1. a) The BJT is turned by a continuous base current strong enough to drive the device into saturation so that a low collector-emitter voltage is obtained ($V_{CE(SAT)}$) to reduce the on-state losses. To enhance turn-on current peaking at the base is employed and for turn off a negative voltage is applied at the gate leading to a negative base current pulse. This speeds up the charging and discharging of the base-emitter capacitance C_{BE}.

A MOSFET is turned on by a continuous voltage between gate and source. To insure operation in the linear region, with low V_{DS}, the gate-source voltage has to be strong enough with initial current sourcing capability to charge the gate to source capacitance. A negative current source capability will discharge C_{GS} quickly and speed up the turn-off process.

A GTO is turned on by a positive current pulse at the gate having a duration longer than the turn-on time of the device and strong enough to initiate the latching process. The GTO is turned off by a negative current pulse at the gate ($\sim \frac{1}{3}$ load current) with a duration longer than the turn-off time of the device.

b) The elevator is usually operated by an AC induction motor the speed of which needs to be controlled allowing for comfortable acceleration and deceleration. The block diagram set up is shown Fig. 1 below. The 3-phase 50Hz supply is first rectified and then inverted using a PWM 3-phase inverter whose frequency is controlled for direct speed control of the elevator.

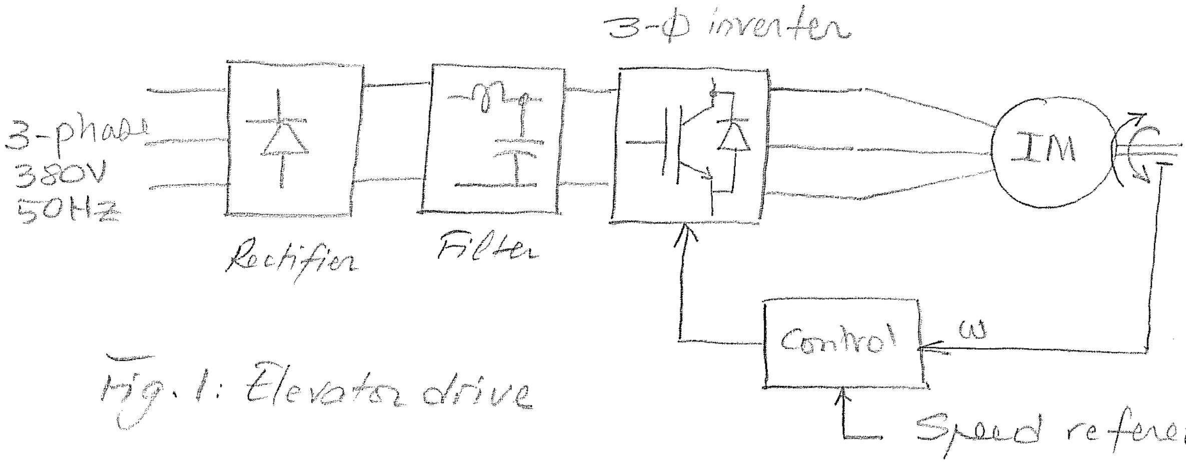


Fig. 1: Elevator drive

The electric car may have an induction motor or a dc motor. If an induction motor is used then the drive would be similar to that of Fig. 1 except that the initial rectifier stage is not needed, since the initial supply in this case is a battery bank. If the car has a permanent magnet dc motor then a dc-dc drive is used with voltage and current reversal capability to allow 4 quadrant operation. The drive must be able to accelerate and decelerate the car in two direction. (Fig. 2).

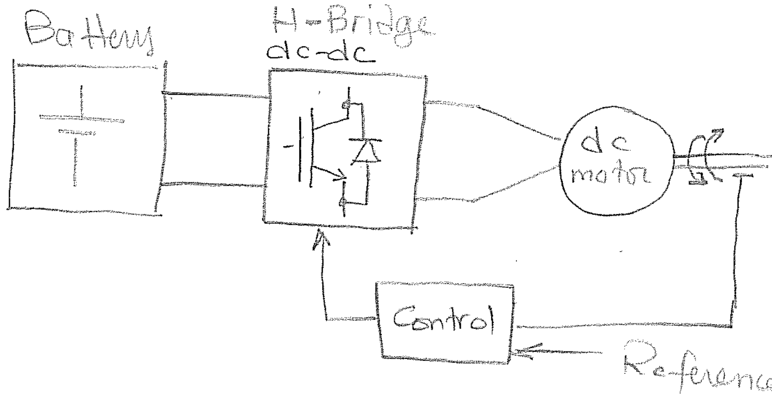


Fig. 2: Car drive with dc motor

In HVDC we need to transmit power at one frequency (e.g. 50 Hz) to another system frequency (e.g. 60 Hz). This is achieved as shown in Fig. 3 by rectifying the voltage and current using a controlled ac-dc rectifier or converter usually using thyristors or SCR. DC power then flows on a dc line and is then inverted back to ac at the second frequency. The two, so called grid-commutated converters have the same topology, i.e. 3-ϕ thyristor converters. But one converter is waking at firing delay $\alpha < 90$ as a rectifier while the second is operating as an inverter with $\alpha > 90$. The direction of power flow can be reversed by switching the operating roles of rectifier and inverter of the two converters, which causes a voltage polarity reversal and thus power flow reversal.

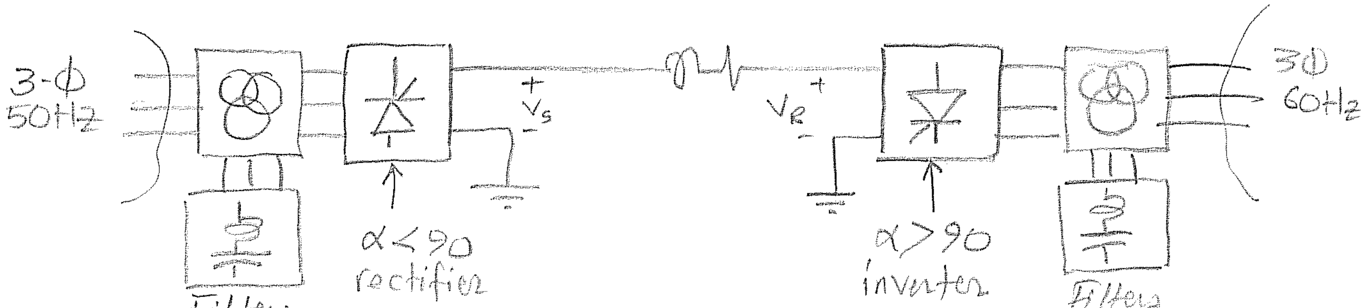
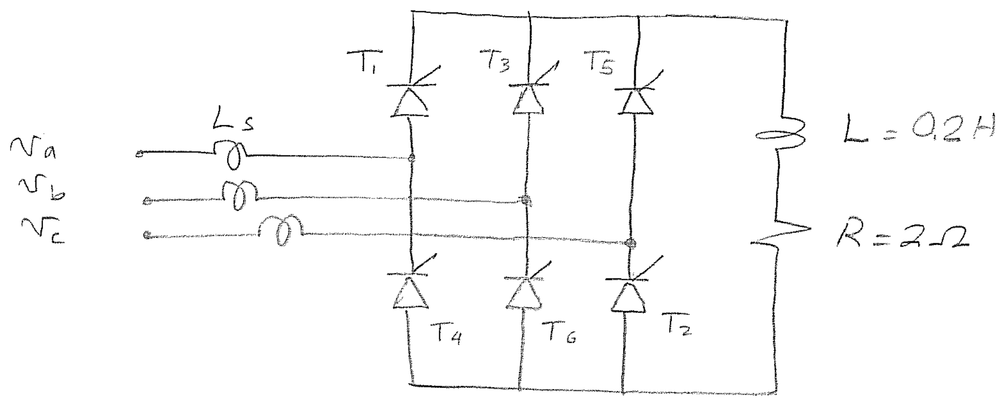


Fig. 3: HVDC link

2. a)



$v_a = V_m \sin(\omega t)$

$v_b = V_m \sin(\omega t - 120°)$

$v_c = V_m \sin(\omega t - 240°)$

$V_m = V_{ll}\sqrt{\frac{2}{3}} = 1200 \times \sqrt{\frac{2}{3}} = 979.8\,V$

The voltage waveforms are on the plot sheet on the next page.

b) $V_d = 1400\,V$

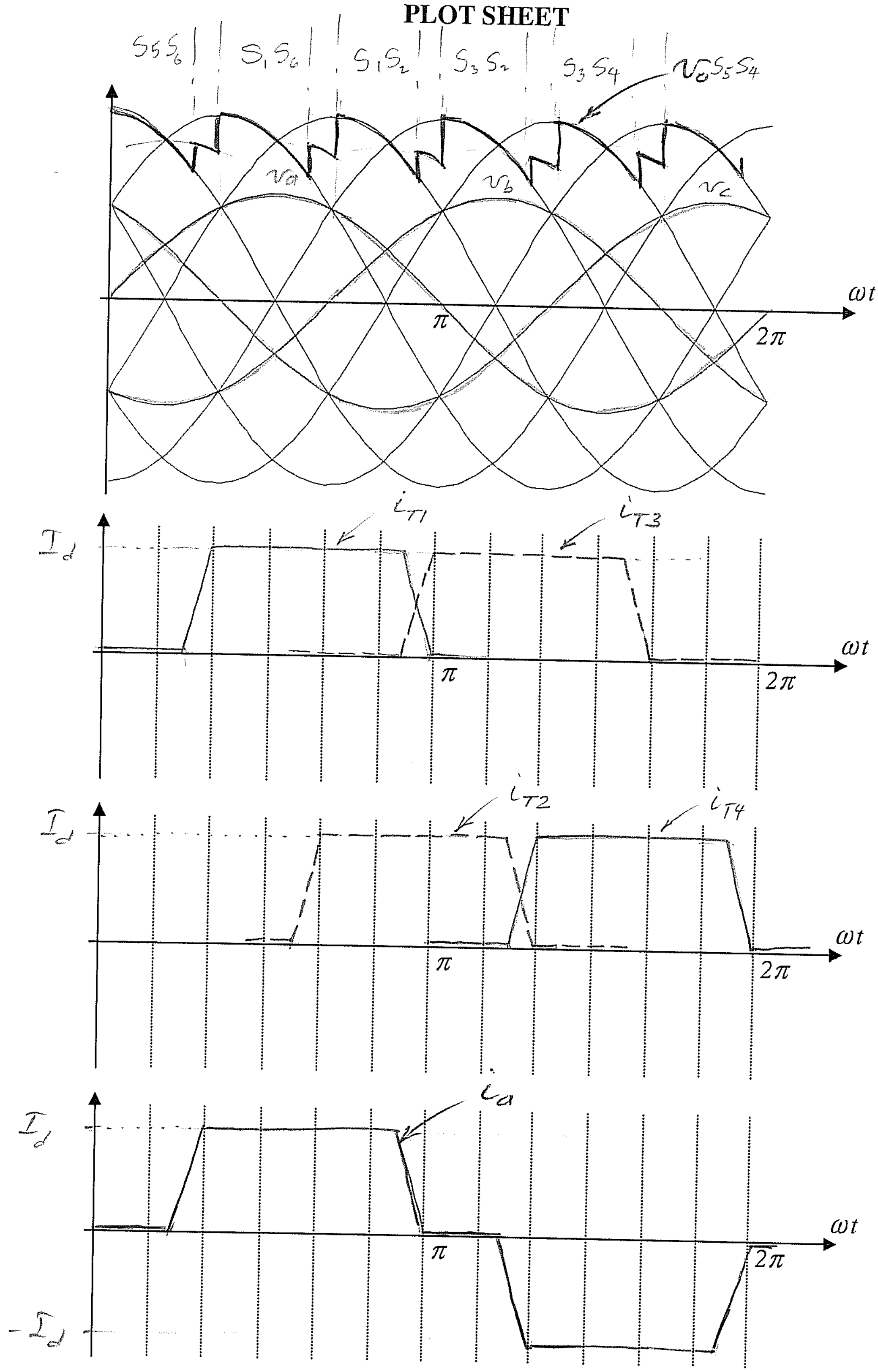
$I_d = \frac{V_d}{R} = 700\,A$ is the average output current.

The output current may be considered nearly constant since the load time constant is much larger than the current pulse duration in one of the devices which is nearly $\frac{2\pi}{3}$:
$\frac{L}{R} \gg \frac{2\pi}{3\omega} = \frac{1}{3f} \Rightarrow \frac{L}{R} = 0.1 \gg \frac{1}{3 \times 50} = 6.67 \times 10^{-3}\,s$

$V_d = \frac{3\sqrt{2}\,V_{ll}\cos\alpha}{\pi} - \frac{3\omega L_s I_d}{\pi} \Rightarrow$

$1400 = 1620\cos\alpha - 42 \Rightarrow \cos\alpha = 0.89 \Rightarrow \alpha = 27.1°$

PLOT SHEET



$i_a = i_{T1}$ when T_1 is on and $i_a = -i_{T4}$ when T_4 is on.

4A

The angle of commutation overlap u is obtained from:

$$\cos(\alpha+u) = \cos\alpha - \frac{2\omega L_s I_d}{\sqrt{2}\, V_{ll}} \Rightarrow$$

$$\cos(\alpha+u) = 0.89 - 0.052 = 0.838 \Rightarrow$$

$$\alpha+u = \cos^{-1}(0.838) = 33^\circ \Rightarrow$$

$$u = 33 - 27.1 = 5.9^\circ$$

c) The rms value of a thyristor current is:

$$I_{T(rms)} = \sqrt{\frac{2}{2\pi}\left(\int_0^u \left(\frac{I_d}{u}\right)^2 \theta^2 d\theta + \int_0^{\pi/3 - u/2} I_d^2\, d\theta\right)}$$

$$= \sqrt{\frac{I_d^2}{\pi}\left(\frac{u}{3} + \frac{\pi}{3} - \frac{u}{2}\right)} = I_d\sqrt{\left(\frac{1}{3} - \frac{u}{6\pi}\right)}$$

$$= 700 \times \sqrt{\frac{1}{3} - \frac{5.9}{6\times180}} = 700\sqrt{0.328}$$

$$= \frac{700}{1.746} = 401\,A \qquad \left(\simeq \frac{I_d}{\sqrt{3}} = 404\,A\right)$$

The rms of input phase-current is:

$$I_{(rms)} = I_{T(rms)} \times \sqrt{2} = 567\,A$$

$$PF = \frac{P}{S} = \frac{700\times1400}{\sqrt{3}\times1200\times567} = 0.832$$

But $PF = \frac{I_{s1}}{I_s}\cos\phi \Rightarrow \frac{I_{s1}}{I_s} = \frac{PF}{\cos\phi}$ with $\phi \simeq \alpha + \frac{u}{2}$

So the current distortion factor is:

$$\frac{I_{s1}}{I_s}^{*} = \frac{0.832}{\cos\left(\underbrace{27.1 + \frac{5.9}{2}}_{\sim 30.0^\circ}\right)} = 0.961$$

and the THD is given by:

$$THD = \sqrt{\left(\frac{I_s}{I_{s1}}\right)^2 - 1} \times 100 = 28.8\ \%$$

d) To recover the energy stored in L, the converter has to be operated in inverter mode with $\alpha > 90^\circ$. The maximum firing delay is given by:

$$\alpha_{max} = 180 - u - \gamma$$

γ is the angle needed to allow the device (SCR) to turn off before the next zero crossing. So:

$$\alpha_{max} = 180 - 5.9 - 1 \cong 173^\circ$$

We will allow a further 3° to avoid any commutation failure due to perturbations:

$$V_d = \frac{3\sqrt{2}\, V_{LL} \cos\alpha}{\pi} - \frac{2\omega L_s I_d}{\pi}$$

$$= -1596 - 42 = -1638\ V$$

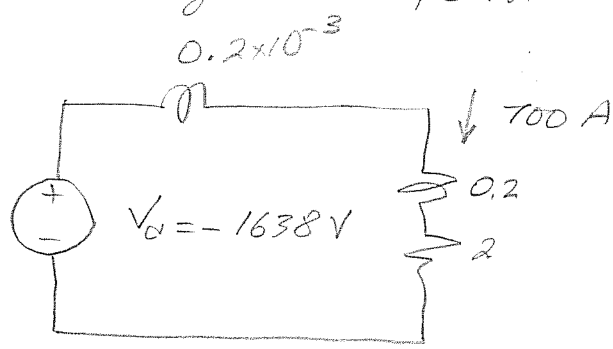
---

* From Fourier Series:

$$I_{s1} = \frac{4 I_d}{\sqrt{2}\pi u}\left[\sin\left(\frac{\pi}{12} + \frac{\alpha}{2} + u\right) - \sin\left(\frac{\pi}{12} + \frac{\alpha}{2}\right)\right] = \frac{4 \times 700}{\sqrt{2} \times \pi \times \underset{u}{0.103}}(0.566 - 0.478)$$

$$= 537.3\ A$$

Bonus: The approximate equivalent circuit during discharge is as follows:



The current will decay in an exponential form according to:

$$i_d(t) = A + Be^{-t/\tau}$$

$$\tau \simeq \frac{L}{R} = 0.1 \text{ s}$$

$$i(0) = I_d \Rightarrow \quad A + B = 700 \text{ A}$$

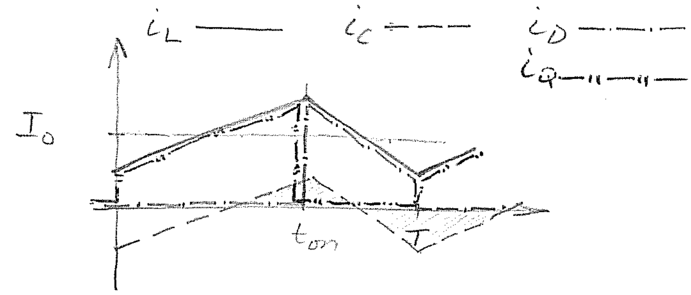
$$i(\infty) = \frac{V_d}{R} = \frac{-1638}{2} = -819 \text{ A} = A \Rightarrow B =$$

so $i(t) = -819 + 1519\, e^{-10t}$ and the time needed to discharge the energy in L back to the supply is t_1 obtained by solving $i(t_1) = 0$:

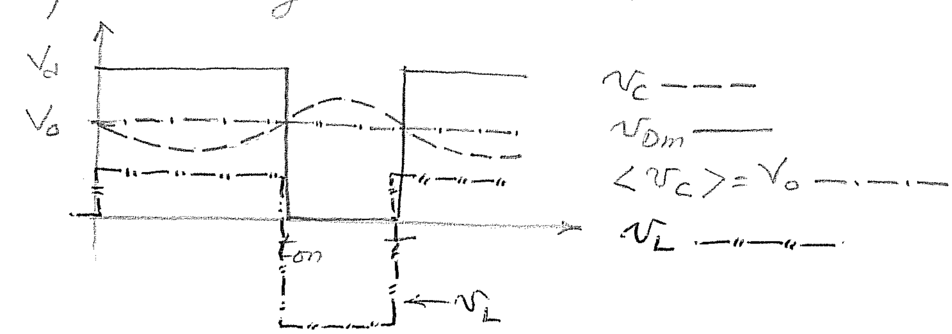
$$0 = -819 + 1519\, e^{-10t_1} \Rightarrow t_1 = 0.062 \text{ s} \quad \text{or}$$

$$t_1 = 62 \text{ ms}$$

3. a) When Q is on diode D_m is reverse biased and the current in L increases and when Q is off, the inductor supplies its energy to capacitor C and load via the diode. The current and voltage waveforms are as follows:



The average inductor current is equal to the load current I_o since the average capacitor current is zero. The average input current is equal to the sum of the average diode and inductor currents.



The average value of the diode voltage is equal to the voltage at the output (across C). The ripple across C has been exagerated for illustration purposes; C is usually large enough to keep voltage ripple to within few percentages.

b) The range of duty cycle is calculated from the values of output voltages:

$$V_{01} = V_d D_1 \Rightarrow D_1 = \frac{V_{01}}{V_d} = \frac{100}{240} = 0.417$$

and $D_2 = \frac{V_{02}}{V_d} = \frac{200}{240} = 0.833$

so $D \in (0.417 - 0.833)$

L is obtained from:

$$\Delta I_L = \frac{V_d(1-D)D}{f_s L} \Rightarrow L = \frac{V_d(1-D)D}{f_s \Delta I}$$

For each duty cycle we obtain a value for L:

$$L_1 = \frac{240\,(1-0.417)\,0.417}{10\times10^3\times 10} = 0.583\times10^{-3}\,H$$

$$L_2 = 0.334\times10^{-3}\,H$$

So we select the larger of the two values!

The capacitance C is obtained from:

$$\Delta V_o = \frac{V_o(1-D)}{8f_s^2 LC} \Rightarrow C = \frac{V_o}{\Delta V_o}\,\frac{(1-D)}{8f_s^2 L}$$

The larger capacitance value at the lower duty cycle is selected:

$$C_1 = \frac{1}{0.05} \times \frac{(1-0.417)}{8\times10^2\times10^{+6}\times0.583\times10^{-3}} = 25\times10^{-6} = 25\,\mu F$$

Peak transistor current is:

$$I_p = I_o + \frac{\Delta I_L}{2} = 10+5 = 15\,A.$$

c) The drive circuit in Fig. 2 is a proportional drive circuit. When Q_1 is pulsed the current i_B increases and causes Q to conduct which causes a secondary current to flow into the transformer winding. As a result a primary current flows out of the primary and into the base of Q thus sustaining conduction of Q even when Q_1 is turned off.

Q is turned off by pulsing Q_2 with a negative voltage pulse with respect to ground. The base capacitance of Q discharges through Q_2, R_2 and $-V_{cc}$, and Q turns off. When Q is off the magnetizing current I_μ decays out of the transformer secondary and into the primary side through R_2 and the diode.

$$I_E \cong I_{Bf} + I_c = I_{Bf} + I_{Bf}\beta_f = I_{Bf}\left(1 + \frac{\beta}{ODF}\right)$$

which implies: $\frac{I_E}{I_{Bf}} = N = (1 + \beta/ODF) \Rightarrow$

$$\beta + 1 = ODF \times N. \qquad (3.1)$$

The transformer core area is obtained using Faraday's law:

$$v_p = N_p \frac{d\phi_p}{dt} \simeq N_p \frac{A_c B_s}{t_{on}} \Rightarrow A_c = \frac{v_p t_{on}}{N_p B_s}$$

during turn on $v_p \simeq V_{cc}$ so

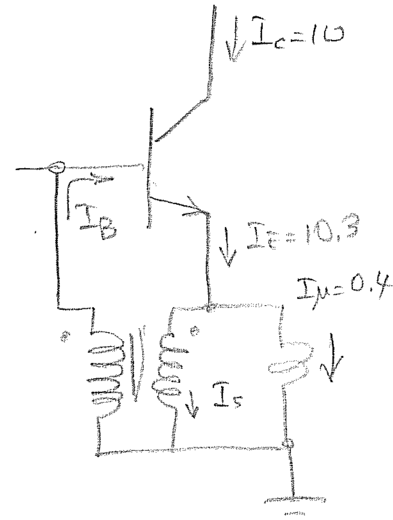
$$A_c = \frac{V_{cc} t_{on}}{N_p B_s} \qquad (3.2)$$

d)

Since β is large we will select an overdrive factor larger than usual, so let ODF = 3. Then

$$N = (\beta+1)/ODF = \frac{101}{3} = 33.7 \Rightarrow N = 33$$

$$I_B = I_c/\beta_f = 10/((100/3)) = 0.3A$$



$$I_E = I_c + I_B = 10. + 0.3 = 10.3$$

$$I_s = N I_B = 33 \times 0.3 = 9.9$$

and so $I_\mu = 10.3 - 9.9 = 0.4A$

The magnetizing inductance is:

$$L_\mu = \frac{V_s\, t_{on}}{I_\mu} = \frac{V_{BE} \times t_{on}}{(N-1)\; I_\mu}$$

$$= \frac{1.8 \times 0.833 \times 10^{-4}}{32 \times 0.4} = 12 \times 10^{-6}\, H$$

But $A_c = \dfrac{L_\mu\, l_c}{\mu\, N_s^2} = \dfrac{12 \times 10^{-6} \times 34 \times 10^{-3}}{1500 \times 4\pi \times 10^{-7} \times 4} = 0.54 \times 10^{-4}\, m^2$

$$= 54\, mm^2$$

Note that $A_c > \dfrac{t_{on}\, V_p}{N_p\, B_s}$ indicating that the core is not saturated.

To determine R_1 we write KVL during turn-on:

$$V_{cc} = I_B R_1 + V_{CE(Q_1)} + V_p \Rightarrow R_1 = \frac{V_{cc} - V_{CE(Q_1)} - V_p}{I_B}$$

$$V_p = V_{BE} \frac{N}{N-1} = 1.9V$$

$$R_1 = \frac{12 - 0.7 - 1.9}{0.3} = 31\Omega$$

R_2 is such that $I_B R_2 \ll V_{cc} \Rightarrow I_B R_2 \cong 0.2 V_{cc} \Rightarrow$

$R_2 = 8\Omega$