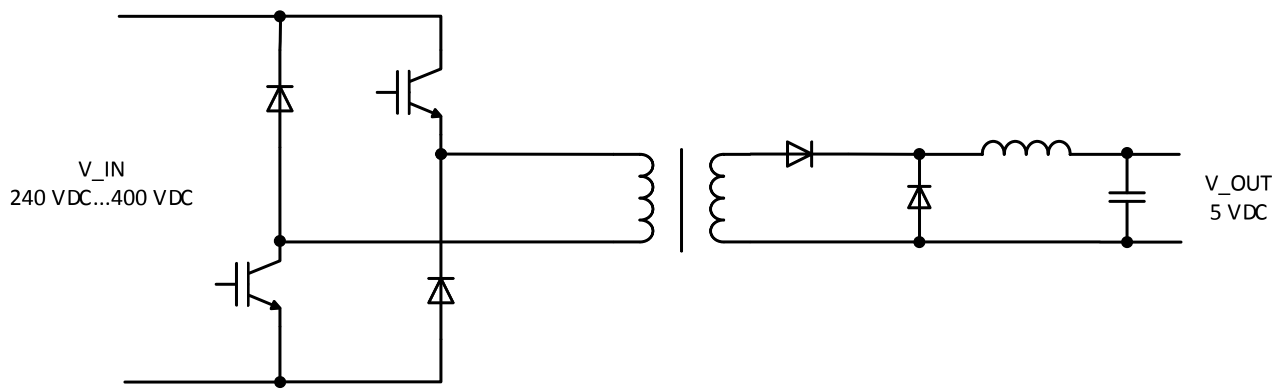
Tehoelektroniikan komponentit

ELEC-E8421

Harjoitus 8, ratkaisut

First we should go through the 2 transistor forward converter operation principle. With 2 transistors the demagnetization winding is removed as unnecessary. However demagnetization current needs a path during the off-state and freewheeling diodes are installed. Switch voltage stress is also halved in this configuration vs typical forward converter.



Two transistor Forward converter

Figure 1: Kaksitransistorinen Forward-hakkuri

Converter has 2 states, on- and off-state. Figure 2 depicts on-state, in which power is transmitted through the transformer, and secondary diode is conducting

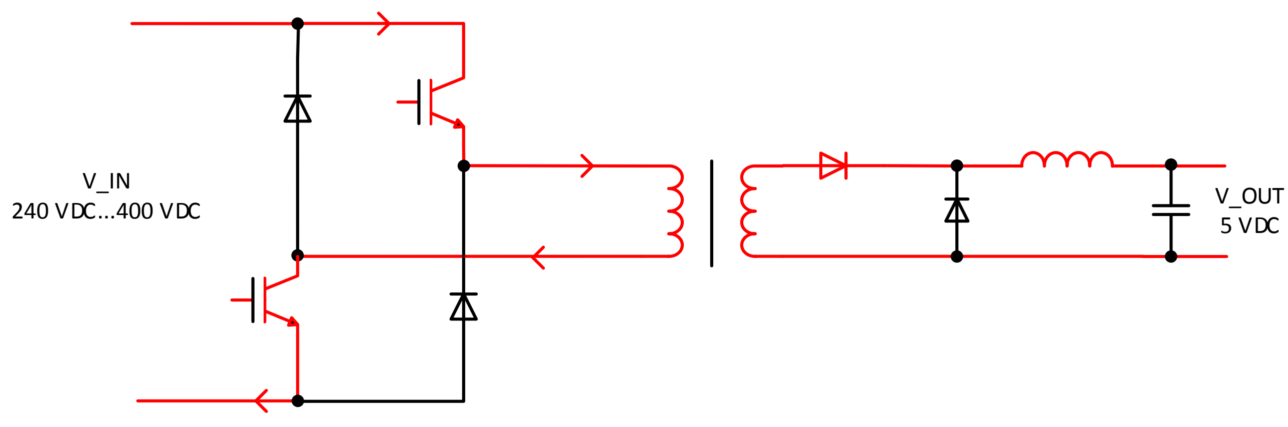


Figure 2: Kaksitransistorinen Forward-hakkuri kun kytkimet ovat päällä

Two transistor Forward converter during on state

Off-state is depicted below. Demagnetization current discharges through diodes back to DC link. Without diodes the transistors would break. Secondary current uses the parallel diode to disconnect the transformer.

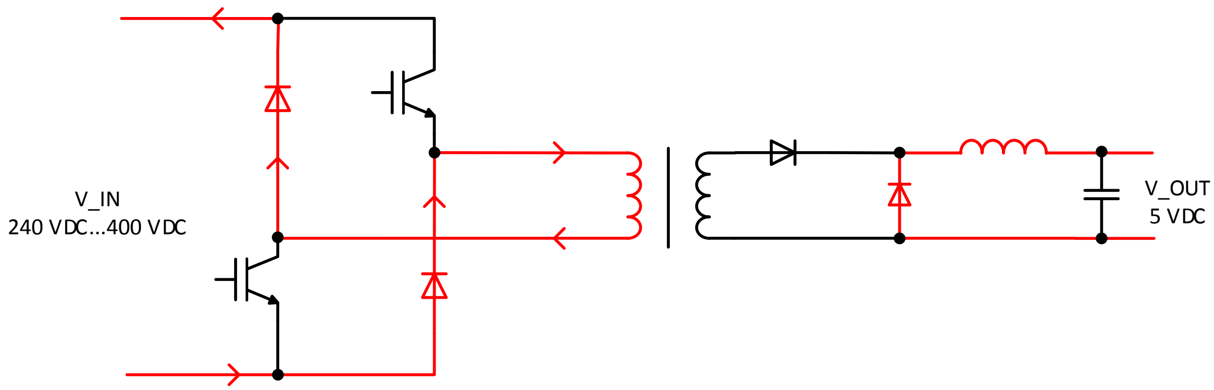
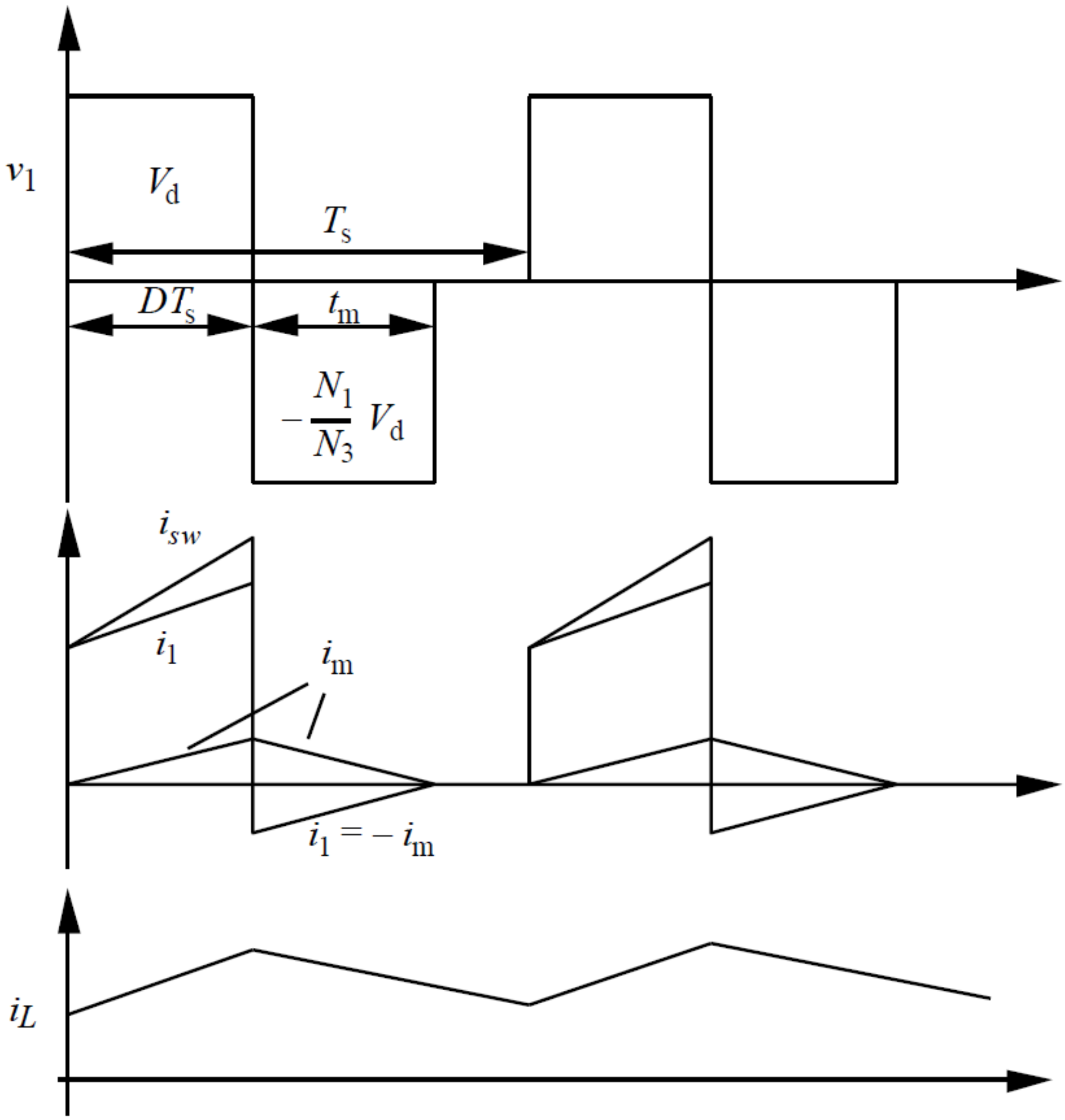


Figure 3: Kaksitransistorinen Forward-hakkuri kun kytkimet ovat pois päältä

Two transistor Forward converter during off-state

Transformer voltage and current



Forward converter voltage and current waveforms

Demagnetization time t_m, demag current i_m, input voltage V_d and switch current i_{sw}. Picture is for forward converter with demagnetization winding N3 but when it it absent the analysis exactly similar to N1 = N3, as primary winding is used for demagnetization

$$1 - D_{MAX} = \frac{N_1}{N_3} D_{MAX}$$

, josta edelleen saadaan

Leads to

$$D_{MAX} = \frac{1}{1 + \frac{N_1}{N_3}} \quad N_1 = N_3$$

$$D_{MAX} = \frac{1}{2}$$

In two transistor Forward, demagnetization winding is the primary winding N1 = N3 .

Tehtävä 1

Transformer design is iterative process by nature. This is because the fact the an accurate all sizes fits solution is extremely difficult to come up with

Required transformer thermal power requiredment can be calculated with 20% oversizing

$$P_{th} = 5\,V * 30\,A * \frac{1}{0{,}8} \approx 190\,W$$

The added 1/0.8 factor takes account the commutation loss and the fact that transformer efficiency is much below 100 %

Looking at the figures we can conclude the following

- EE 42/42/15 — Could work
- EE 42/42/20 — Could work
- EE 42/54/20 — Easily doable
- EE 42/66/20 — Overdimensioned
- ETD 39 — Underdimensioned
- ETD 44 — Might work
- EC 52 — Might Work
- EC 70 — Easily doable
- ETD 49 — Easily doable

Select ETD49 as a starding point, points to consider are availability and ease of construction

Tehtävä 2

Starting values for problem 2

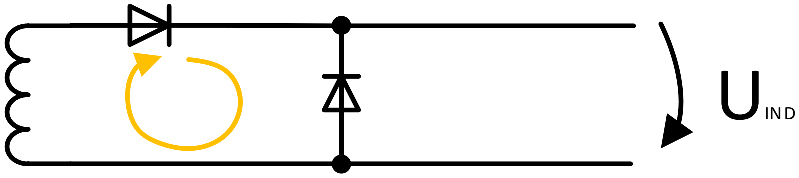
T = 40 µs
UCE = 1 V
UF = 1 V

Primary and secondary turns

With a minimum supply voltage of 240 VDC, you should still be able to get a 5 VDC voltage to the load. A commutation margin of 10% is also specified, which means that the input terminal of the series coil should have at least 5.5 VDC. In addition, the diodes' emission voltage is estimated to be 1 V and UCE = 1 V is left over the switch components. Since the maximum of the pulse ratio is 0.5, we get

$$t_{on} = t_{off} = \frac{1}{2}T$$

Focusing on the secondary



Note, that output inductor input voltage equation is

$$\frac{t_{on}(U_2 - U_F) - t_{off} * U_F}{T} = U_{IND}$$

$$\frac{\frac{T}{2}(U_2 - U_F) - \frac{T}{2}(U_F)}{T} = U_{IND}$$

Is equal to

$$(U_2 - U_F - U_F)\frac{1}{2} = U_{IND}$$

$$U_2 = 2U_{IND} + 2U_F = 2 * 5{,}5\ V + 2 * 1V = 13\ V$$

As we know, between primary and secondary it holds

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

Estimate turns ratio with switch voltage drops

$$k = \frac{N_1}{N_2} = \frac{240\ V - 2\ U_{CE}}{U_2} = \frac{240\ V - 2\ V}{13\ V} \approx 18{,}3$$

Using equation for flux density (11.35a, page 201 old book (B * N * Ac * K * f = U)),
Select the worst case situation

$$t_{on} = t_{off} = t_{onmax} = \frac{1}{2}T$$

core should not saturate

$$B_{MAX} = \frac{U_{MAX} * \frac{t_{onmax}}{K}}{N_1 * A_{CPmin}} \leq \hat{B}$$

Solve for N1

$$N_1 = \frac{U_{MAX} * \frac{t_{onmax}}{K}}{B_{MAX} * A_{CPmin}} \leq \hat{B}$$

For Forward converter K=1 and for ETD49, Bmax = 320 mT and Ac = 209 mm^2, when 100 ^{O}C. inserted to equation when conduction losses are accounted for

$$N_1 = \frac{(400\,V - 2\,V) * \frac{40\,\mu s}{2 * 1}}{320\,mT * 209\,mm^2} \approx 119$$ Turns

Now we can calculate N2

$$N_2 = \frac{N_1}{k} = \frac{119}{18{,}3} = 6{,}5$$ Turns

Round to whole number, and check primary

$$N_1 = N_2 * k = 7 * 18{,}3 = 128{,}1$$

Selected

- $N_1 = 128$
- $N_2 = 7$

Core losses

Calculate core losses. Maximum conduction time $t_{on\ max}$ is half the period T/2. In normal operation the peak to peak flux density Bp-p is

$$B_{p-p} = B_{MAX} = \frac{U_{MAX} * \frac{t_{onmax}}{K}}{N_1 * A_{CPmin}}$$

$$B_{p-p} = B_{MAX} = \frac{(240\,V - 2\,V) * \frac{40\,\mu s}{2 * 1}}{128 * 209\,mm^2} \approx 178\,mT$$

From the datasheet for ETD29 we can read $\hat{B} = \frac{B_{p-p}}{2} = 89\,mT$,

losses are $P_{HC} \approx 0{,}84\,W$.

Primary winding

ETD49 bobbin width is 32.7 mm minimum.After reducing creepage of 8 mm is we arrive at b_w, which will tell the total width for a one side of winding. Book page 194 explain more.

$$b_w = 32{,}7\text{ mm} - 8\text{ mm} = 24{,}7\text{ mm}$$

Average turn length is

$$l_n = 85\,mm \dots 86\,mm$$

Start dimensioning the winding layers by determining the skin depth

$$\delta = \sqrt{\frac{2\rho_{Cu}}{\omega\mu}}$$

Where ρ_cu = 22.5 10-9 Ωm when temperature is 100 C, and μ = μr = 4 * π * 10-7 H/m. inserted to the equation

$$\delta = \sqrt{\frac{2 * 22{,}5 * 10^{-9}\Omega m}{2\pi * 25\,kHz * 1}} \approx 0{,}48\,mm$$

Book page 196 figure 11.14 present the optimimum skindepth as a function of turns. Assuming filling ratio Fl = 0.75 and h=b, the case for round wire. In this case h and b are conductor width and height.

slope factor α is calculated using:

$$\alpha = \frac{h}{b}\frac{b_w * F_l^{3/2}}{\delta * N_1} = \frac{24{,}7\,mm * 0{,}75^{3/2}}{0{,}48\,mm * 128} = 0{,}26$$

From figure 11.14 select optimum p (number of stacked layers of wire), we have to select a round number. And calculate number of turns per layer

$$N_l = \frac{N_1}{p} = \frac{128}{3} \approx 42{,}7$$

One turn differences are not critical. Select 43, 42, 43 turn layers. Calculate conductor diameter

One turn incline

$$y_x = \frac{b_w}{N_{lmax}} = \frac{24{,}7\,mm}{43} = 0{,}574\,mm$$

IEC-chart for suitable wire, book table 1.2 page 190:

- d = 0,450 mm
- d_0 = 0,516 mm
- **t**$_{min}$ = 0,538 mm ← T_{min} does not indicate time!
- r_{dc} = 0,1397 Ω/m

After this we can recalculate the equivalent filling ratio Fl for square wire

$$F_l = \frac{N_l b}{b_w} = \frac{42{,}7 * 0{,}886 * 0{,}45\,mm}{24{,}7\,mm} \approx 0{,}69$$

, We will get

$$\frac{h\sqrt{F_l}}{\delta} = \frac{0,45\ mm * 0,886 * \sqrt{0,69}}{0,48\ mm} \approx 0,69$$

This gets us to book figure 11.13 on page 195, to estimate the resistance ratio Fr

$$F_R = 1,2$$

Primary AC winding resistance with 25 kHz at 100 C is

$$R_{ac1} = F_R * r_{dc} * N_1 * l_N = 1,2 * \ 0,1397\ \frac{\Omega}{m} * 128 * 85,5\ mm = 1,83\ \Omega.$$

Secondary winding

Secondary has 7 turns. Lets use foil winding for secondary and rememer that b_w = 24.7 mm. For foil p = N2 and Fl = 1. Optimum foil thickness can be read from book figure 11.14 page 196 with p=7:

$$\frac{h\sqrt{F_l}}{\delta} = 0,55$$

lets solve for foil thickness h

$$h = \frac{\delta}{\sqrt{F_l}} * 0,55 = \frac{0,48\ mm}{\sqrt{1}} * 0,55 = 0,26\ mm$$

Selected h = 0.3 mm and check if it holds for 0.3 mm

$$\frac{h\sqrt{F_l}}{\delta} = \frac{0,3\ mm * \sqrt{1}}{0,48\ mm} = 0,625$$

Figure 11.13 on page 195 tells the resistance factor Fr

$$F_R = 1,8$$

Secondary winding resistance with p= N2, comparing previous equation

$$R_{ac2} = \frac{F_R * \delta * p * l_N}{b_w h} = \frac{1,8 * 22,5 * 10^{-9} * 7 * 85,5\ mm}{24,7\ mm * 0,3\ mm} \approx 3,3\ m\Omega.$$

Winding losses

Secondary peak current is 30 A, so we will assume current ripple in the output inductor to be small, note that diode losses are produced using increased secondary voltage, not cause by current. Worst case losses are when current is conductor the maximum time T/2. Lets calculate the secondary copper losses

$$P_{HCu2} \approx R_{ac2} * \hat{I}_2^2 * \frac{t_{onmax}}{T} \approx 3,3\ m\Omega * (30\ A)^2 * 0,5 \approx 1,49\ W$$

Primary current can be calculated from turns ratio (k=18.3)

$$\hat{I}_1 = \frac{\hat{I}_2}{k} = \frac{30\ A}{18,3} \approx 1,64\ A$$

Primary side must also provide the magnetizing current, with peak value

$$\hat{I}_m = U\frac{t_{on}}{L_1} = U_{min}\frac{t_{max}}{L_1}$$

Where L1 is determined from the core data, that was supplied with the questions

$$L_1 = \frac{\mu_r \mu_0 N_1^2}{\frac{\varepsilon l}{A}} = \frac{4 * \pi * \frac{10^{-7} H}{m} * 1600 * 128^2}{0{,}54\ \frac{1}{mm}} \approx 61\ mH$$

Core factor C = εl/A also comes from Siemens datasheets. Now we can calculate the magnetization current

$$\hat{I}_m = \frac{240\ V * 20\ \mu s}{61\ mH} \approx 80\ mA$$

This is relatively small addition to 30 A. Magnetization current waveform can be seen at the start of this document, Magnetization current is triangle wave type. Lets approximate so that during t_{onmax} time primary + magnetization current are combined 1.72 A. in this case

$$\hat{I}_1 = 1{,}72\ A$$

Copper losses in primary are

$$P_{HCu1} \approx R_{ac1} * \hat{I}_1^2 * \frac{t_{onmax}}{T} \approx 1{,}83\ \Omega * (1{,}72\ A)^2 * 0{,}5 \approx 2{,}70\ W$$

Now total copper losses are

$$P_{HCu} = P_{HCu1} + P_{HCu2} = 2{,}70\ W + 1{,}49\ W = 4{,}19\ W$$

Therefore total losses are

$$P_{HTOT} = P_{HC} + P_{HCu} = 5{,}03\ W$$

<u>Thermal rise</u>

Datasheet has no useful data for thermal consideration, lets use rule of thumb equation 8.16 from book page 157. Equation has been altered slightly

$$R_{th} = 11{,}7 * A^{-0{,}7} * P_{HTOT}{}^{-0{,}15}$$

Thermal surface area in dm^2 can be calculated from datasheet

$$A = (49{,}8\ mm + 48{,}5\ mm) * 16{,}7\ mm * 2 + 49{,}8\ mm * 48{,}5\ mm * 2 \approx 8110\ mm^2 = 0{,}81\ dm^2$$

Here we assume that cooling is symmetric from allaround the transformer

$$R_{th} = 11{,}7 * (0{,}81\ dm)^{-0{,}7} * 5{,}03^{-0{,}15} \approx 10{,}8\ \frac{°C}{W}$$

Thermal rise using obtained thermal resistance

$$\Delta T = R_{th} P_{HTOT} = 10{,}8\ \frac{°C}{W} * 5{,}03\ W \approx 54{,}32\ °C$$

Maximum allowed temperature is 100 C so maximum ambient becomes

$$T_{AMAX} = T_{MAX} - \Delta T = 100\ °C - 54{,}32\ °C = 45{,}68\ °C$$

This is reasonable maximum ambient temperature. Still tight casings are surely not working because natural cooling ambient is typically 60 .. 70 C.
Transformer could be optimized. Specially primary winding conduction losses are somewhat high. Let us see if there is more room for copper

Bobbin
Maximum diameter is determined by the core

$$D_{MAX} = 36{,}1\ mm$$

Maximum diameter is determined by bobbin

$$D_{MIN} = 19\ mm$$

Winding section height

$$\frac{D_{MAX} - D_{MIN}}{2} = 8{,}5\ mm$$

How much room will we have for winding when the whole winding height can be max 8.5 mm

Primary

Primary has 3 layers and each layer thickness is taken from IEC-chart tmin = 0.538 mm, so in total 1.614 mm
Three layers with insulating material in between. Insulator thickness is 0.1 mm so 0.2 mm in total

Primary assembly total height is 1.814 mm

Secondary

Secondary has 7 layers and each layer thickness 0.3 mm so 2.1 mm in total
Each layers has insulating material in between. Insulator thickness is 0.1 mm so 0.2 mm in total

Secondary assembly total height is 2.7 mm

Total assembly height is 1.814 mm + 2.7 mm = 4.514 mm. It can be concluded that there is plenty of room for more copper or more optimized built. Primary conductor losses could be reduced using Litz-wire

But initial way to increase conductor area could be using two parallel winding in primary. (electrically isolated, but connected at the ends in parallel). In this way b would now be double for the conductor but h would be the same

Conclusions

as can be seen, transformer design is iterative and multistep process. This document is just a single process to design a transformer and other processes exist. Link for a book by Kazimierczuk shows an alternative way of designing. This exercise uses figure tables for estimating eddycurrent losses. However in certain types of design these eddycurrent are calculated case by case basis more accurately. Doing this would require lots of familiarizations

Literature

- M.K. Kazimierczuk: High-frequency magnetic components (e-book)
    - https://alli.linneanet.fi/vwebv/holdingsInfo?searchId=1174&recCount=20&recPointer=0&bibId=681364