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131 iEC

Electric Drives Project

I Introduction

This project aims to design a basic electric drive system using a DC motor supplied through a controlled rectifier with thyristors. The goal is to efficientely control the motor's speed & torque by adjusting voltage & current. Calculations will be carried out to select a suitable thyristor & other necessary components to ensure proper system operation.

II Electric motor parameters

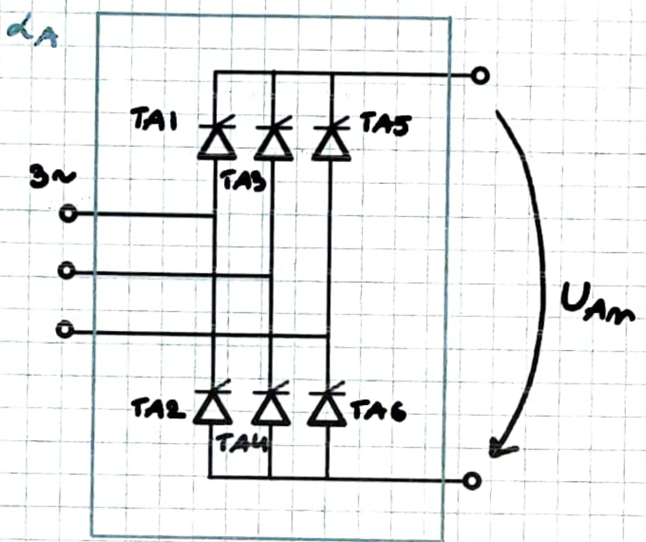
- → nominal power - $P_n = 4{,}9$ kW
- → nominal armature voltage - $U_n = 460$ V
- → nominal armature current - $i_{An} = 12{,}4$ A
- → nominal speed - $n_n = 3200$ rpm
- → nominal torque - $M_n = 14{,}9$ Nm
- → armature inductance - $L_A = 17{,}8$ mH
- → armature resistance - $R_A = 2{,}55\ \Omega$
- → rotor moment of inertia - $J = 0{,}0142$ kgm^2
- → motor mass - $m = 40$ kg

These parameters are the starting point for dimensioning the converter & associated components.

III Choosing the static converter topology

To control a DC motor, we need a converter that changes AC voltage into adjustable DC voltage. For this project, a three-phase fully controlled bridge rectifier (CTCCP) was chosen, as it is commonly used in medium & high-power applications.

This setup uses 6 thyristors arranged in a bridge. It can work in both directions (driving the motor & recovering energy) making it suitable for full four-quadrant control when combined with the right control system. The output voltage is adjusted by changing the firing angle (α) of the thyristors. This type of converter is strong, reliable & widely used in DC motor control.



IV Dimensioning & Selection of Power Semiconductor Devices

The selection of appropriate thyristors is fundamental to the design of the static converter. The main parameters that dictate the choice of a thyristor are its current & voltage ratings, which must be sufficient to handle the stresses imposed by the circuit operation with adequate safety margins.

① Determination of current ratings

For a three-phase fully controlled bridge rectifier supplying a DC load with current i_{Am} the average & RMS current flowing through

For a three-phase fully controlled bridge rectifier supplying a DC load with current i_{Am}, the average & RMS current flowing through each individual thyristor in the bridge must be determined. For continuous conduction mode, these currents are calculated based on the formulas provided.

The average current through each thyristor: $i_{TAV} = \frac{i_{Am}}{3} = \frac{12,4}{3}$

$$\boxed{i_{TAV} \simeq 4,133\ A}$$

The RMS current through each thyristor: $i_{TRMS} = \frac{i_{Am}}{\sqrt{3}} = \frac{12,4}{\sqrt{3}}$

$$\boxed{i_{TRMS} = 7,159\ A}$$

According to the project guidelines, the catalog values for the avg. & RMS current of the chosen thyristor must exceed the calculated values multiplied by a safety factor of $2 \cdot 1,1 = 2,2$

- $(i_{TAV})_{catalog} > 2,2 \cdot i_{TAV} = 2,2 \cdot 4,133 \simeq \underline{9,093\ A}$
- $(i_{TRMS})_{catalog} > 2,2 \cdot i_{TRMS} = 2,2 \cdot 7,159 \simeq \underline{15,75\ A}$

② Determination of voltage rating (U_{RRM})

The repetitive peak reverse voltage U_{RRM} is a critical voltage rating for a thyristor, representing the max reverse voltage it can repeatedly block. This voltage is directly related to the AC voltage on the secondary side of the power transformer (U_{2f}), which is dictated by the required average DC output voltage U_{Am} & the voltage drop within the converter circuit. The avg DC voltage is related to the ideal no-load DC voltage (U_{A0}), the firing angle (α) & the voltage drops (U_R & U_X) by the equation:

& the voltage drops (U_R & U_γ) by the equation:

$$* \quad U_{Am} = \overset{1}{U_{A0}\cos\alpha} - \overset{2}{U_R} - \overset{3}{U_\gamma} = 460\ V$$

The ideal no-load DC voltage U_{A0} for a three-phase bridge rectifier (p=6) is given by:

1 $U_{A0} = \sqrt{2}\cdot U_{2l}\cdot \frac{p}{\pi}\sin\frac{\pi}{p}$ for $p=6 \Rightarrow U_{A0} = \sqrt{2}\cdot U_{2l}\cdot\frac{6}{\pi}\cdot\sin\frac{\pi}{6}$

$$= \sqrt{2}\cdot U_{2l}\cdot\frac{6}{\pi}\cdot 0{,}5$$

$$U_{A0} = \frac{3\sqrt{2}}{\pi}\cdot U_{2l} \simeq \underline{1{,}35\cdot U_{2l}}$$

2 $\alpha = 30^\circ$ = firing angle

3 $U_R = \dfrac{\overset{a}{P_{semicond}} + \overset{b}{P_{Cu}} + \overset{c}{P_{sig}}}{I_{Am}}$

total avg power dissipated in all thyristors in the bridge

a $P_{TAV} = t_c\cdot(V_{T0}\cdot i_{TAV} + r_T\cdot i_{TRMS}^2)$ $\Rightarrow P_{TAV} = 1\,[1\cdot 4{,}133 + 0{,}016\cdot(7{,}159)^2]$

$$= 4{,}133 + 0{,}82$$

$$\boxed{P_{TAV} = 4{,}953\ W} \Rightarrow$$

$t_c = 1$

SKKT 20/16 E $\Rightarrow V_{T(TO)} = 1\ V$

$r_T = 0{,}016\ \Omega$

$\Rightarrow P_{semicond} = 6\cdot P_{TAV} = 6\cdot 4{,}953$

$$\boxed{P_{semicond} = 29{,}718\ W}$$

b P_{Cu} = power dissipated in the transformer windings = $\frac{1{,}5}{100}\cdot S_T = P_{Cu}$

$S_T = K_p\cdot U_{Am}\cdot I_{Am}\cdot 2\cdot 1{,}1$ = rated power of the transformer

$K_p = 1{,}05 \Rightarrow S_T = 1{,}05\cdot 460\cdot 12{,}4\cdot 2{,}2 = 1{,}05\cdot 12548{,}8$

$\boxed{S_T = 13176{,}24\ VA} \Rightarrow P_{Cu} = \frac{1{,}5}{100}\cdot 13176{,}24$

$\boxed{P_{cu} = 197,644\ W}$

c $P_{sig} = 0\ W$

$\Rightarrow U_R = \dfrac{29,718 + 197,644 + 0}{12,4} = \dfrac{227,362\ W}{12,4\ A} = \boxed{18,336\ V = U_R}$

4 $U_x = 0,5 \cdot u_{sc} \cdot U_{A0} = 0,5 \cdot 0,05 \cdot 1,35 \cdot U_{2l} = 0,03375 \cdot U_{2l}$

* $460 = 1,35 \cdot U_{2l} \cdot \cos 30° - 18,336 - 0,03375 \cdot U_{2l}$

$460 + 18,336 = U_{2l}(1,35 \cdot \cos 30° - 0,03375)$

$478,336 = U_{2l} \cdot 1,13538 \Rightarrow \boxed{U_{2l} \simeq 421,29\ V} \Rightarrow U_{A_0} = 1,35 \cdot 421,29$
$= 568,74\ V$

$U_{RRM} = (2 \to 2,5) \cdot 1,1 \cdot \sqrt{2} \cdot U_{2l} = 2 \cdot 1,1 \cdot \sqrt{2} \cdot U_{2l} = 2,2 \cdot 1,41421 \cdot 421,29\ V$

$\boxed{U_{RRM} = 1310,8\ V} \Rightarrow (U_{RRM})_{catalog} \geq 1310,8\ V$

③ Selection of thyristor module

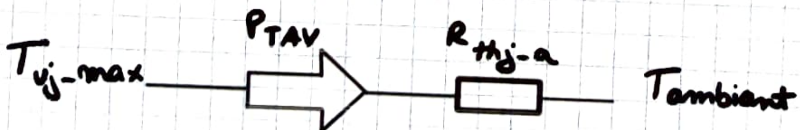
Based on the calculated current & voltage rating requirements, I select the Semikron SKKT 20/16 E thyristor module.

V Thermal verification of power semiconductor devices

Thermal verification ensures that the junction temperature (T_{vj}) of the selected thyristors remains within safe limits during operation.

① Steady-state thermal verification

This verifies continuous operation at nominal load. T_{vj} depends on power dissipation & thermal resistances.



T_{vj} = virtual junction temp. $= (0,7 \ldots 0,9) \cdot T_{vj\,max}$

T_c = package temp.

T_K = heatsink temp.

T_K = heatsink temp.

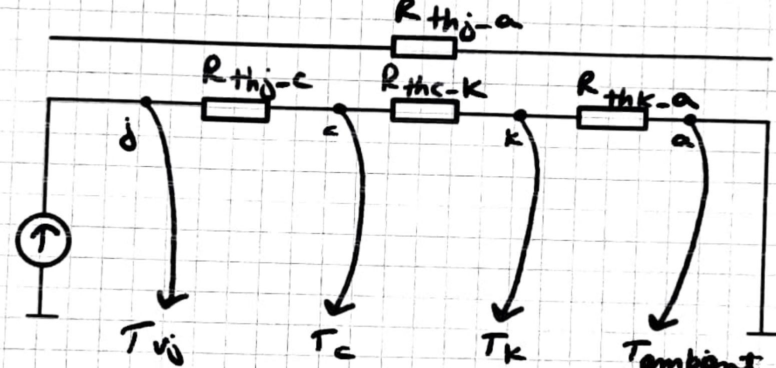
$\boxed{T_{ambient} = 40^\circ C}$

$\boxed{T_{vj\,max} = 125^\circ C} \Rightarrow T_{vj} = 0{,}75 \cdot 125 = \boxed{93{,}75^\circ C = T_{vj}}$

R_{thj-c} = junction to capsule thermal resistance $[C^\circ/W] = [K/W]$

R_{thj-k} = capsule to radiator thermal resistance

R_{thk-a} = radiator to ambient medium thermal resistance



$T_{vj\,max} - T_{a-max} = P_{TAV} \cdot R_{thj-a}$

$R_{thc-a} = \dfrac{T_{vj} - T_{amb.}}{P_{TAV}} - R_{thj-c} - \Delta r$ → corelation coefficient $\begin{cases} < 0 \Rightarrow \text{doesn't need radiator} \\ > 0 \Rightarrow \text{needs radiator} \end{cases}$

$= R_{thc-k} + R_{thk-a}$

$\Delta r = 1{,}79 - 1{,}3 = \underline{0{,}49\ K/W}$

$r_t = \underline{0{,}016\ \Omega}$

$R_{thj-c} = \underline{1{,}3\ K/W}$

$V_{TO} = \underline{1V}$

} Values from my chosen thyristor

$t_c = 1$ as it is continuous conduction regime

so $P_{TAV} = 1(1 \cdot 4{,}133 + 0{,}016 \cdot 7{,}159^2) = 4{,}133 + 0{,}82$

$\boxed{P_{TAV} = 4{,}953\ W}$

$R_{thc-a} = \dfrac{93{,}75 - 40}{4{,}953} - 1{,}3 - 0{,}49 = \underline{9{,}062\ K/W} > 0$ so it needs a radiator

I choose Wakefield-Vette 392-180

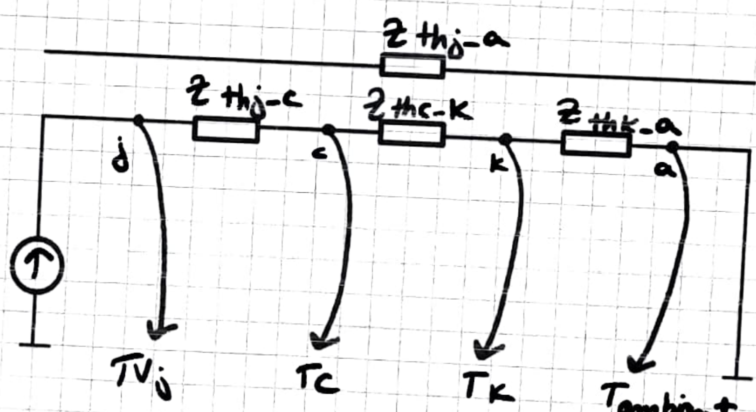
So to verify we use this formula:

$$P_{TAV}(R_{thj-c}+R_{thc-k}+R_{thk-a})+T_{ambiant} \leq T_{vj}$$

$$4{,}953(1{,}3+0{,}49+7{,}5)+40 \leq 93{,}75 \Rightarrow 86{,}013 \leq 93{,}75 \quad (A)$$

Following the steady-state thermal verification, the calculated junction temperature ($T_{vj}=86{,}01°C$) falls within the safety limits ($T_{vj-max}=125°C$) & below the design target temperature ($93{,}75°C$). Therefore, the selected cooling system (Wakefield-Vette 392-180 heatsink with $R_{thk-a}=7{,}5$ K/W) is adequate for continuous operation at nominal load.

② Transient regime



$P_{T(OV)}$ = power dissipated in thyristor during the overload

t_{ov} = duration of overload

$Z_{thj-a}(t_{ov})$ = total transient thermal impedance from junction to ambient for the duration t_{ov}

overload current → $i_{T(OV)}=2\cdot i_{TAV}\cdot 1{,}1$ ⇒ $i_{T(OV)}=2{,}2\cdot 4{,}133=\underline{9{,}093\ A}$

$i_{TAV}\cong 4{,}133\ A$

$$P_{T(OV)}=t_c\cdot(V_{TO}\cdot i_{T(OV)}+r_T\cdot 3\cdot i^2_{T(OV)})=1(1\cdot 9{,}093+0{,}016\cdot 3\cdot 9{,}093^2)$$

4

$\boxed{P_{T(OV)} = 13{,}062\ W}$

$t_{OV} = 1s \Rightarrow Z_{thj-c}(1s) = 0{,}38\ K/W$

$Z_{thj-a}(t_{OV}) = Z_{thj-c}(t_{OV}) + R_{thc-k} + Z_{thk-a}(t_{OV})$

$Z_{thk-a}(1s) = 0{,}8 \cdot R_{thk-a} = 0{,}8 \cdot 6{,}3 = 5{,}04\ K/W$

$Z_{thj-a}(1s) = 0{,}38 + 0{,}49 + 5{,}04 = 5{,}91\ K/W$

$T_{vj} = T_{ambient} + P_{T(OV)} \cdot Z_{thj-a}(1s) \Rightarrow T_{vj}(1s) = 40 + 13{,}062 \cdot 5{,}91 = 117{,}2\,°C < 125\,°C$

(A)

Since the result is below the maximum allowed junction temperature of 125°C, the thermal performance is acceptable under the defined conditions.

③ Based on the selection criteria & available commercial catalogs, the following power transformer ~~can be~~ was chosen

Siemens → 4AM6542-8DD40-0FA0

dry type transformer

$S_T = 15\,kVA$, $U_{1pr} = 460\,V$, $U_{2sec} = 400\,V$

④ (VII) Smoothing inductor (filter inductor) sizing & selection

① calculation of required ~~resist~~ inductance

The min inductance required for the smoothing inductor is calculated to ensure satisfactory performance, such as maintaining cont. conduction mode of the motor current & limiting current ripple.

$$L_{u_1} = K_1 \frac{U_{A0}}{K_{u_3} \cdot I_{Am}} = 0,3 \cdot \frac{568,75}{0,03 \cdot 12,4} = 275,2\ mH$$

$$L_{u_2} = K_2 \frac{U_{A0}}{K_{u_3} \cdot I_{Am}} = 0,13 \cdot \frac{568,75}{0,17 \cdot 12,4} = 35,08\ mH$$

$$L_{u\,\cancel{max}} = max(L_{u_1}, L_{u_2}) = 275,2\ mH$$

② selected smoothing inductor

Based on the calculated required inductance & available commercial catalogs, a suitable smoothing inductor was selected;

VII Sizing of protections. Short circuit protection

$$I_{n-fuse} \geq I_{TRMS} = 7,159\ A$$
└ from thyristor

$$U_{n-fuse} > \sqrt{2}\, U_{2e} \cdot 1,1 = 655,9\ V$$

$$U_{arc} < (1,5 \ldots 2)\sqrt{2}\, U_{2e} = 2 \cdot \sqrt{2} \cdot U_{2e}$$

$$i_p = (i_{TRMS}) / u_{sc}$$ └ chosen TRAFO $= 0,05$

└ presumed current = available fault current

$$i_p = \frac{7,159}{0,05} = 143,18A$$

$$K_1 (i^2 \cdot t)\ fuse < K_2 (i^2 t)\ thyristor$$

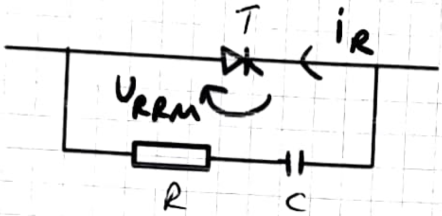
$$U_{arc} < U_{RRM}$$

So basically the fuse has to be capable to sustain the thyristor without breaking, that's why all these values have to be greater than the ones for the thyristor. Because of this, I've chosen the ETi CH10x38 gR 8A/700 V AC/DC fuse. Its specifications are:

- → rated current : 8A $\geq i_{TRMS}$
- → rated voltage: 700 V AC/DC

- → rated current: 8A $\geq I_{TRMS}$
- → rated voltage: 700V AC/DC $\geq 655{,}9V$
- → breaking capacity: 50 kA AC / 8 kA DC
- → pre-arcing i^2t: 30 A^2s
- → operating i^2t total: 98 A^2
- → arc voltage $< U_{RRM} = 1310{,}8V$

VIII) Overload protection sizing



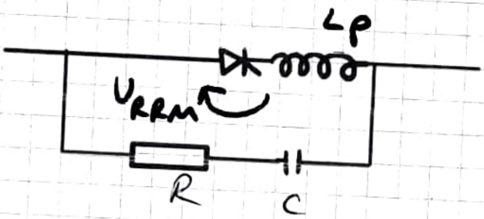
	CTCCP
R'	$\frac{3R}{5}$
C'	$\frac{5C}{3}$

$$R' \geq (U_{mu\,thyr} - 100) / (40...80) = \frac{1600-100}{50}$$

$$\geq \underline{30\,\Omega} \Rightarrow R' = 30\,\Omega \Rightarrow R = \frac{30 \cdot 5}{3} = \frac{150}{3} = 50\,\Omega$$

for $C' = 0{,}975 \Rightarrow C = \frac{3 \cdot 0{,}975}{5} = \underline{0{,}585}$

$$P_R = 4 \cdot f \cdot C\,(U_{2e} \cdot 1{,}1)^2 = 4 \cdot 50 \cdot 0{,}585 \cdot (421{,}29 \cdot 1{,}1)^2 \cdot 10^{-9} = \underline{41{,}877\,W}$$

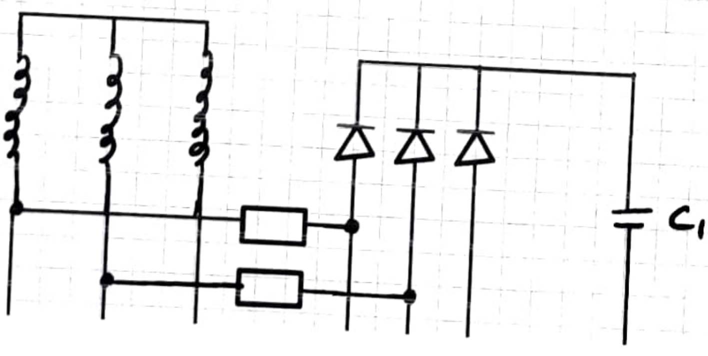


$$L_{ST} = \frac{u_{sc} \cdot U_{2e}^2}{2\pi f S_T} = \frac{0{,}05 \cdot 421{,}29^2}{2 \cdot \pi \cdot 50 \cdot S_T} = 5{,}088\,\mu H \;;\; S_T = 13176{,}24\,VA$$

$$\left(\frac{dU}{dt}\right)_{max} = \frac{\sqrt{2}\,U_{2e} \cdot R}{5} \cdot \frac{2L_{ST}}{(2L_{ST}+L_p)L_p}$$

L_p = max current value that goes through the thyristor [4]

Option 1:



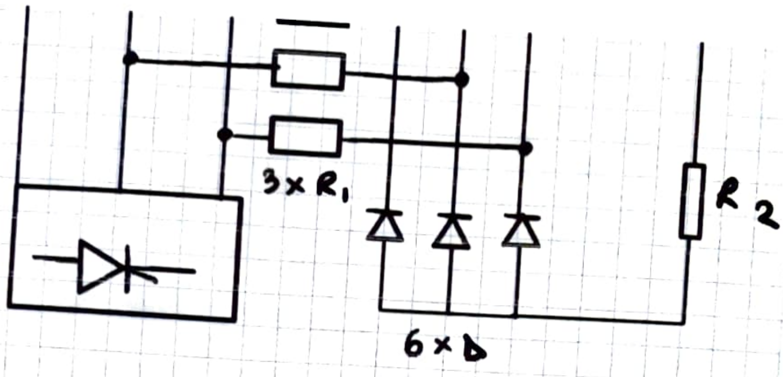
Ⓐ Vérifications

$K_1 (i^2 \cdot t)_{fuse} < K_2 (i^2 t)_{thyr}$ (A)

~~0,3~~

$i_{lim\_fuse} \leq K_3 \cdot i_{TSM}$ (A)

$V_{arc} < U_{RRM}$ (A)



$R_1 = 2\sqrt{\frac{L_{ST}}{C_1}}$; $P_{R_1} = 2\,(U_{2l}\cdot 2\pi \cdot f \cdot C_1)^2\, R_1$

$R_2 = \frac{25}{f\cdot C_1}$; $P_{R_2} = \frac{1{,}8\cdot U_{2l}^2}{R_2}$

$C_1 = 6{,}4 \cdot \frac{i_0 \cdot S_1 \cdot 10^{-6}}{U_{RRM}^2}$

$U_C = U_{RRM}$

$i_{TAV} \geq \frac{\sqrt{2}\, U_{2l}}{3(R_1+R_2)}$

$i_{FSM} \geq \frac{U_{RRM}}{R_1(0{,}3 \dots 0{,}6)}$

$(U_{RRM})_{diode} \geq U_{RRM}$

VIII Power transformer sizing

Smoothing inductivity, circuit current limiting inductivity
nominal data for the transformer

→ power - S_T [VA]

→ primary voltage - U_{1n} [V]

→ secondary voltage - U_{2e} [V]

→ no load current - i_0 [%]

→ short-circuit voltage - u_{sc} [%]

→ secondary current - $I_{2ef} = \frac{S_T}{\sqrt{3}\,U_{2e}}$

→ primary current

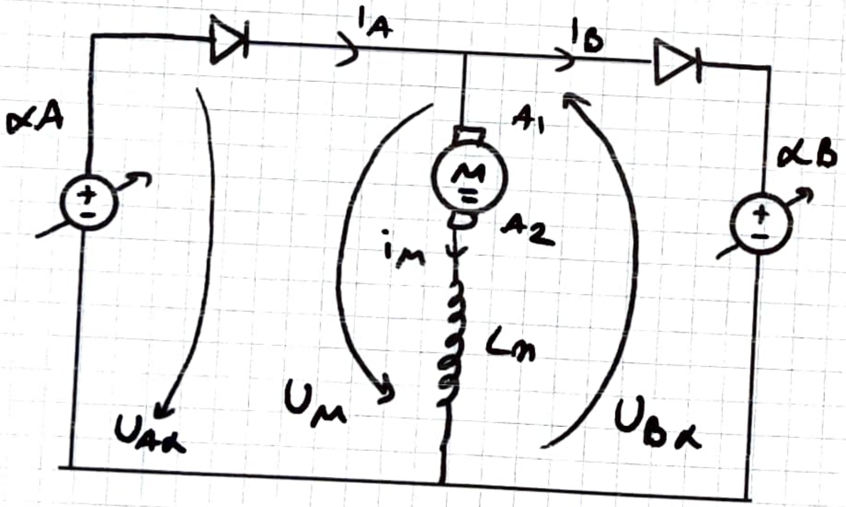
→ delta-star connection

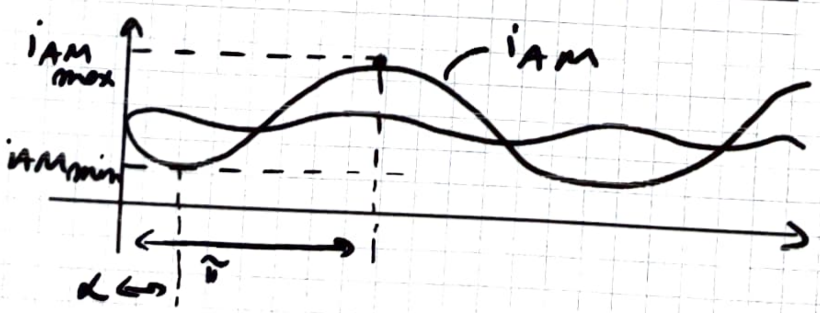
$$L_{m1} = \underbrace{K_{1L}}_{0,3} \frac{U_{A0}}{\underbrace{K_{1i}}_{0,05} \cdot i_{Am}}$$

$$L_{m2} = \underbrace{K_{2L}}_{0,13} \frac{U_{A0}}{\underbrace{K_{2i}}_{0,17} \cdot i_{Am}}$$

→ we can either avoid the interrupted current or we can diminish the harmonics

$L_m = \max(L_{m1}; L_{m2})$



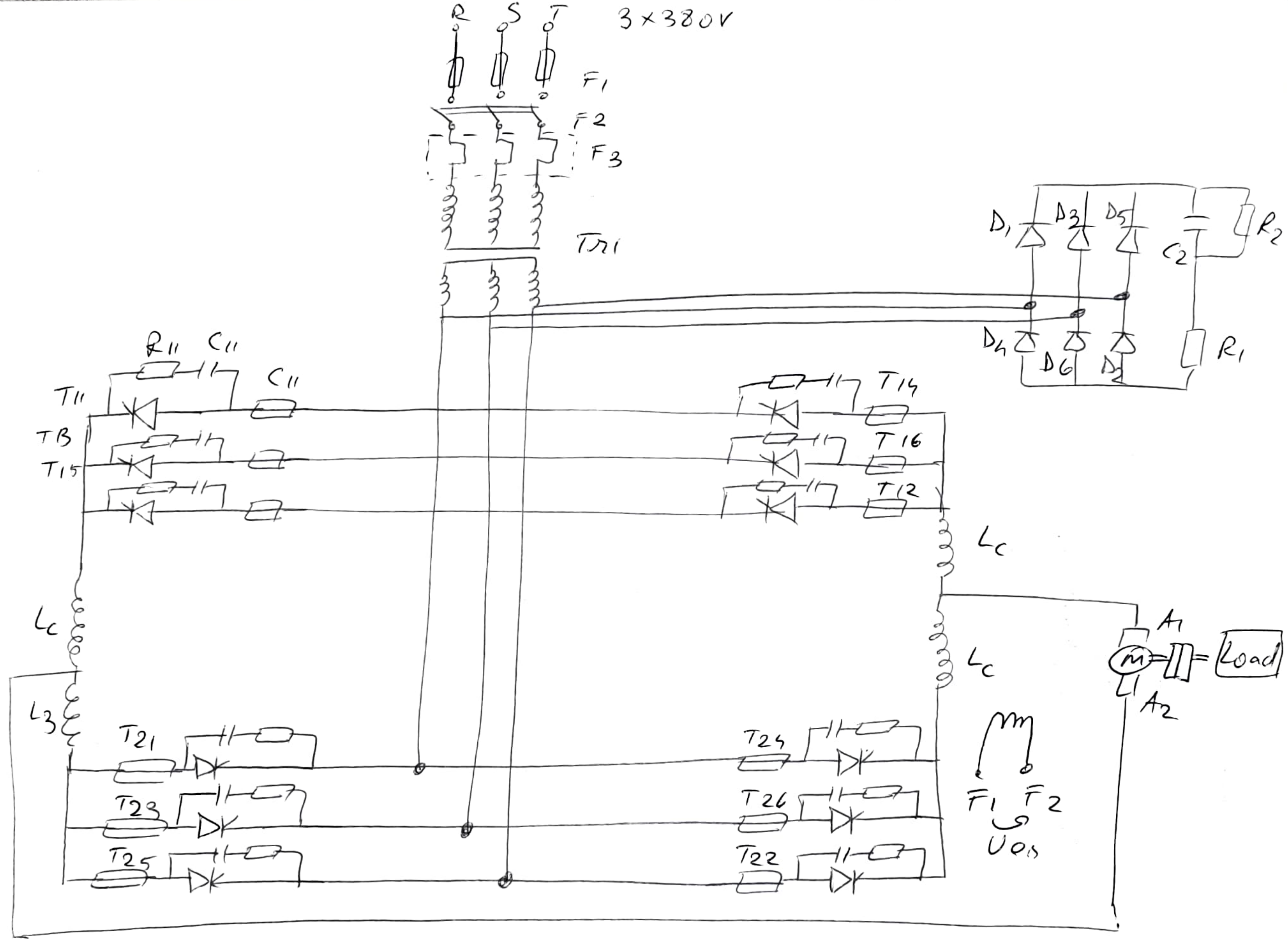


$$L_c = k_{i_{c1}} \cdot \frac{U_{A0}}{k_{i_{c2}} \cdot i_{Am}} = 1{,}09 \cdot \frac{568{,}75}{0{,}1 \cdot 12{,}4} = \frac{619{,}9266}{1{,}24}$$

$$k_{i_{c1}} = 1{,}09 \qquad k_{i_{c2}} = 0{,}1$$

$$= 499{,}94\ A$$

$$i_{Lc-\text{long regime}} = 1{,}3 \cdot i_{Am}$$



R
S
T
3×380V
F1
F2
F3
Tr1
D1
D3
D5
R2
C2
D4
D6
D2
R1
R11
C11
C11
T11
TB
T15
T14
T16
T12
Lc
Lc
Lc
L3
A1
A2
M
Load
T21
T23
T25
T24
T26
T22
F1
F2
Uos