

Exercise 1

A flyback converter is working in the incomplete demagnetization area with the control ratio $D = 0,4$. To realize this setting, two flyback converters can also be connected in parallel like in the figure 1 to reduce the power in each converter.

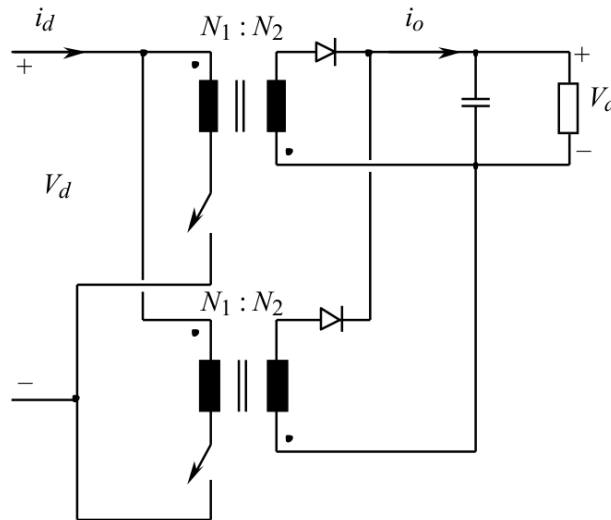


Figure 1: Two Flyback-converters connected in parallel.

Compare the input current i_d and output current i_o in the two possibilities when the output voltage is considered as constant. What are the current peak values in both cases when the transformer ratio $N_1 : N_2 = 1$? The parallel flyback converters are controlled with a π delay with the other one.

Solution

For one flyback converter (session 7 exercise 2):

When the switch is one the current increases linearly and is formed only of the magnetizing current. When the switch is conducting we have

$$I_m(t) = i_{sw}(t) = I_m(0) + \frac{V_d}{L_m}t, \quad 0 \leq t \leq t_{on} \tag{1}$$

and with a peak value of

$$\hat{I}_m = \hat{I}_{sw} = I_m(0) + \frac{V_d}{L_m}t_{on} = I_m(0) + \Delta i_m \tag{2}$$

Where $I_m(0)$ is the magnetizing current at the begin of the cycle.

When the switch is not conducting, the energy in the core of the transformer flows in the secondary winding and at the same time the current taken from the DC-voltage source is zero.

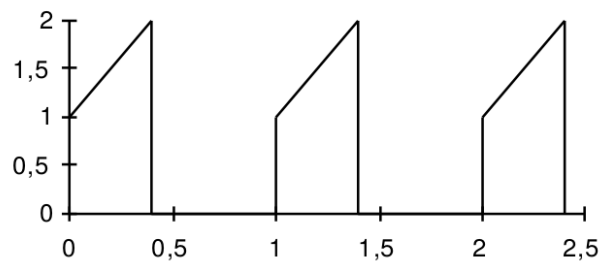


Figure 2: Current taken from the DC-voltage source in case of single flyback structure.

When the switch is not conducting the voltage over the secondary is $-V_o$ which is the same as the over the primary but with the ratio of the transformer. The current decreases linearly.

$$i_m(t) = \hat{I}_m - \frac{N_1 V_o}{N_2 L_m}(t - t_{on}) \quad t_{on} \leq t \leq T_s \quad (3)$$

When the switch is conducting the current in the diode is zero otherwise the current is

$$i_D(t) = \frac{N_1}{N_2} i_m(t) = \frac{N_1}{N_2} \left(\hat{I}_m - \frac{N_1 V_o}{N_2 L_m}(t - t_{on}) \right) \quad t_{on} \leq t \leq T_s \quad (4)$$

The current in the diode i_D is represented in the figure 3. Its minimal and maximal values are the same as i_d .

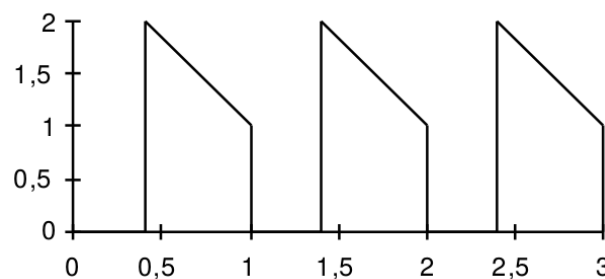


Figure 3: Current i_D when $N_1/N_2 = 1$.

For two flyback converters connected in parallel:

When two flyback converters are connected in parallel, they are controlled with a π -delay. They are both taking current by turn from the DC-source. The current is represented in figure 4.

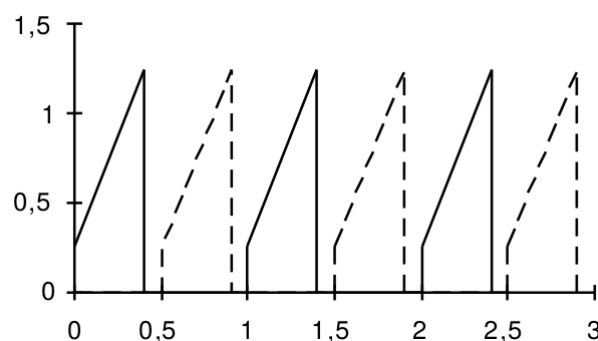


Figure 4: Current $i_d(t)$ when $D = 0.4$. (solid line 1st flyback, dash line 2nd flyback)

In both cases, single flyback and dual, the power at the output is the same since the switching circuit is lossless and the DC-source is constant.

For clarity, the index 1 is for one flyback structure and 2 is for the two flyback mounted in parallel. Both current i_{d1} and i_{d2} are from the same DC-source, so we can write the average current using the figure 4 as

$$I_{d1} = \frac{I_{m1}(0) + \frac{\Delta i_{m1}}{2}}{T_s} DT_s = I_{d2} = 2 \frac{I_{m2}(0) + \frac{\Delta i_{m2}}{2}}{T_s} DT_s \quad (5)$$

where $\Delta i_{mi} = \hat{I}_{mi} - I_{mi}(0)$ with $i \in \{1, 2\}$. Since we are using identical flyback converters, the magnetizing inductance is the same and we can write that $\Delta i_{m1} = \Delta i_{m2} = \Delta i_m$.

$$I_{m1}(0) + \frac{\Delta i_m}{2} = I_{d2} = 2I_{m2}(0) + \Delta i_m \quad (6)$$

and we obtain

$$I_{m2}(0) = \frac{1}{2}I_{m1}(0) - \frac{\Delta i_m}{4} < I_{m1}(0) \quad (7)$$

and the peak current in the primary for single flyback structure is

$$\hat{I}_{m1} = I_m(0) + \Delta i_m \quad (8)$$

and for the "dual" flyback structure

$$\hat{I}_{m2}(0) + \Delta i_m = \frac{1}{2}I_{m1}(0) - \frac{\Delta i_m}{4} + \Delta i_m = \frac{1}{2}I_{m1}(0) + \frac{3}{4}\Delta i_m = \frac{1}{2}\hat{I}_{m1} + \frac{\Delta i_m}{4} \quad (9)$$

The figures of the exercise were drawn with the minimal and maximal current being respectively 1A and 2A. So, we have $I_{m1}(0) = 1$ and $\hat{I}_{m1} = 2$ which gives $\Delta i_m = 1$. With these numerical we obtain, $\hat{I}_{m2} = \hat{I}_{d2} = 5/4$ and $I_{m2}(0) = I_{d2}(0) = 1/4$. When the turns ratio is one, those currents are also the output maximal and minimal values.

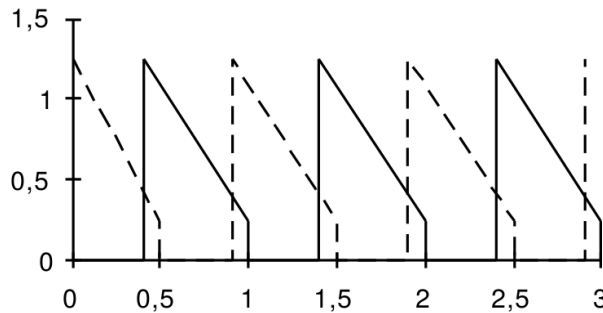


Figure 5: Current in the diodes when $D = 0, 4$. (solid line 1st flyback, dash line 2nd flyback)

The output current $i_o(t)$ of the two flyback mounted in parallel is the sum of the current flowing in the diodes (figure 5).

Exercise 2

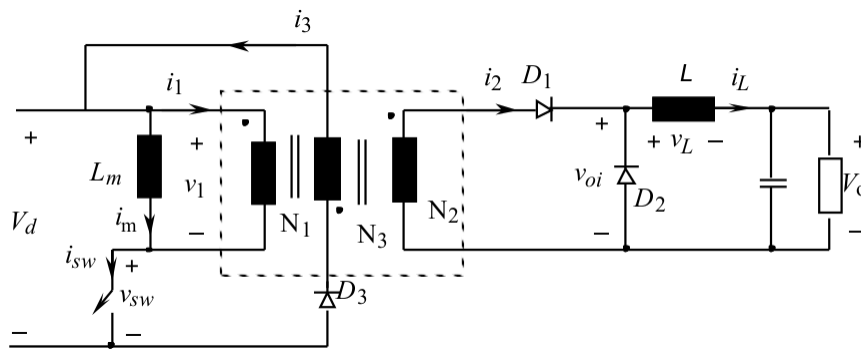


Figure 6: Forward-converter.

The characteristics of the Forward-converter of figure 6 are as followed:

$V_d = 48V \pm 10\%$, $V_o = 5V$, $f_s = 100kHz$, the power in the load P_o varies between 15W and 50W. The demagnetization winding number of turn is $N_3 = N_1$.

- a) Calculate the minimal value of the ratio N_2/N_1 allowed.
- b) Calculate the inductance of the choke L that keeps the converter working in continuous conduction mode (CCM).

Solution

The waveforms of the Forward converter are given in figure 7.

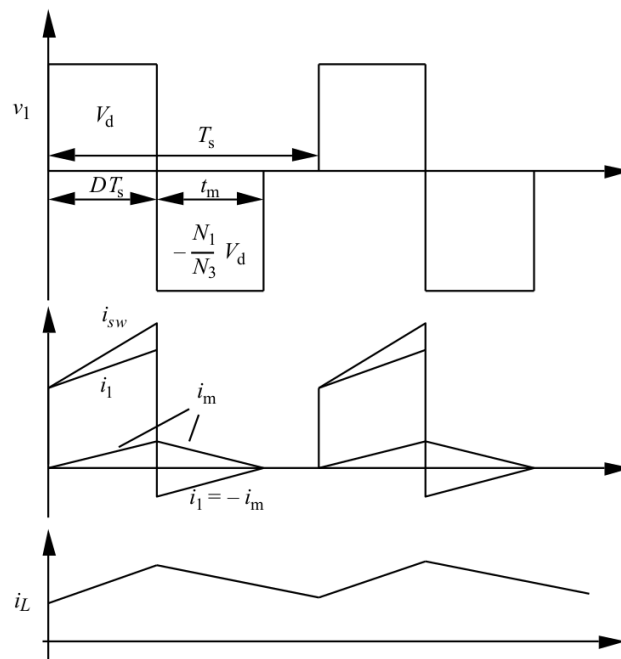


Figure 7: Waveforms of the Forward-converter.

First, we need to find the maximal value of the duty cycle D_{max} . To do that let us first check the demagnetization circuit operation. When the switching is conducting the voltage over the demagnetization circuit is V_d . Its current is

$$i_m = \frac{V_d}{L_m} t \quad 0 \leq t \leq t_{on} \quad (10)$$

When the switch is not conducting any longer, $i_{sw} = i_m + i_1 = 0 \Rightarrow i_1 = -i_m$. The winding N_2 induces a voltage which is reversed to the diode D_1 implying $i_2 = 0$ and the other diode D_2 conducts. The magnetomotive force in the transformer is

$$F_m = N_1 i_1 + N_3 i_3 = N_2 i_2 \quad (11)$$

and we obtain the current in the reset winding

$$i_3 = \frac{N_1}{N_3} i_m \quad (12)$$

When the switch is not conducting the diode D_3 is conducting and the voltage over the winding N_3 is $-V_d$. And the voltage over N_1 is

$$u_1 = -\frac{N_1}{N_3} V_d \quad t_{on} \leq t \leq t_{on} + t_m \quad (13)$$

and the magnetizing current is

$$i_m = \hat{I}_m - \frac{N_1}{N_3} \frac{V_d}{L_m} (t - t_{on}) \quad t_{on} \leq t \leq t_{on} + t_m \quad (14)$$

where t_m is demagnetization time. It is obtained by calculated the average value of the voltage over the magnetizing inductance L_m which is equal to zero in steady state. Using the figure 7 and same triangle geometry we get

$$i_m(t_{on} + t_m) = \frac{V_d}{L_m} t_{on} - \frac{N_1}{N_3} \frac{V_d}{L_m} t_m = 0 \quad (15)$$

and we obtain

$$t_m = \frac{N_3}{N_1} t_{on} = \frac{N_3}{N_1} D T_s \quad (16)$$

It is assumed that the magnetizing current is zero before the next cycle. And we obtain

$$t_{m,max} = (1 - D_{max}) T_s = \frac{N_3}{N_1} D_{max} T_s \quad (17)$$

And the maximal value of the duty cycle is

$$D_{max} = \frac{1}{1 + \frac{N_3}{N_1}} \quad (18)$$

In this exercise $N_3 = N_1$ which give $D_{max} = 0,5$. If D is higher than 0,5, the transformer magnetization grows after each cycle.

Part a

When the switch is conducting the current in the filtering choke L is

$$i_L(t) = I_{L0} + \frac{1}{L} \left(\frac{N_2}{N_1} V_d - V_o \right) t \quad 0 \leq t \leq t_{on} \quad (19)$$

When it is not conducting

$$i_L(t) = \hat{I}_L - \frac{V_o}{L} t \quad t_{on} \leq t \leq T_s \quad (20)$$

In steady state, with the equation 19 and 20, we have at $t = T_s$

$$i_L(T_s) = \hat{I}_L - \frac{V_o}{L} (T_s - t_{on}) = I_{L0} \quad (21)$$

the peak values \hat{I}_L is given by the equation 19 at $t = T_s$ which leads to

$$I_{L0} + \left(\frac{N_2}{N_1} V_d - V_o \right) \frac{DT_s}{L} - \frac{V_o}{L} (T_s - t_{on}) = I_{L0} \quad (22)$$

After simplification, we get

$$\frac{N_2}{N_1} = \frac{V_o}{DV_d} \quad (23)$$

With the numerical values, $V_d = 48 \pm 10\% \Leftrightarrow 43,2 \leq V_d \leq 52,8$. To get the minimal transformer winding turns ratio we need to use the smaller value of V_d and the maximal value of D . Otherwise, the magnetic circuit would not demagnetize for all cases possible.

$D = D_{max} = 0,5$ when $V_d = V_{d,min} = 43,2V$. With the values in the equation 23, we get

$$\left(\frac{N_2}{N_1} \right)_{min} = \frac{1}{4,32} \approx \frac{1}{4} \quad (24)$$

Using equation 23 we obtain:

when $V_d = 43,2V$ we get $D = 0,463$

when $V_d = 52,8V$ we get $D = 0,379$

In both case D remains under $D_{max} = 0,5$.

Part b

The limit between the continuous conduction mode (CCM) and the discontinuous conduction mode is when the minimal current in the choke L $I_{L0} = 0A$. In other words and using the equation 20, we obtain

$$i_L(T_s) = \hat{I}_L - \frac{V_o}{L} (T_s - t_{on}) = 0 \Rightarrow \hat{I}_L = \frac{V_o}{L} (1 - D) T_s \quad (25)$$

The average value on the current in the choke is the average value of the output current $i_o(t)$.

$$I_o = \frac{1}{T_s} \left(\frac{1}{2} DT_s \hat{I}_L + \frac{1}{2} t_{off} \hat{I}_L \right) = \frac{1}{2} \hat{I}_L = \frac{V_o}{2L} (1 - D) T_s \quad (26)$$

The average output current is given by $I_o = P_o/V_o$ and with the numerical values we get $3A \leq I_o \leq 10A$. The converter must remain in CCM when the average output current is minimal. Using the equation 26, we get

$$L_{min} = \frac{1 - D_{min}}{2I_{LB,min}} V_o T_s = \frac{1 - 0,379}{2 \times 3} 5 \times 10 \times 10^{-6} \approx 5\mu H \quad (27)$$

Exercise 3

Using the results of the previous exercise, calculate the RMS-value of the current in the inductance I_L when $V_d = 48\text{V}$, $N_2/N_1 = 1/4$, the output power $P_o = 50\text{W}$ and the inductance is $L = 20,68\mu\text{H}$.

Solution

To solve this exercise, the waveforms of the forward converter are given in the figure 8.

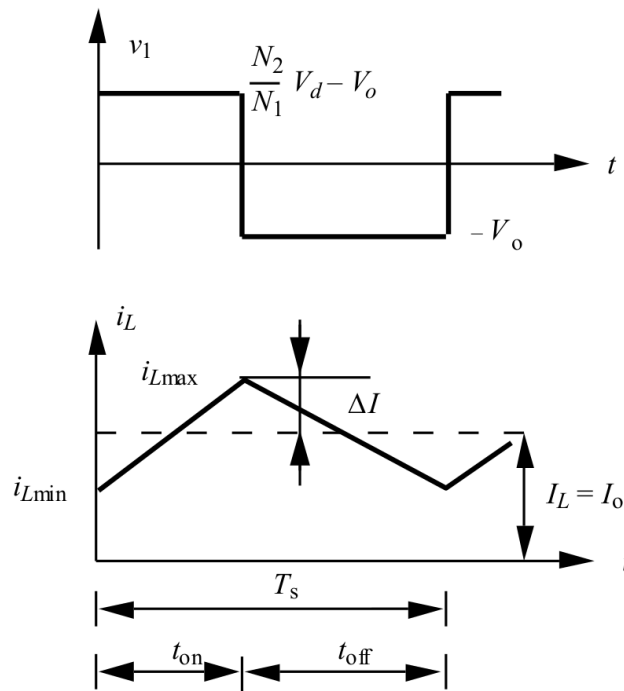


Figure 8: Waveforms of the Forward-converter.

When the switch is conducting the current increases according to the figure 8 with the following equation

$$i_{L,on}(t) = i_{L,min} + \frac{2\Delta I}{DT_s}t \quad 0 \leq t \leq t_{on} \quad (28)$$

and decreases with the following equation

$$i_{L,off}(t) = i_{L,max} - \frac{2\Delta I}{(1-D)T_s}t \quad 0 \leq t \leq t_{off} \quad (29)$$

and the rms-value is given by

$$I_{L,rms} = \sqrt{\frac{1}{T_s} \int_0^{DT_s} i_{L,on}^2(t)dt + \frac{1}{T_s} \int_{DT_s}^{T_s} i_{L,off}^2(t)dt} \quad (30)$$

using equations 28 and 29, we get

$$I_{L,rms} = \sqrt{\frac{1}{T_s} \left(\int_0^{DT_s} i_{L,min}^2 + \frac{4\Delta I i_{L,min}}{DT_s} + \left(\frac{2\Delta I}{DT_s}t \right)^2 dt + \int_{DT_s}^{T_s} i_{L,min}^2 + \frac{4\Delta I i_{L,min}}{(1-D)T_s} + \left(\frac{2\Delta I}{(1-D)T_s}t \right)^2 dt \right)} \quad (31)$$

and with same basic integration techniques, we obtain

$$I_{L,rms} = \sqrt{(i_{L,min}^2 - i_{L,max}^2)D + i_{L,max}^2 + 2\Delta I((i_{L,min}^2 - i_{L,max}^2)D - i_{L,max}) + \frac{4}{3}\Delta I^2(D + 1 - D)} \quad (32)$$

This equation can be simplified using the average value of the output current.

$$I_{o,av} = \frac{i_{L,max} + i_{L,min}}{2} = i_{L,min} + \frac{i_{L,max} - i_{L,min}}{2} = i_{L,min} - \Delta I \quad (33)$$

which leads to

$$I_{L,min} = I_o - \Delta I \quad \text{and} \quad I_{L,max} = I_o + \Delta I \quad (34)$$

and equation 32 becomes

$$I_{L,rms} = \sqrt{i_{L,max}^2 - 2\Delta I i_{L,max} + \frac{4}{3}\Delta I^2} \quad (35)$$

In CCM, we can write

$$\frac{V_o}{V_d} = \frac{N_2}{N_1} D \quad (36)$$

With the numerical values from the exercise and previous exercise, we obtain $D \approx 0,417$. From the figure 7, the difference between $i_{L,max}$ and $i_{o,av}$ is Δ . From equations of the previous exercise 25 and 26, we obtain

$$\Delta I = \frac{V_o}{L}(1 - D)T_s - \frac{V_o}{2L}(1 - D)T_s = \frac{V_o}{2L}(1 - D)T_s \approx 0,705A \quad (37)$$

From the equations 34, we have $i_{L,min} = 9,295A$ and $i_{L,max} = 10,705A$. And finally using the equation 35 we get $I_{L,rms} = 10,008A$.

The rms value is often used to measure the needed inductance because it is close to the average value.