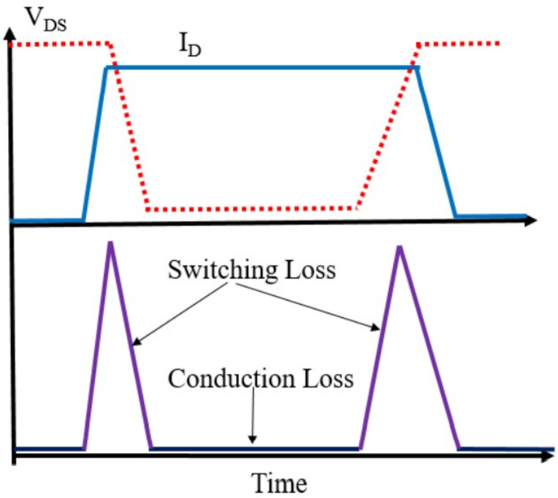

Figure 3: Commutation Losses

$$W_{OFF\to ON} = (V_{in} + \frac{n_1}{n_2} V_{out}) \frac{i_{mag,min}\, t_r}{2} \tag{10}$$

With $t_r = 53[ns]$ the rising time (time between blocking state and passing state)

We know that the energy dissipated in the transistor when it turns off can be expressed as

$$W_{ON\to OFF} = (V_{in} + V_{sn}) \frac{i_{mag,max}\, t_f}{2} \tag{11}$$

With t_f the falling time (time between passing state and blocking state)

Therefore the losses associated to the commutation can be expressed as

$$P_{commutation} = \frac{W_{OFF\to ON} + W_{ON\to OFF}}{T_{sw}} \tag{12}$$

	$P_{commutation}$
$P_{load,min}$	3.5646e-6W
$P_{load,nominale}$	1.2288e-5W
$P_{load,max}$	4.1629e-5W

4.4 Losses in the Diode in the secondary

There are 2 types of losses in the diode :

1. **Conduction Losses** : When the diode is blocking, the voltage fall on its edges is not equal to zero but. This leads to power losses.
2. **Commutation Losses** : The commutation losses in a diode are negligible because both recover time and voltage are small compared to the values studied in this circuit.

4.5 Conduction Losses

As explained, when the diode is blocking, the voltage fall on its edges is not equal to zero but equal to a voltage that we will call v_f. This leads to power losses. We can then express the conduction losses as

$$P_{cond} = v_f i_2$$

Considering that $v_f = V_f + r_{slope} i_2$, composed of a constant part and a part varying linearly with the current, we can write

$$P_{cond} = (V_f + r_{slope} i_2) i_2 = V_f i_2 + r_{slope} i_2^2$$

Taking the mean value of the expression leads us to µ

$$P_{cond,avg} = V_f i_{2,avg} + r_{slope} i_{2,RMS}^2$$

Based on the datasheet of the choosen diode, we get

$$P_{cond,avg} = 0.67\, i_{2,avg} + 0.007\, i_{2,RMS}^2$$

	P_{cond}
$P_{load,min}$	1.059W
$P_{load,nominale}$	4.716W
$P_{load,max}$	25.271W

4.6 losses rectifier diode

There are two types of losses: the conduction losses and commutation losses which are negligible. The conduction losses is directly founded in the datasheet for the forward current of 1A on fig 3 of Bridge 1, it gives losses of about 1,25 W.

5 efficiency

The efficiency of the circuit is given by:

$$\eta = \frac{P_{load}}{P_{load} + P_{sn} + P_{core} + P_{copper} + P_{cond,transistor} + P_{commutation} + P_{cond,diode} + P_{losses,rectifier}} \tag{13}$$

For each case of P_{load} we obtain the following table:

	P_{load}	η
$P_{load,min}$	30W	0.9076
$P_{load,nominale}$	100W	0.9149
$P_{load,max}$	300W	0.8593

Table 2: efficiencies

6 heatsink

We have to test without heatsink the temperature in steady state of the transistor and the two diodes by taking an ambient temperature of $T_A = 25$ degrees Celsius.

- For the transistor without heatsink the temprature would be:

$$T_j = T_A + \underbrace{R_{\theta JA}}_{=62.5^\circ C/W \text{from datasheet}} \cdot P_{cond,P_{load,max}} = 42.5^\circ C \tag{14}$$

  Which is inferior to $T_{max} = 150^\circ C$ from the datasheet. So no need of a heatsink for the transistor

- Similarly for the diode in the secondary circuit:

$$T_j = T_A + \underbrace{R_{\theta JA}}_{=70^\circ C/W \text{from datasheet FIG 10 in the worth case}} \cdot P_{cond,P_{load,max}} = 1793.97^\circ C \tag{15}$$

  So here we are above the limit of $T_{max} = 175^\circ C$ so to find the thermal resistances needed for heatsink we solve:

$$T_J \leq T_A + (R_{\theta JC} + R_{\theta Ch} + R_{\theta hA}) * P_{cond,P_{load,max}} \tag{16}$$

  this gives us (with $R_{\theta JC} = 1.2^\circ C$ and we neglect $R_{\theta JC}$): $R_{\theta hA} \leq 8.3^\circ C/W$
  (Note: For the choice of the heatsink thoose of CSM have a too high resistance but for the HSE we don't really understand the datasheet even if in the first table there seems to be some resistance lower than $8.3^\circ C$)

- For the diode rectifier we have:

$$T_j = T_A + \underbrace{R_{\theta JA}}_{=20^\circ C/W} \cdot P_{losses,P_{load,max}} = 50^\circ C \tag{17}$$

  which is under the maximum temperature of 150 $^\circ C$