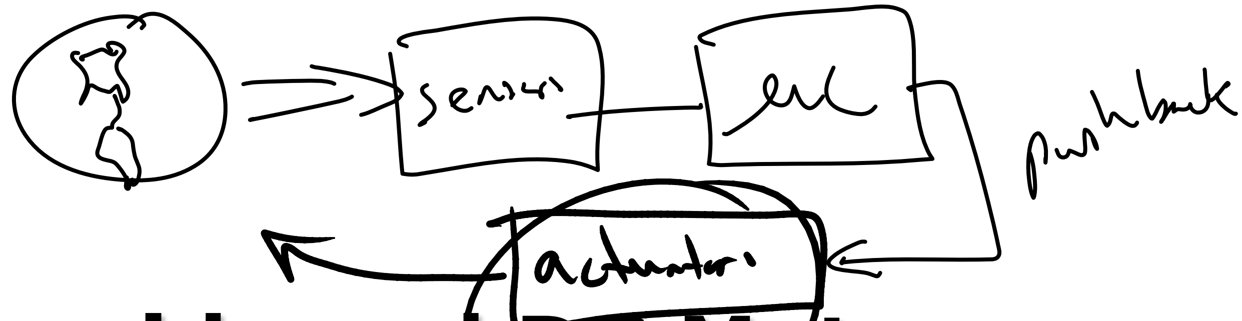
Electromechanical actuators



Solenoids and DC Motors

Cyrus Bazeghi

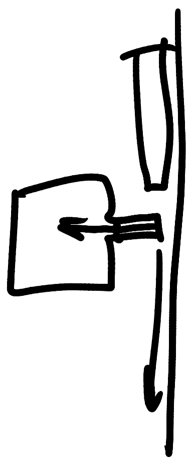
Winter 2010

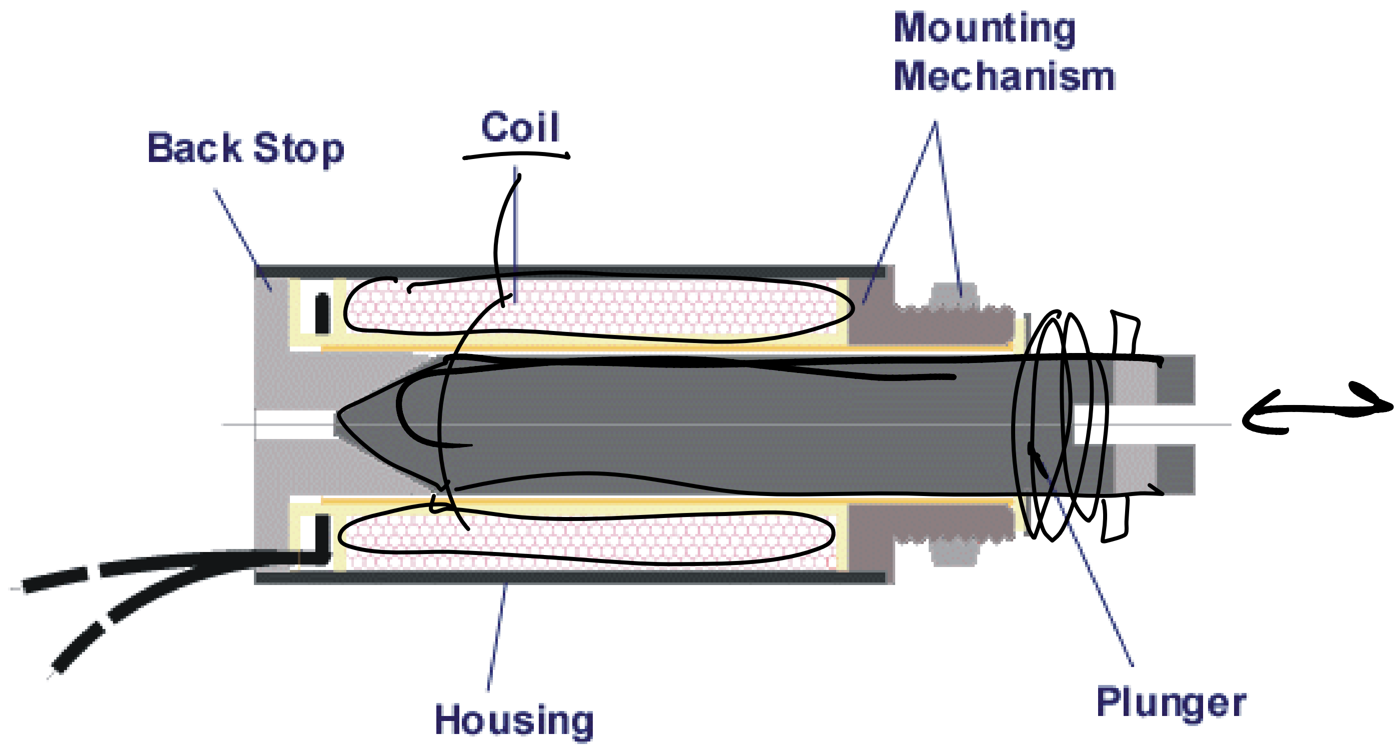
Solenoids and DC Motors

- What they are
- How they work
- Snubbing
- Why you have to

Solenoids

Cheap & simple

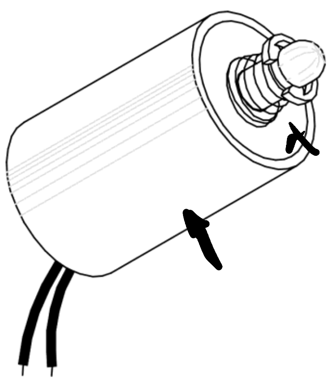




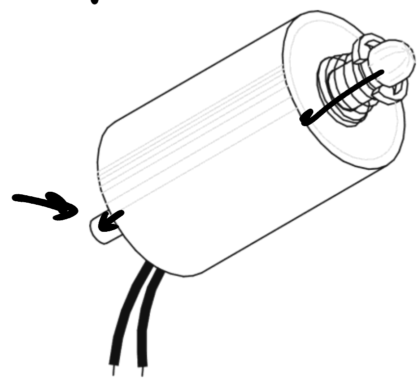
ferrous
metal

Common Solenoid Types

Pull type

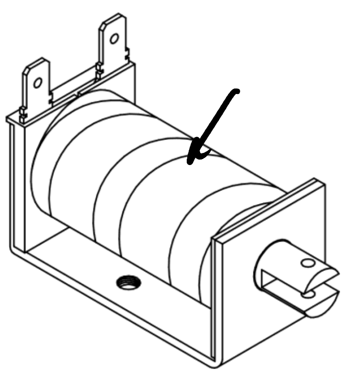


push type

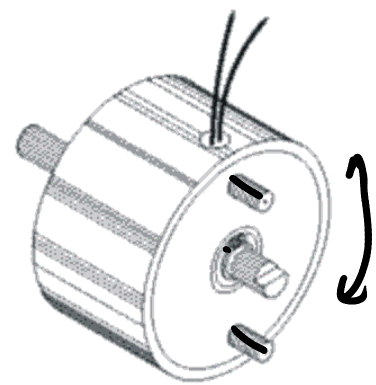


open frame

cheap $0.50

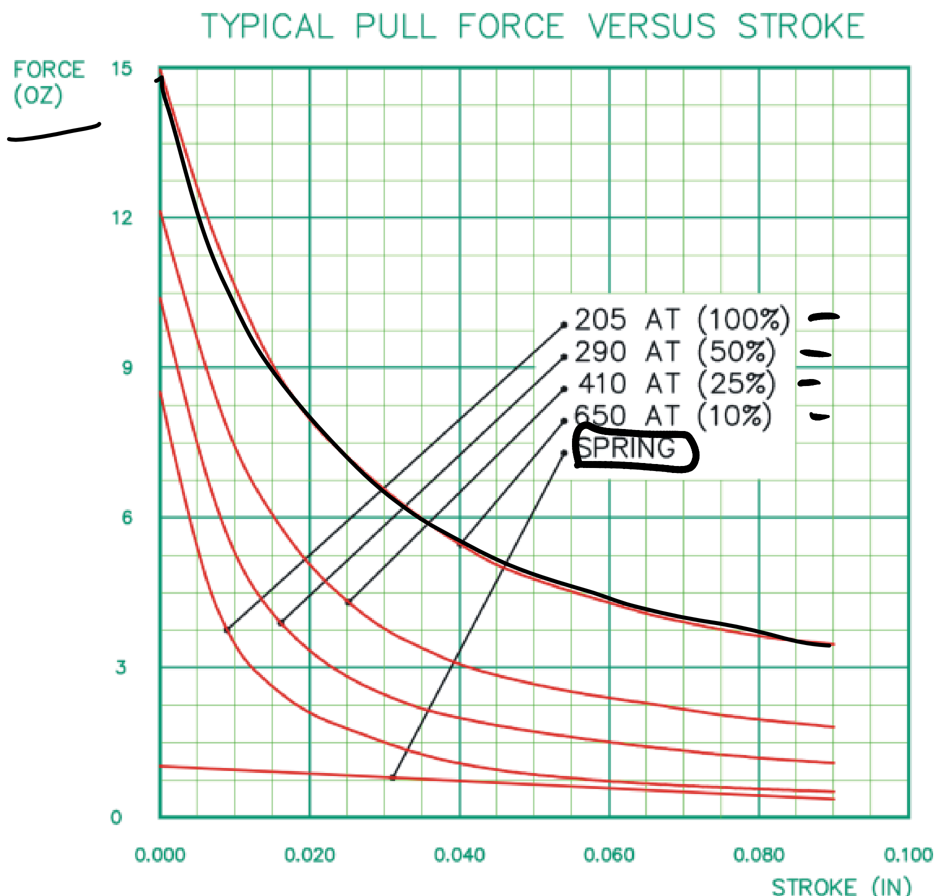


Rotary



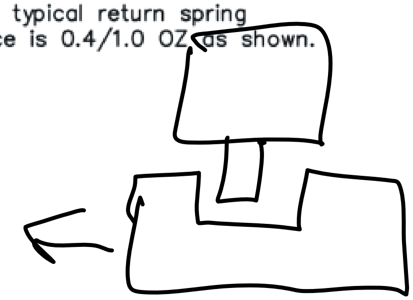
90°

Solenoid Characteristics



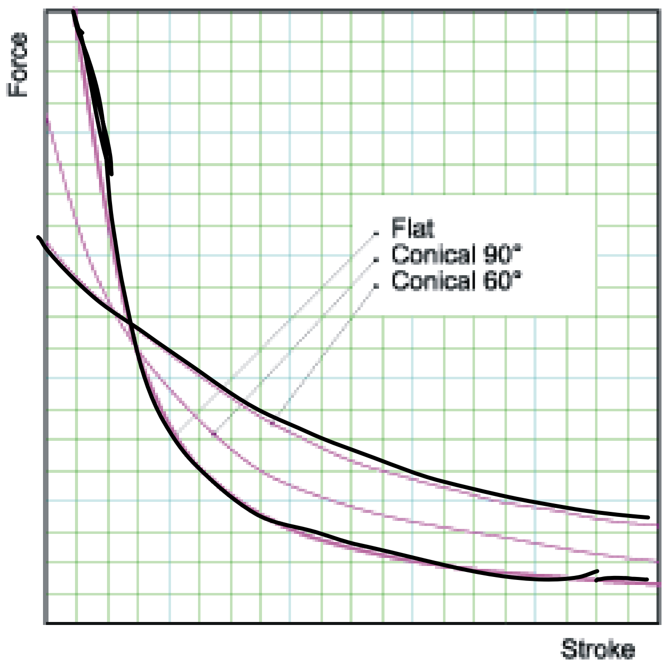
These force curves do not account for return spring.

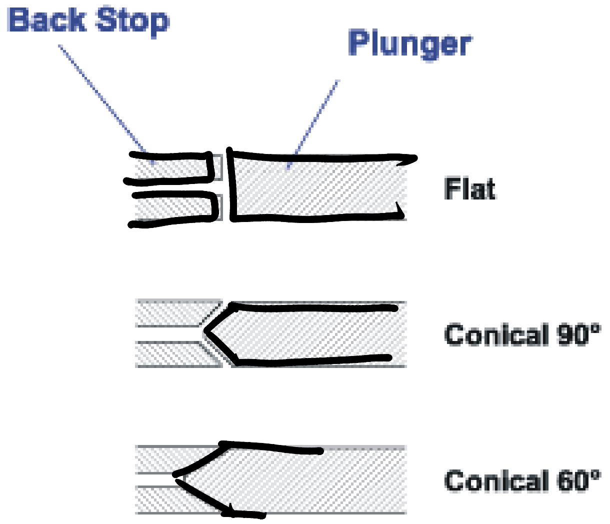
The typical return spring force is 0.4/1.0 OZ as shown.



Not pulling a lot

Design and Stroke vs. Force





Typical Solenoid Spec.'s

duty cycle	1	1/2	1/4	1/10
maximum "ON" time, (Sec.)	∞	25	6	0.5
watts	2	4	8	20
approximate ampere turns	205	290	410	650

Ω

AWG number	resistance	volts DC	volts DC	volts DC	volts DC
27	0.39	0.9	1.3	1.8	2.8
28	0.52	1.1	1.5	2.1	3.4
29	0.69	1.2	1.7	2.5	3.9
30	1.43	1.6	2.3	3.3	5.2
31	1.93	2.0	2.9	4.1	6.4
32	3.20	2.5	3.6	5.0	8.0
33	5.28	3.3	4.6	6.6	10.4
34	7.43	3.9	5.5	7.8	12.4
35	12.1	4.8	6.7	9.5	15.1
36	20.8	6.2	8.8	12.4	19.6
37	30.3	7.7	10.8	15.3	24.3
38	47.8	9.5	13.4	19.0	30.1
39	88.9	13.0	18.4	26.0	41.3
40	127	15.8	22.4	31.7	50.2
41	183	19.2	27.2	38.5	61.0
42	281	24.0	33.9	47.9	76.0

$I = \frac{V}{R} = \frac{3.3}{5.28}$

$\approx .625A$

thinner

$\frac{10.4}{5.25}$ 2A

DC Motors

- provide rotary motion
- where do you find them?
  - Clock
  - phone – vibrator
  - Computer – fan
    - LED

CARS

Motors in Cars

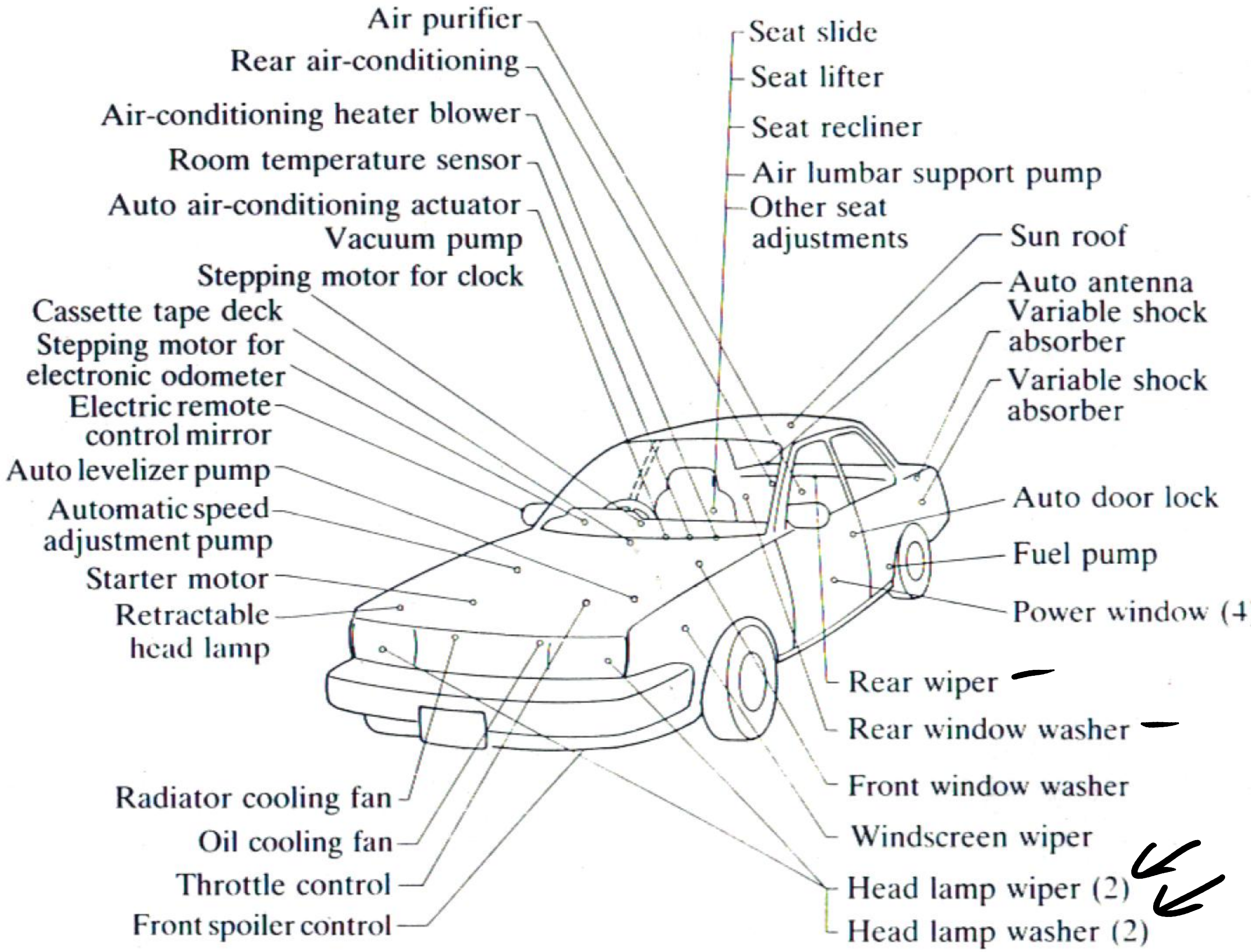


Fig. 1.1 Small motors in an automobile.

The Permanent Magnet DC Motor

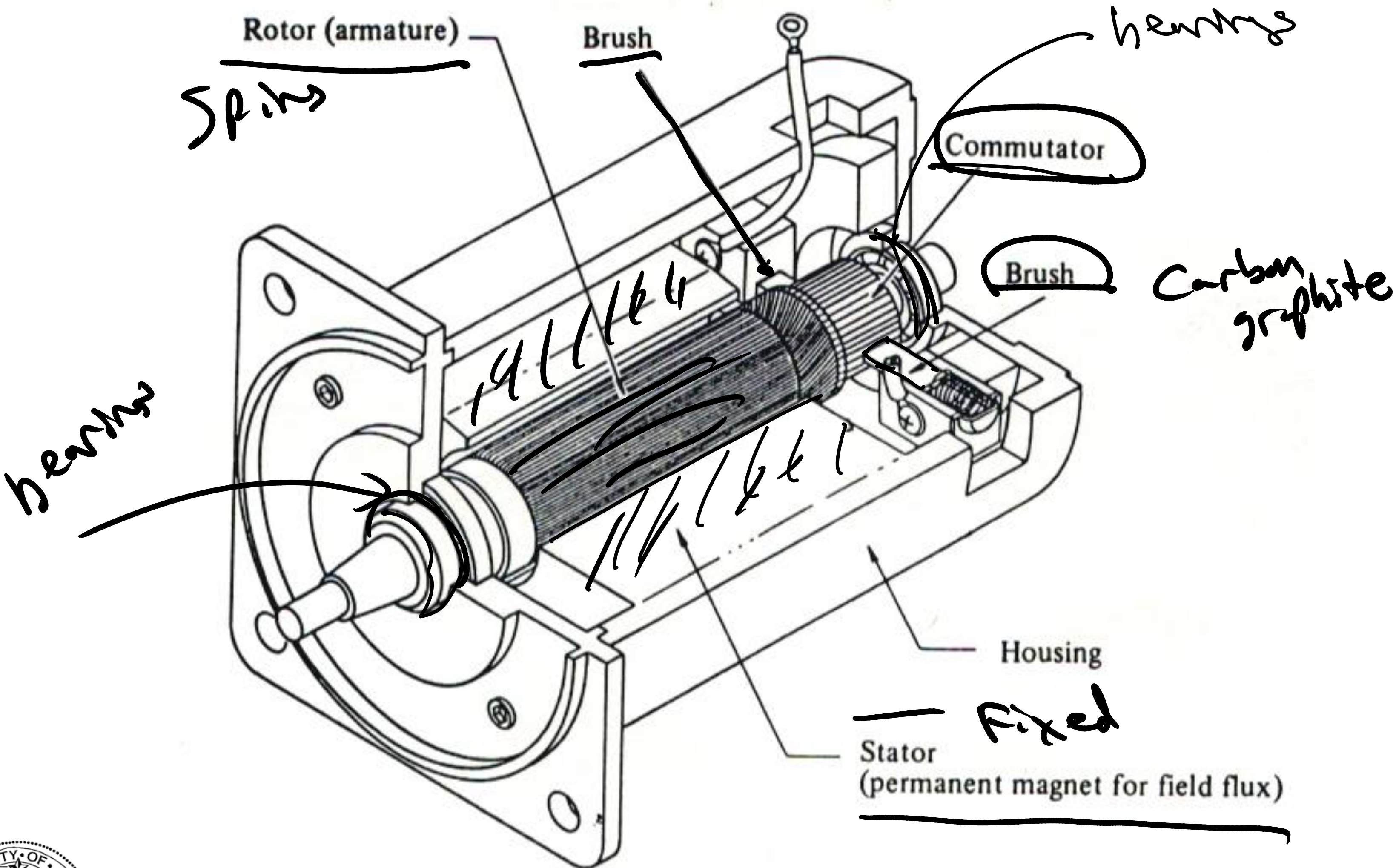


Fig. 1.1. A cutaway view of a DC motor.

Commutation

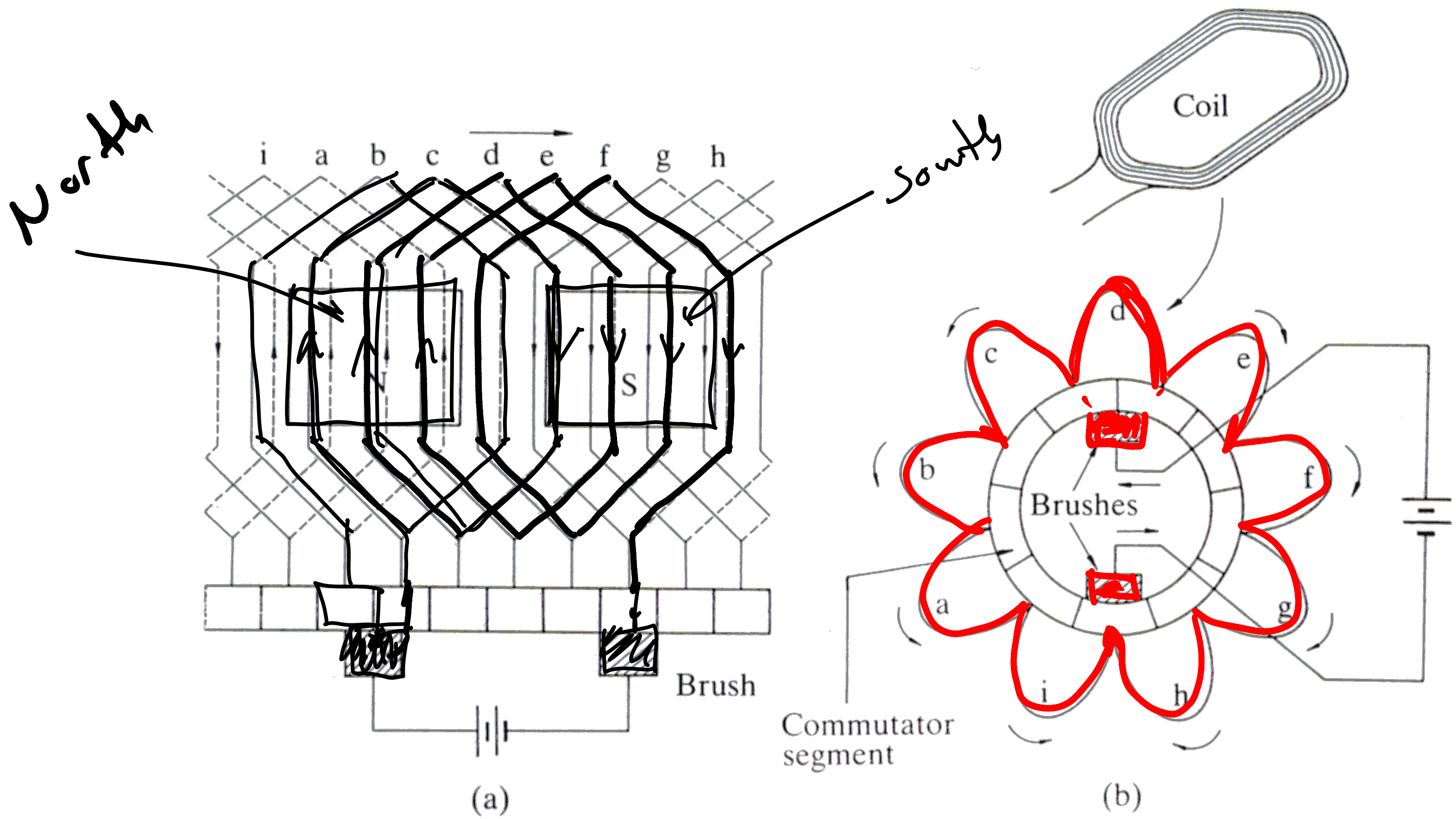


Fig. 3.37 Arrangement of coil, commutator segments, and brushes in a DC motor: (a) exploded diagram of lap winding; (b) coil connections.

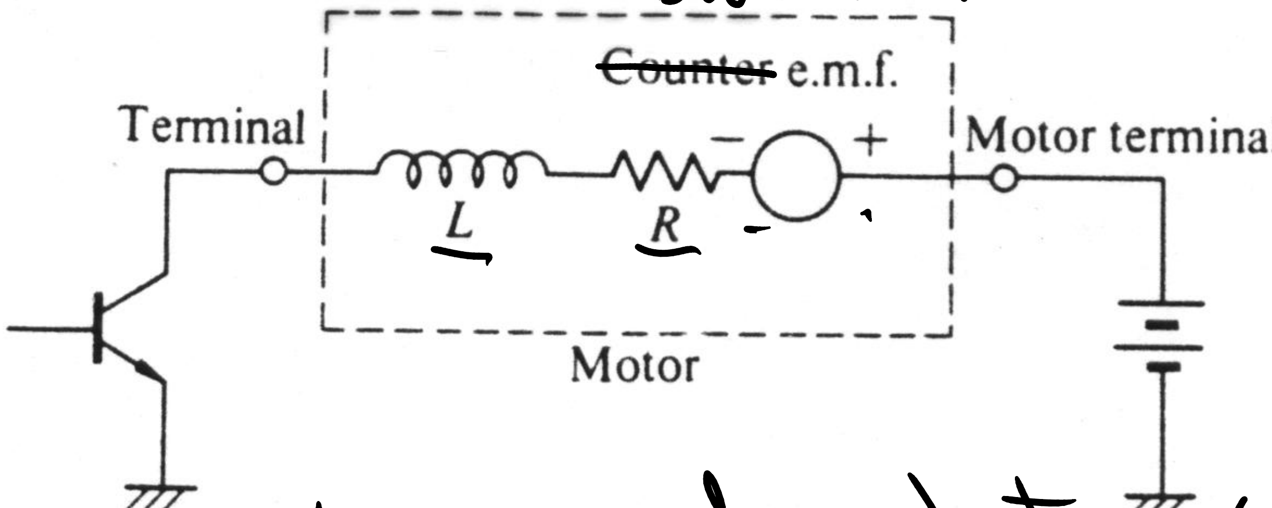
Electrical Model of a DC Motor

$$V - L\cancel{\frac{di}{dt}}^{\,0} - IR - k_e\omega = 0$$

constant

Back e.m.f

electro motive force



k_e – speed constant

S.I. $\boxed{V/\text{rad/s}}$ $\left(V/\text{krpm}\right)$

k_T – torque constant $\boxed{\frac{Nm}{A}}$ $\left(\frac{oz\cdot in}{A}\right)$

$$\boxed{T = k_T \cdot I}$$

Unit conversions

$$K_T = 9.55 \times 10^{-3} K_e$$

$\frac{Nm}{A}$ $\quad$ V/krpm

$$K_T = 1.3524 K_e$$

$\frac{oz\text{-}in}{A}$ $\quad$ V/krpm

$$K_T = K_e$$

$\frac{Nm}{A}$ $\quad$ V/rad/s

DC Motor Relationships (1.3)

$$V = IR + k_e \omega$$

$$T = k_T I$$

$$\therefore I = T/k_T$$

$$V = \frac{T}{k_T} R + k_e \omega \longrightarrow \text{if } T = 0$$

$$V = k_e \omega_{NL}$$

$$\omega_{NL} = \frac{V}{k_e}$$

stall motor

$$\omega = 0$$

$$V = \frac{TR}{k_T} \quad \therefore T_{STALL} = \frac{V}{R} k_T$$

$$\frac{V}{R} \longrightarrow I$$

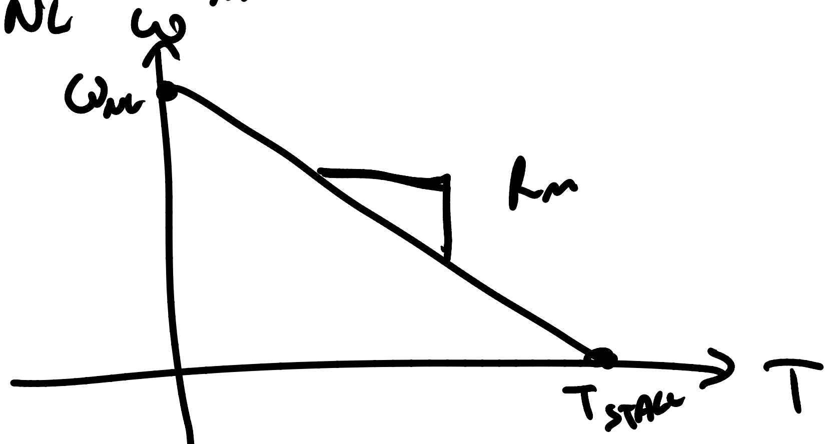
$$\boxed{T_{STALL} = I_{STALL} \cdot k_T}$$

DC Motor Relationships (2.3)

$$V = \frac{TR}{k_T} + k_e\omega \quad \therefore \quad k_e\omega = V - \frac{TR}{k_T}$$

$$\omega = \underbrace{\frac{V}{k_e}}_{\omega_{NL}} - \frac{TR}{k_e k_T} \rightarrow \omega = \omega_{NL} - \underbrace{\frac{R}{k_e k_T}}_{R_m \text{ constant}} T$$

$$\omega = \omega_{NL} - R_m T$$



DC Motor Relationships (3.3)

$$P = T\omega = T(\omega_{NL} - R_m T) \qquad \omega_{NL} = \frac{V}{k_e}$$

$$P = \frac{VT}{k_e} - R_m T^2 \qquad @\ T \triangleq T_0 \text{ constant torque}$$

$$P_1 = VA - B \qquad @1V \quad A, B \text{ constants}$$

$$P_2 = 3VA - B \qquad @3V$$

$$\Delta P = 2VA$$

so $\Delta P \propto \Delta V$ @ constant Torque

[P,V] @ Constant Torque?

$$P = \frac{TV}{k_e} - R_m T^2 \longrightarrow \frac{dP}{dT} = 0$$

$$= \frac{V}{k_e} - 2R_m T$$

$$\frac{V}{k_e} = 2R_m T$$

$$T_{peak} = \frac{V}{2k_e R_m} =$$

$$= \frac{V}{2\cancel{k_e}\frac{R}{\cancel{k_e}k_T}} = \frac{1}{2}\underbrace{\frac{V}{R}k_T}_{T_{STALL}}$$

$$\boxed{T_{peak} = \frac{1}{2}T_{STALL}}$$

DC Motors: P_{max}

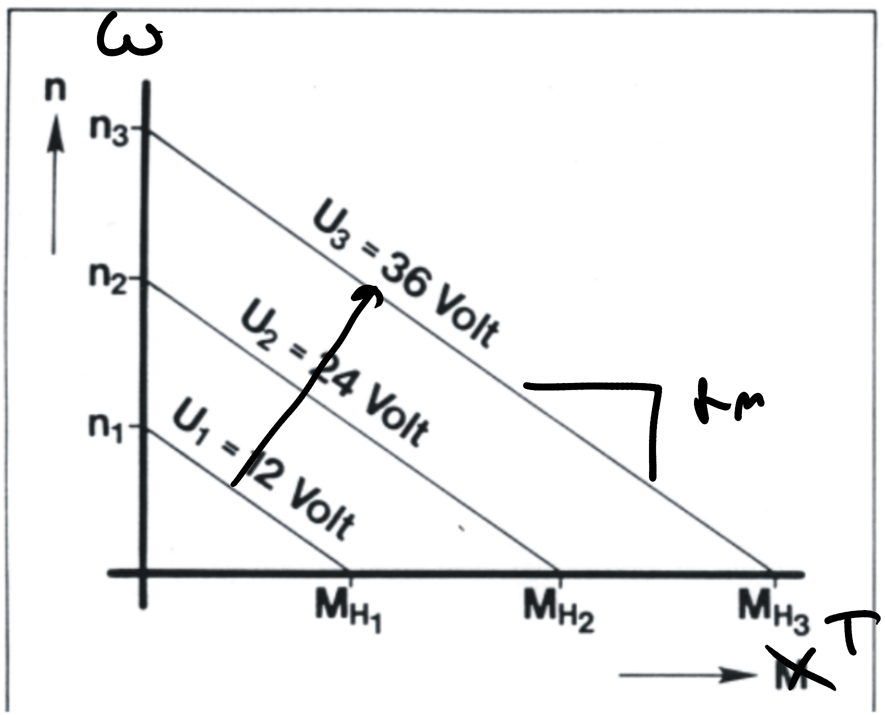
$$P_{max} = \frac{V}{K_e}\underbrace{\left(\frac{V}{2K_eR_m}\right)}_{T_{peak}} - R_m\underbrace{\left(\frac{V^2}{4K_e^2R_m^2}\right)}_{T_{peak}^2}$$

$$= \frac{V^2}{K_e^2 2R_m} - \frac{V^2}{K_e^2 4R_m} = \frac{V^2}{4K_e^2R_m}$$

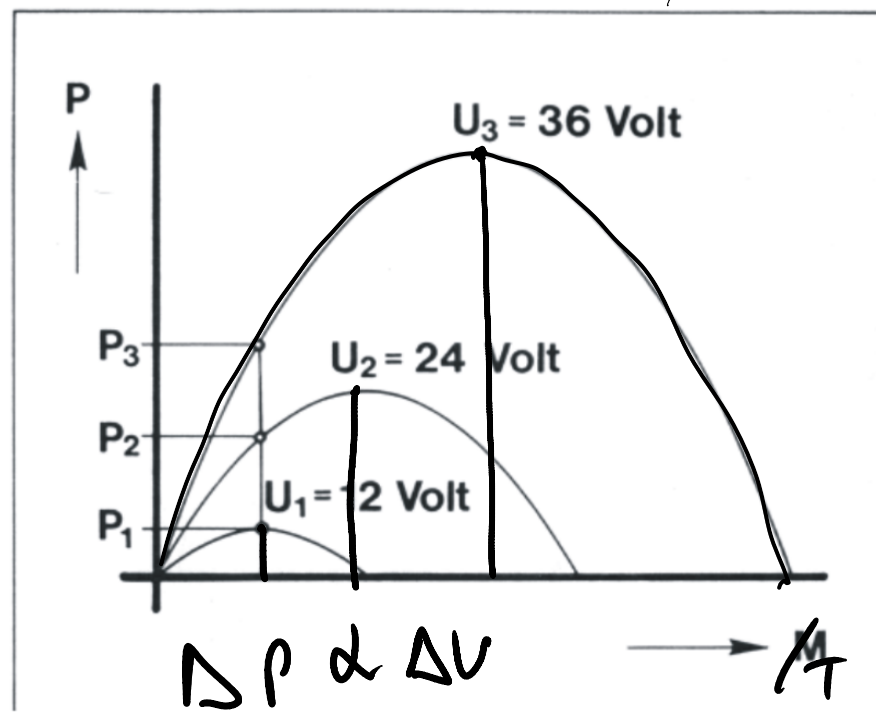
$$P_{max} = \frac{1}{4}\underbrace{\left(\frac{V}{K_e}\right)}_{\omega_{NL}}\underbrace{\left(\frac{V}{K_eR_m}\right)}_{T_{STALL}} = \frac{1}{4}\omega_{NL}T_{STALL}$$

DC Motor Graphs

Torque vs. Speed



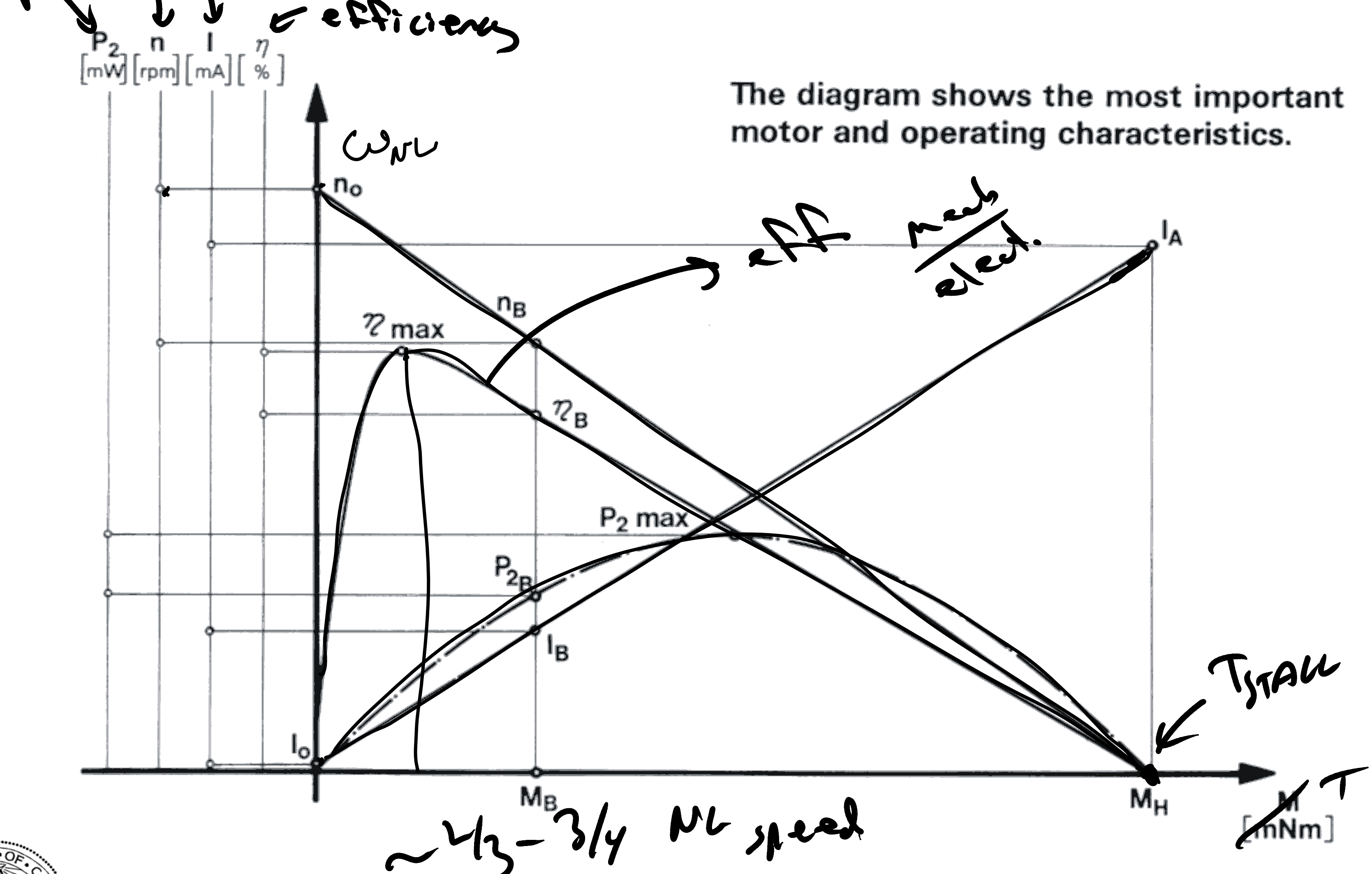
power vs. torque



$\Delta P \propto \Delta V$

Torque vs. Everything

The diagram shows the most important motor and operating characteristics.



DC Motor Spec.'s

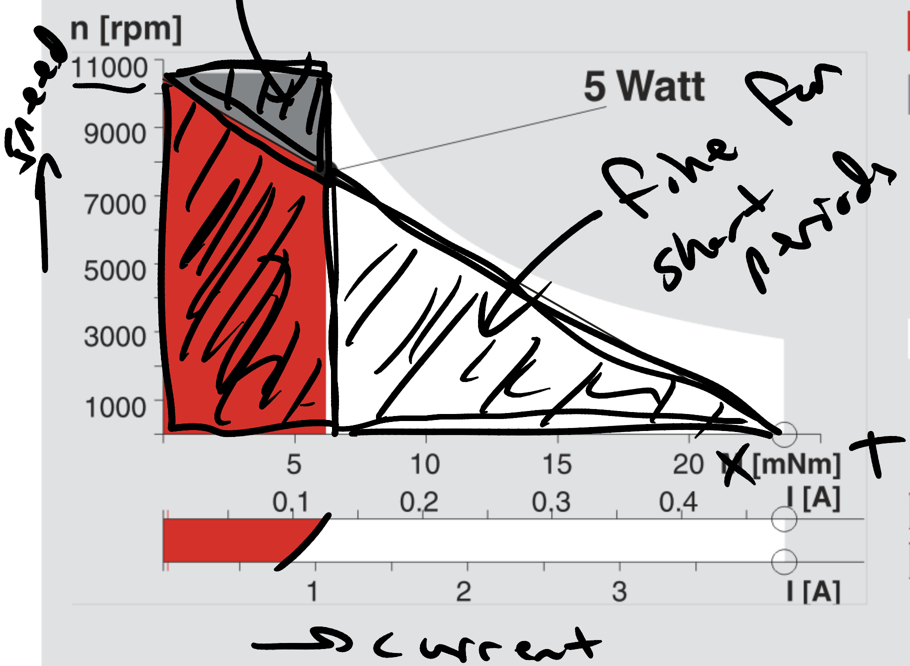
Max speed

	Winding number		930	933	934	948	936	944	937	938	945
Motor Data											
1	Assigned power rating	W	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
2	Nominal voltage	Volt	3.0	7.2	9.0	12.0	12.0	12.0	15.0	18.0	18.0
3	No load speed	rpm	5080	9270	9460	10700	8110	7770	8460	8240	8010
4	Stall torque	mNm	20.9	42.5	45.7	51.7	42.7	35.1	44.4	43.0	38.0
5	Speed/torque gradient	rpm/mNm	260	225	213	211	194	227	194	195	215
6	No load current	mA	114	101	83	73	50	47	42	34	33
7	Starting current I STALL	mA	3960	5910	5160	4920	3090	2440	2680	2100	1810
8	Terminal resistance	Ohm	0.757	1.22	1.74	2.44	3.88	4.92	5.60	8.56	9.96
9	Max. permissible speed	rpm	11000	11000	11000	11000	11000	11000	11000	11000	11000
10	Max. continuous current	mA	1500	1500	1440	1220	972	865	809	656	609
11	Max. continuous torque	mNm	7.92	10.8	12.7	12.8	13.4	12.4	13.4	13.4	12.8
12	Max. power output at nominal voltage	mW	2460	9620	10800	13900	8770	6920	9590	9070	7780
13	Max. efficiency	%	64	73	75	76	75	74	76	76	75
14	Torque constant	mNm/A	5.28	7.19	8.85	10.5	13.8	14.4	16.6	20.5	21.0
15	Speed constant	rpm/V	1810	1330	1080	909	691	664	576	467	455
16	Mechanical time constant	ms	29	22	20	19	18	18	18	18	18
17	Rotor inertia	gcm^2	10.8	9.23	9.07	8.68	9.07	7.76	8.84	8.63	7.87
18	Terminal inductance	mH	0.07	0.12	0.18	0.26	0.45	0.48	0.64	0.98	1.03
19	Thermal resistance housing-ambient	K/W	17	17	17	17	17	17	17	17	17
20	Thermal resistance rotor-housing	K/W	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
21	Thermal time constant winding	s	7	6	6	6	6	5	6	6	5

bearing limitation

Operating Ranges

Operating Ranges | Comments | Example from page 113



Recommended operating range

Continuous operation
In observation of above listed thermal resistances (lines 19 and 20) the maximum permissible rotor temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit

Short term operation
The motor may be briefly overloaded (recurring).

110128 Motor with high resistance winding (Line 8)

110117 Motor with low resistance winding (Line 8)

Speed (n), torque (M), current (I):
The outer edges of the values depicted represent limits for continuous and short term motor operation. Values listed in the tables (lines 3, 4, 6, 7, 12 and 13) are valid for operation at nominal voltage (line 2). These are therefore values which are only reached when operating the motor at higher voltages

- ● Assigned Power Rating P_{2T} (W) (Line 1)
- ○ Starting current I_A at nominal voltage (Line 7) as well as related stall torque

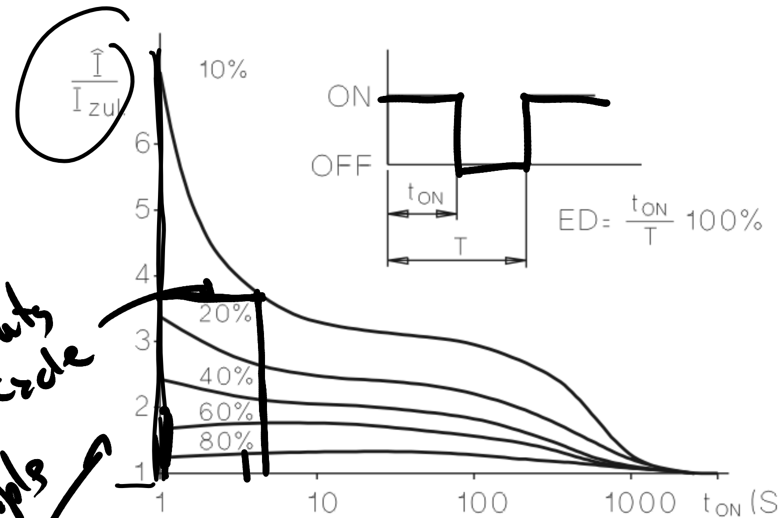
M_H (mNm) (Line 4) $I_A = \frac{U}{R} \cdot 10^3$ (mA)

110128 Winding number with the related current curve at the appropriate torque.

Defining "Short Term Operation"

Short Term Operation

Duty cycle



duty cycle

multiples of current

3 ways heat is realied

1 – through brushes
2 – bearings
3 – air flow

ON	Motor in operation
OFF	Motor inoperative
$\hat{I}$	max. peak current
$I_{cont.}$	max. permissible continuous current Line 10
t_{ON}	ON time
T	cycle time $t_{ON} + t_{OFF}$
DCy	Duty Cycle in percent of the Cycle Time T. The motor may be overloaded by the relationship $\hat{I}/I_{cont.}$ during X% of the total Cycle Time.

An example problem (1.2)

- You have been assigned to follow up on the design of a former employee who had not taken CMPE-118.
- Your supervisor suspects that they didn't know what they were doing.
- The only documentation that you can find shows that the motor chosen has Kt = 9.33 in.-oz./A and produces 2.8 in.-oz. at stall when driven at 12V.
- The design requires that the motor deliver 0.4 in.-oz. at 1500 rpm.
- The motor was supposed to be driven from a 12V supply and switched by a ULN2003. Your boss has asked you:

An example problem (2.2)

1. How can I find out how much current the motor will draw at stall ? $I_{STALL} = 300mA$
2. Can the ULN2003 safely switch the required current? allows 325mA if only 1 device used.
3. How can I find the NL Speed ? $\omega_{NL} = 1739 rpm$
4. How can I find the coil resistance ? 40Ω
5. How can I find the torque at a given speed ? $T=f(\omega)$
6. Will the design meet the requirements for torque & speed? If not, what changes could you suggest? $V=15V$
7. To estimate the current required when running at the design point.
8. You may assume that there are no internal losses within the motor.
9. $K_T = 1.3524 KE$ [oz-in/A ; V/krpm]

ULN2003A Specifications (2.2)

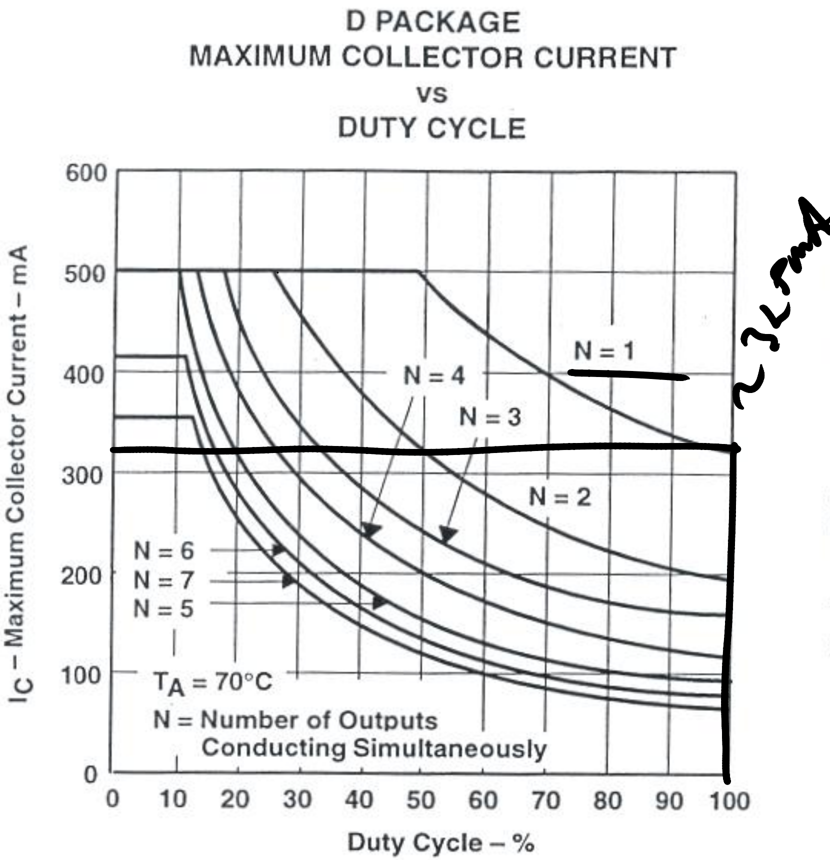


Figure 14

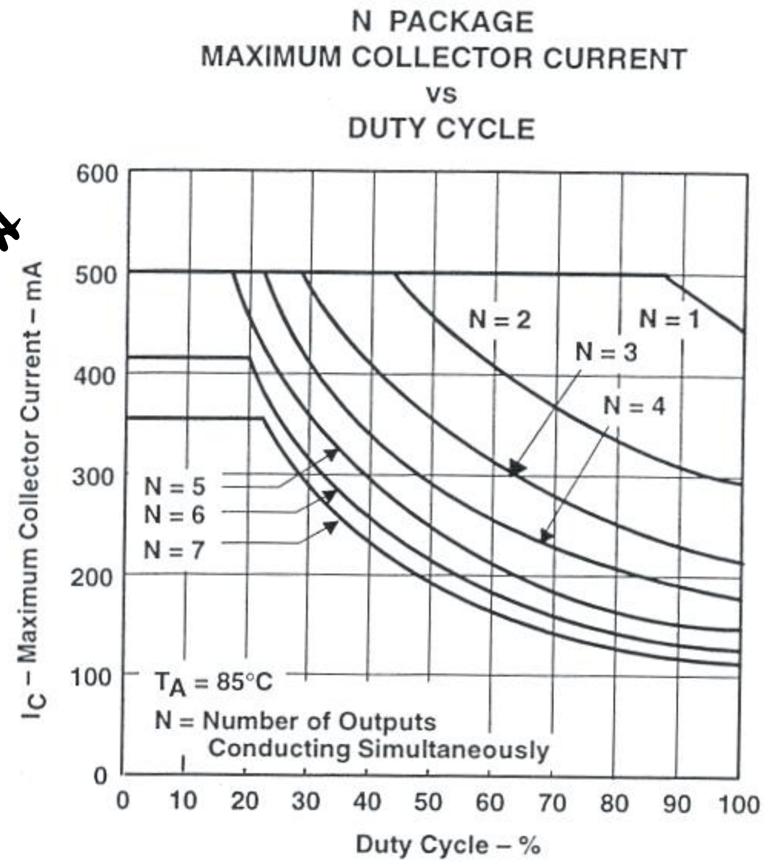


Figure 15

Motor Design Solution (1.3)

K_t = 9.33 in.-oz./A
T_{stall} = 2.8 in.-oz. ←
V_{stall} = 12V. ←
T_{req} = 0.4 in.-oz.
ω_{req} =1500 rpm.
K_T = 1.3524K_E [oz-in/A ; V/krpm]

1) $I_{STALL} = ?$

$$T = K_T I$$

$$I_{STALL} = \frac{T_{STALL}}{K_T} = \frac{2.8 \text{ in-oz}}{9.33 \frac{\text{in-oz}}{A}}$$

$$\boxed{I_{STALL} = 0.3A}$$

2) yes, barely 325 mA if always on + only 1 [illegible]

3) $\omega_{NL} = \frac{V}{K_e} = \frac{12}{9.33 \frac{\text{in-oz}}{A}} \times 1.3524$

$K_e = \frac{K_T}{1.3524} = 6.89 \frac{V}{\text{krpm}}$

$= 1.74$ krpm

$$\boxed{\omega_{NL} = 1739 \text{ rpm}}$$

Motor Design Solution (2.3)

K_t = 9.33 in.-oz./A
T_{stall} = 2.8 in.-oz.
V_{stall} = 12V.
T_{req} = 0.4 in.-oz.
ω_{req} =1500 rpm.
K_T = 1.3524K_E [oz-in/A ; V/krpm]

4) Coil resistance

$$R = \frac{V_{STALL}}{I_{STALL}} = \frac{12}{0.3} = 40\Omega$$

$$T = K_T I \qquad V = IR + k_e\omega$$

$$V = \frac{TR}{K_T} + k_e\omega \longrightarrow T = \frac{K_T V - K_e K_T \omega}{R}$$

5) $$T = \frac{K_T}{R}\left[V - K_e\omega\right] = \frac{9.33}{40}\left[12 - 6.89\,\omega\right]$$

9.33, 40, 12, 6.89, 11.2

$$\boxed{T = 2.799 - 1.607\,\omega}$$

oz-in

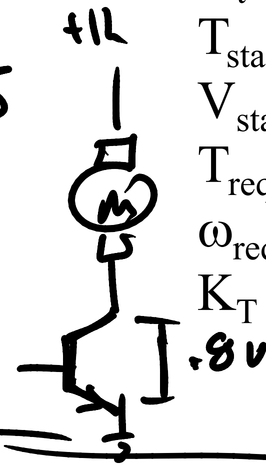
krpm

Motor Design Solution (3.3)

6) 0.4 in-oz @ 1500 rpm

$T = 2.799 - 1.607 \times 1.5$

$= 0.3885$



K_t = 9.33 in.-oz./A
T_{stall} = 2.8 in.-oz.
V_{stall} = 12V.
T_{req} = 0.4 in.-oz.
ω_{req} =1500 rpm.
$K_T = 1.3524 K_E$ [oz-in/A ; V/krpm]

$T = 0.202$ oz-in @ 11.2V

Nope, don't meet spec

$T = K_T V - K_e K_T \omega$

How to fix?

Raise voltage +15V

Motor Design Solution (3.4)

7) Current @ design point $\boxed{0.4 \text{ in-oz} \ @ \ 1500 \text{ rpm}}$

Current

$$T = k_T I$$

$$I = \frac{T}{k_T} = \frac{0.4}{9.33} = 0.043 = 43\text{mA}$$

voltage

$$T = \frac{k_T}{R}(V - k_e \omega)$$

0.4, 9.33, 40, 6.89, 1.5 krpm

$$0.4 = \frac{9.33}{40}(V - 10.34)$$

$$0.4 = 0.23325V - 2.41$$

$$V = \frac{2.81}{0.23325} = 12.05V + 0.8V = \boxed{12.85V}$$

we have 15V
1) voltage divider
2) PWM

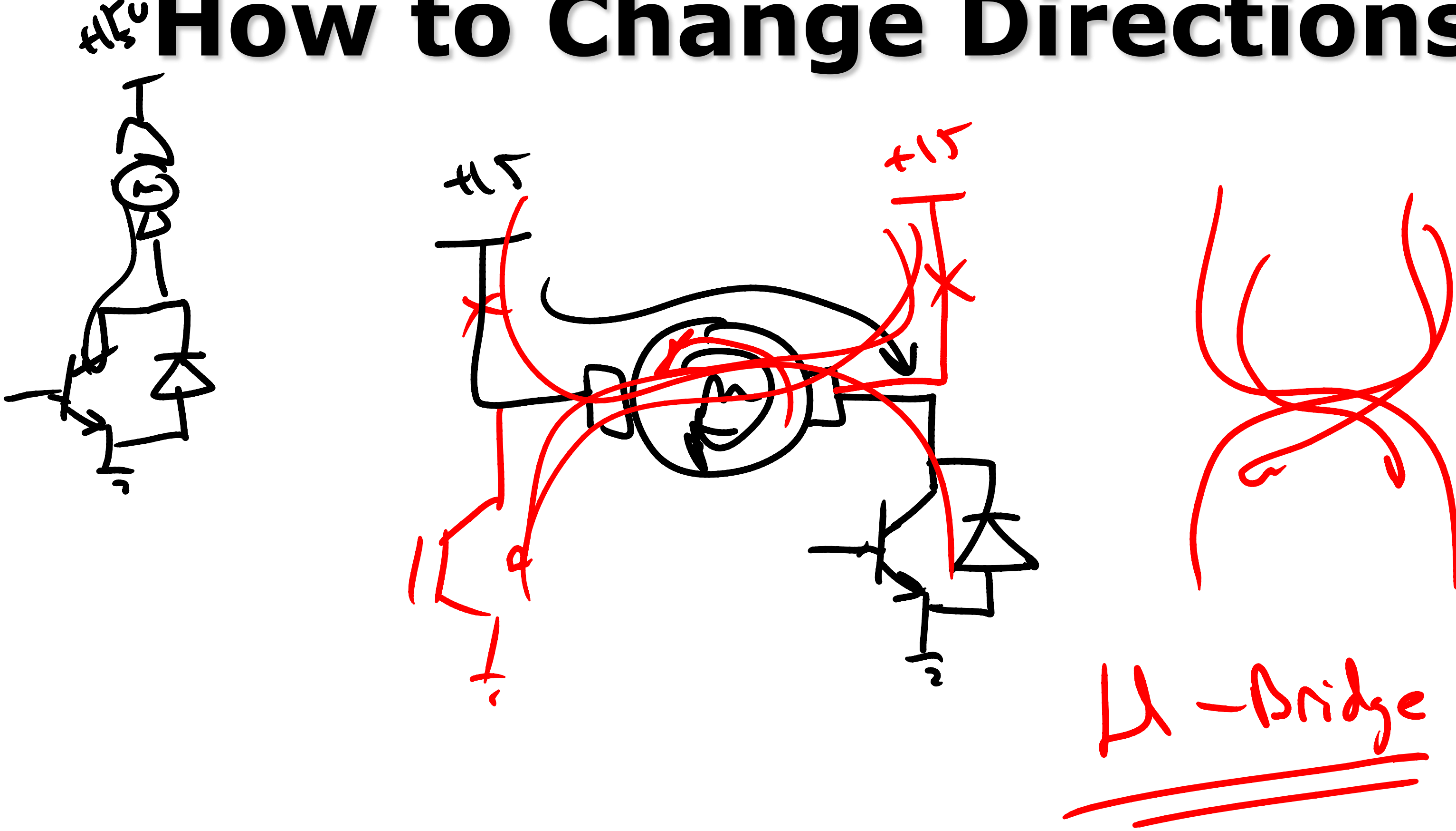
PWM

$$\frac{12.85}{15} \times 100 = \boxed{85\%}$$

Duty cycle

500Hz - 2kHz

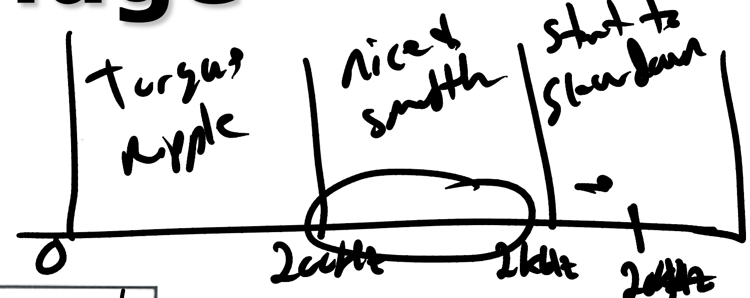
How to Change Directions

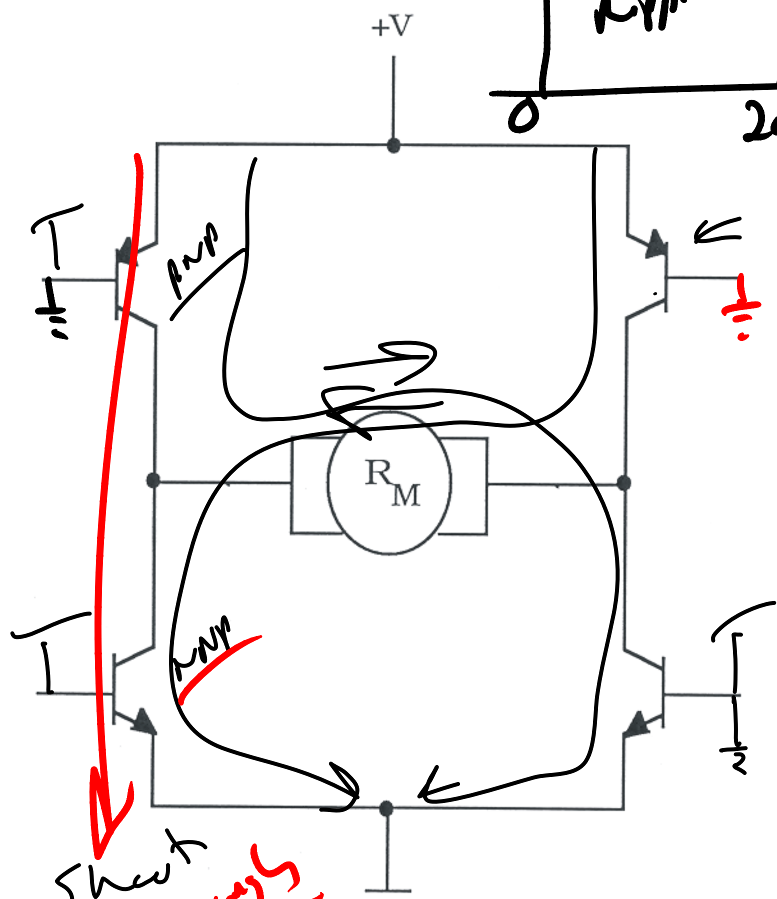


The H-Bridge

Buy a chip
1, 2, ... 5A

CTRL
DIR
ENABLE

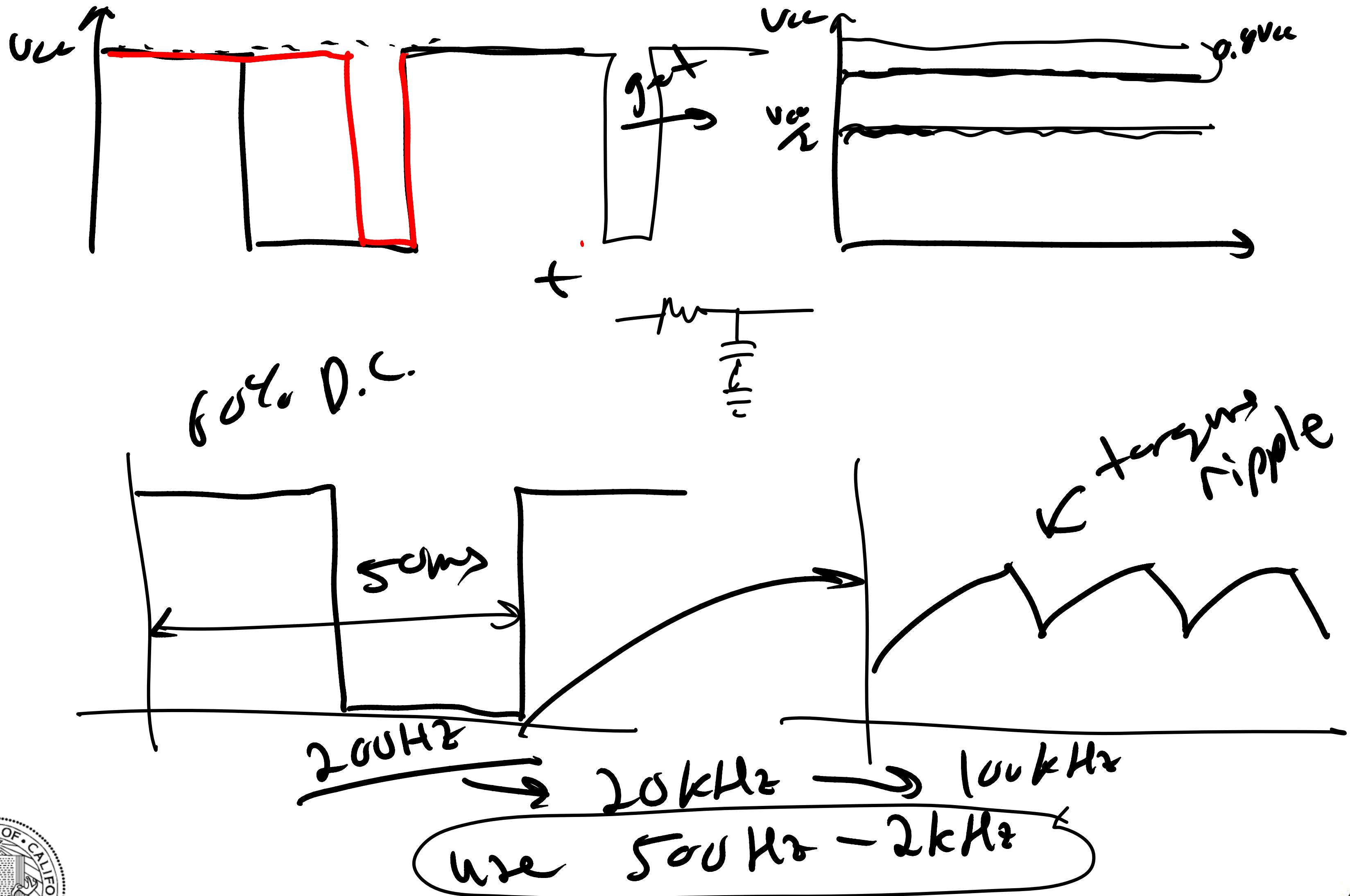




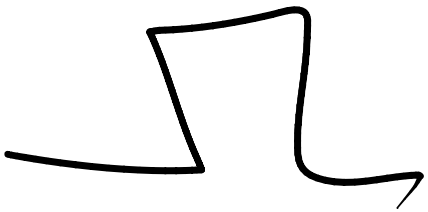
IGBT
3000V
600A

MOSFET
60-1200
60-100A

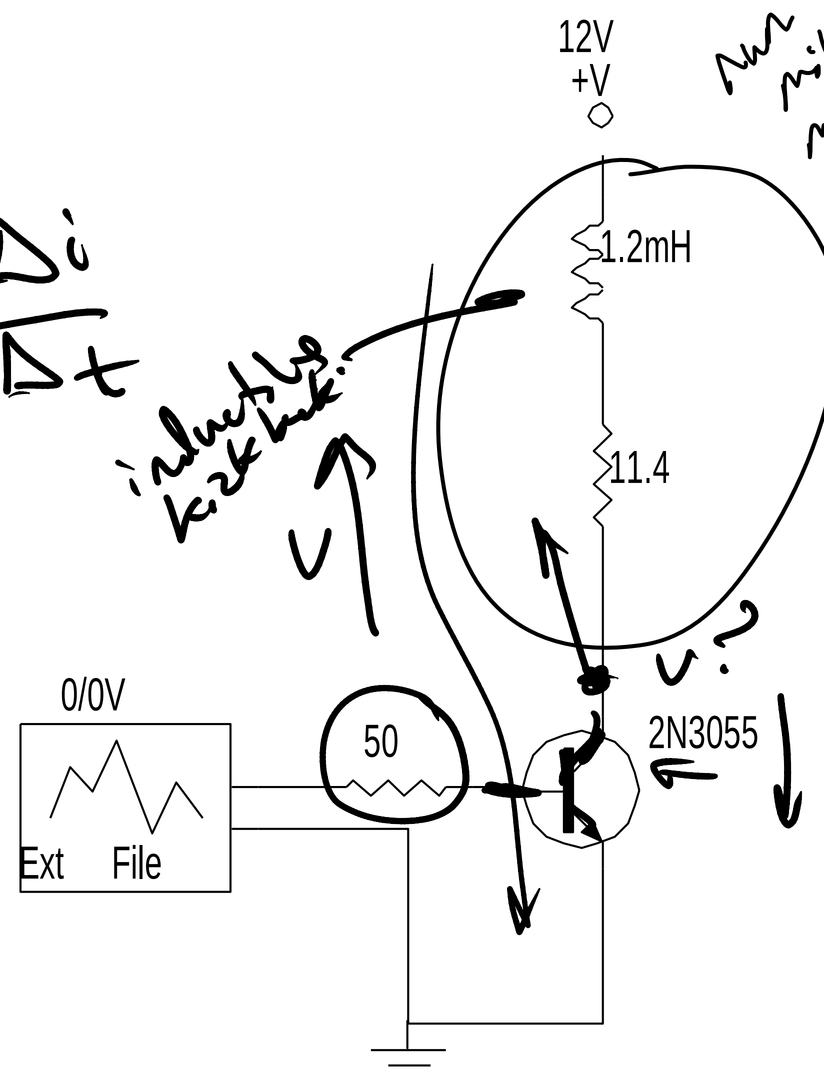
Pulse Width Modulation



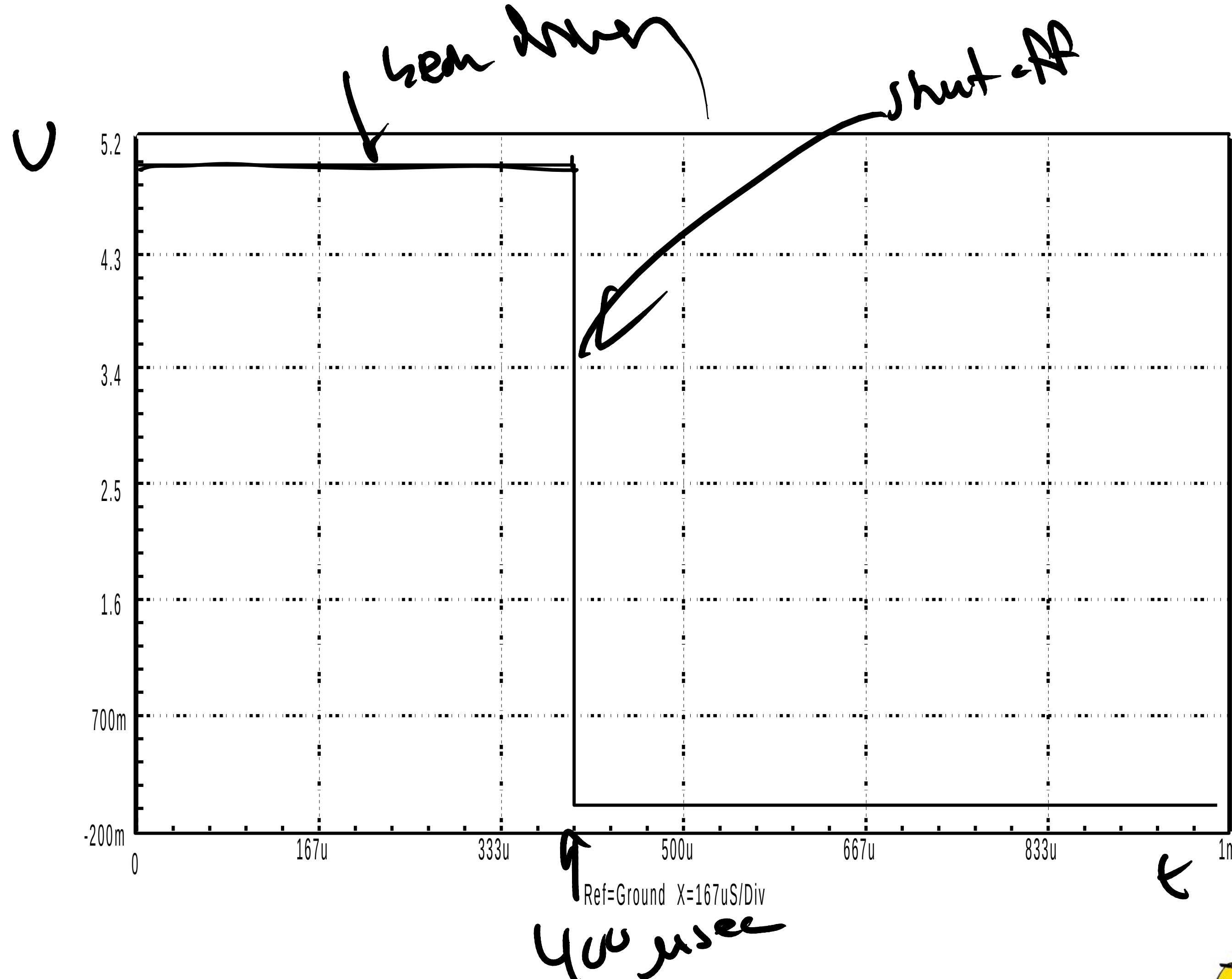
DC Motor Drive Simulation



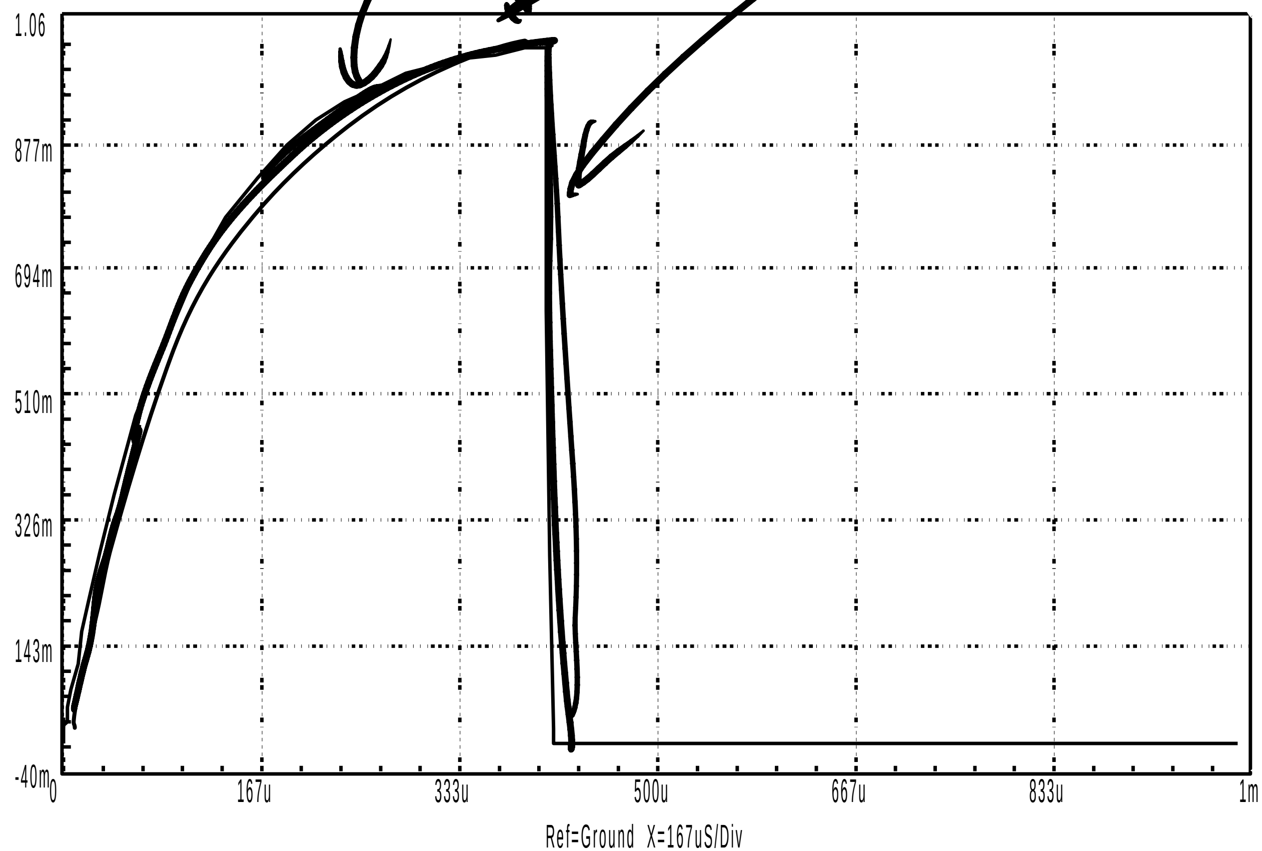
$$V = L\frac{di}{dt} \approx L\frac{\Delta i}{\Delta t}$$



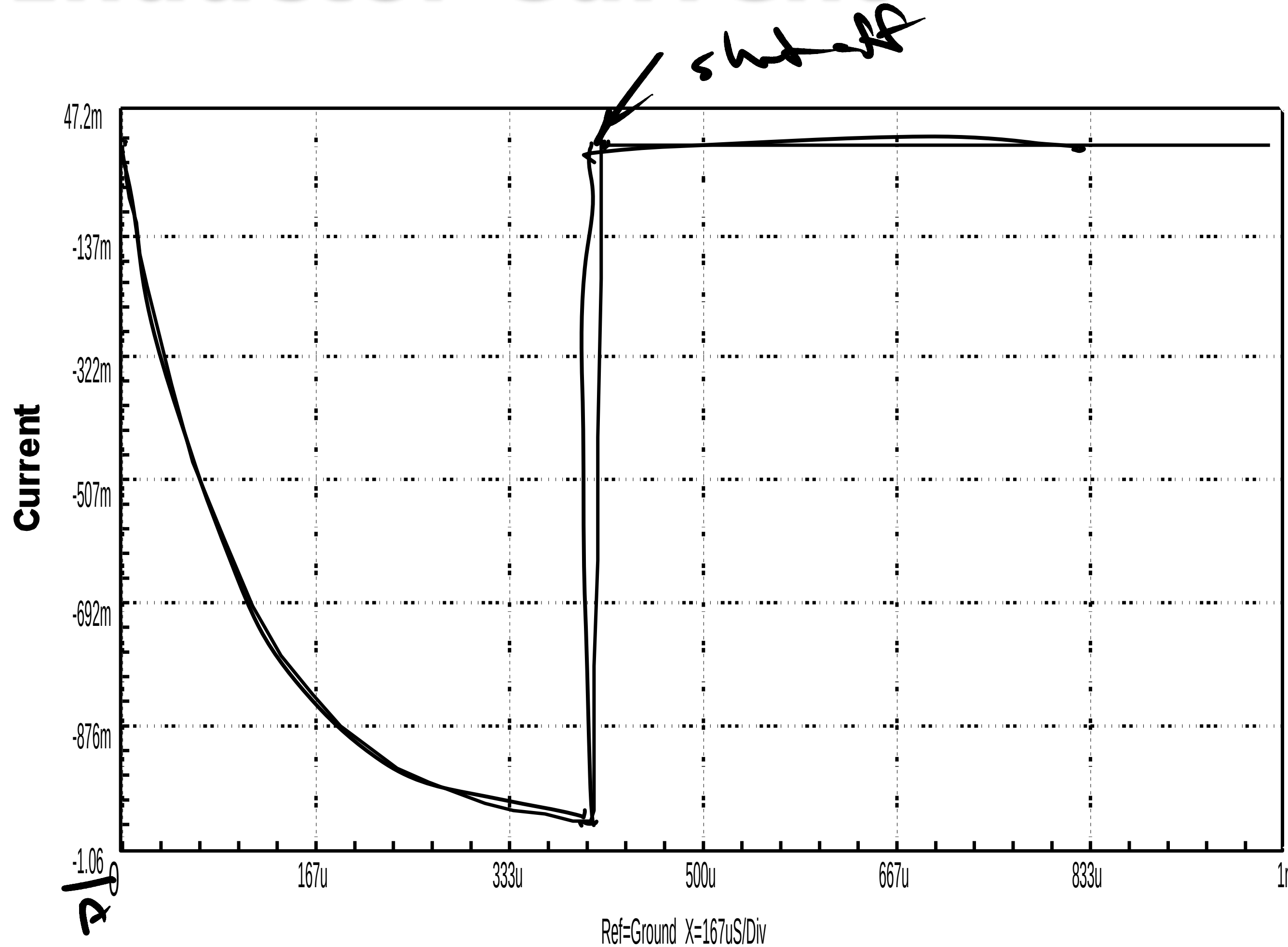
Drive Waveform



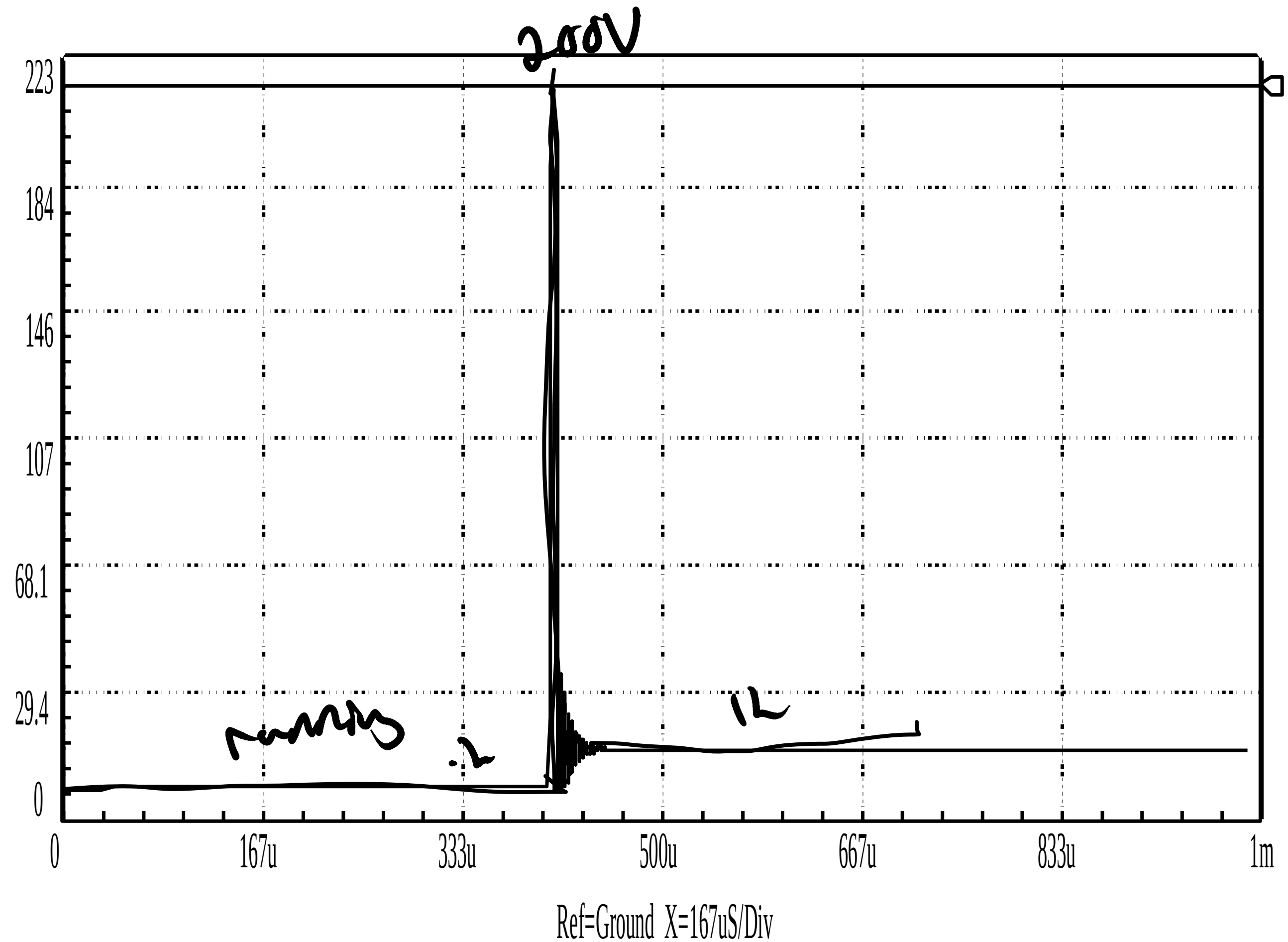
Transistor Current



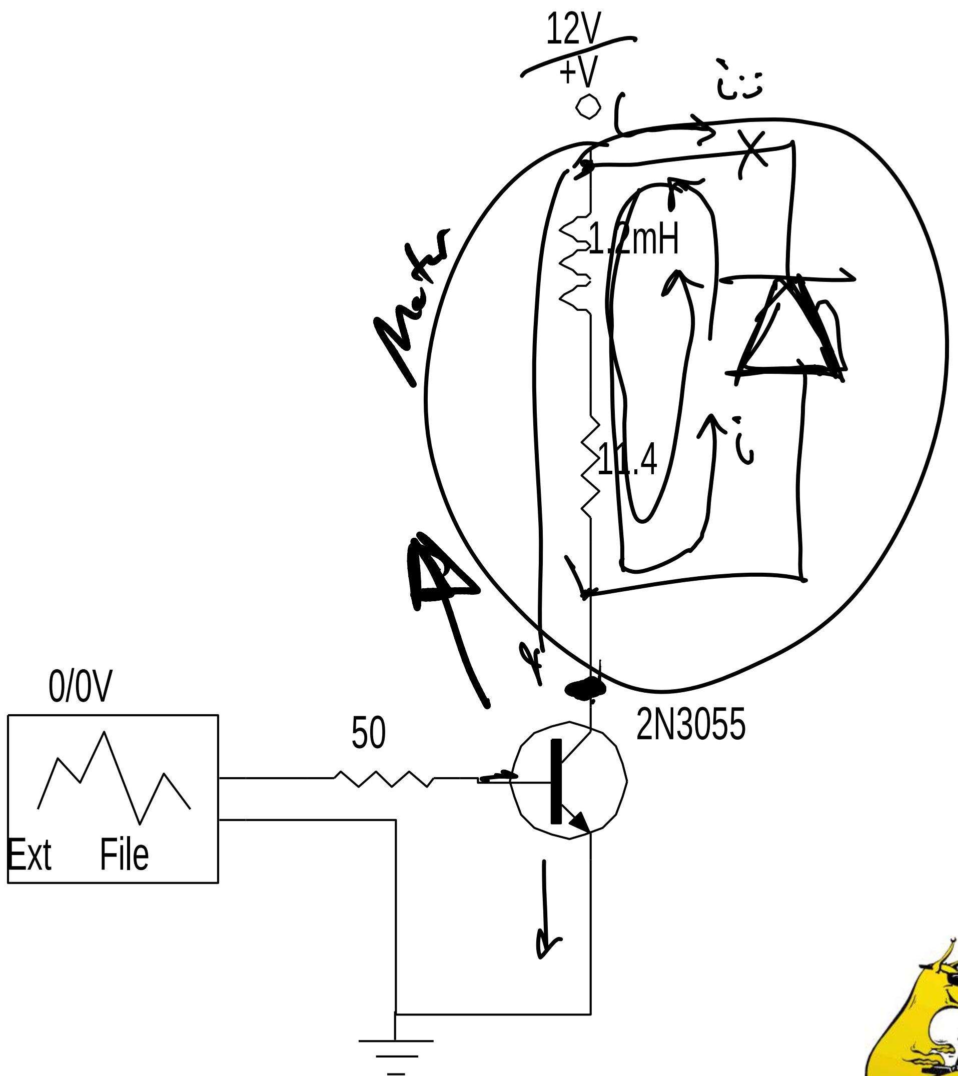
Inductor Current



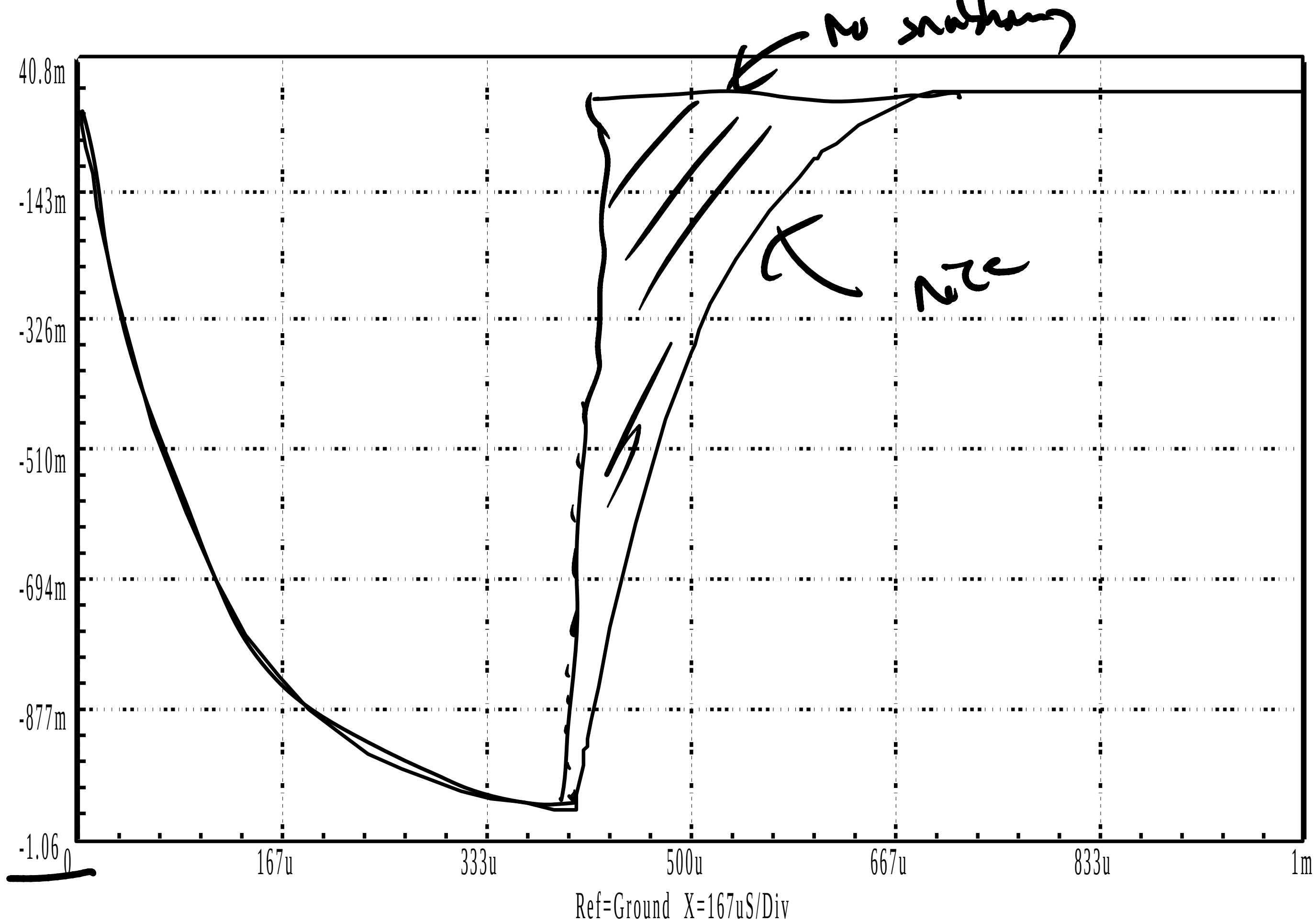
Collector Voltage



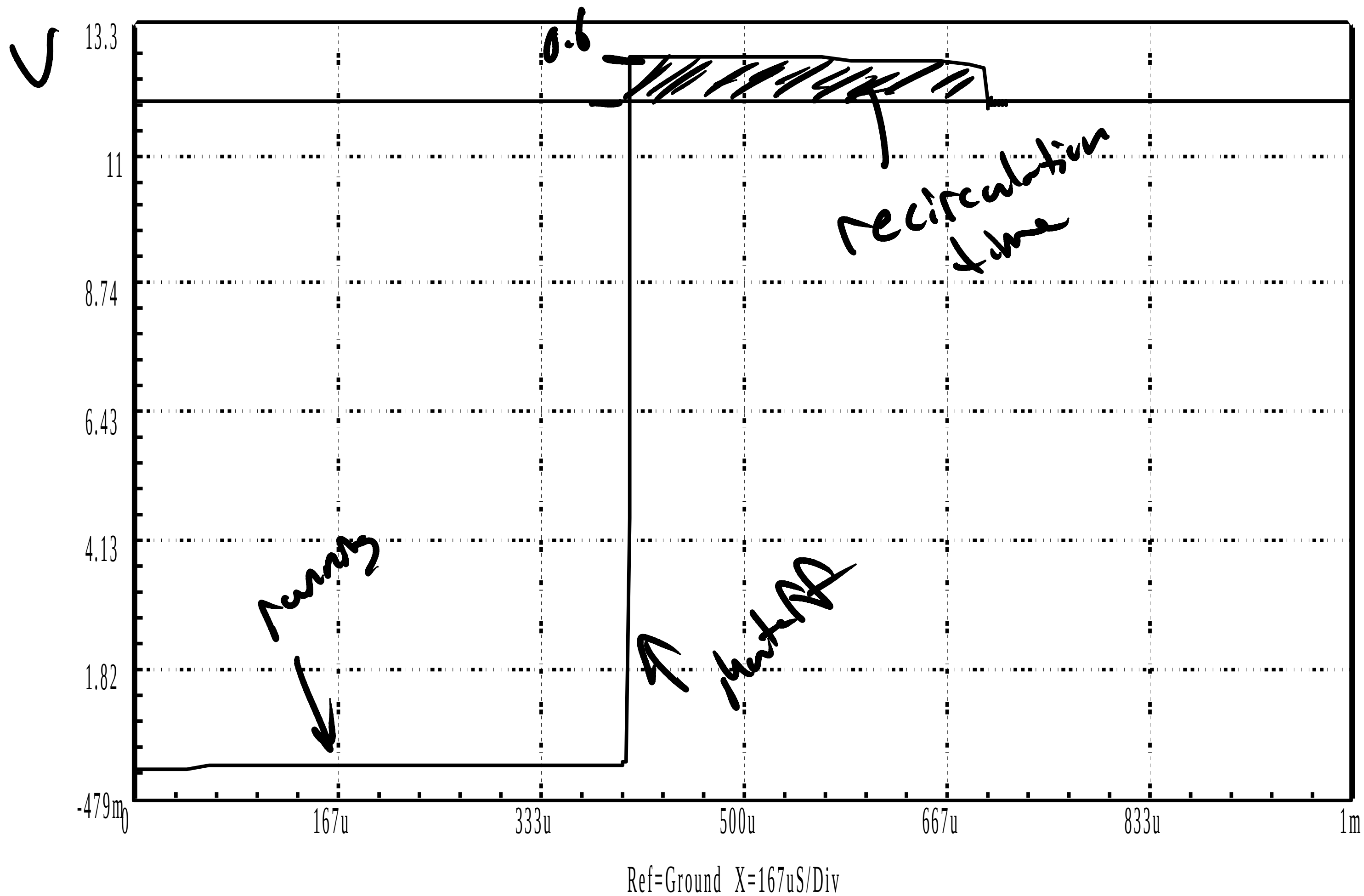
Snubbing: Diode Snubber



Inductor Current w/Diode Snubber



Collector Voltage w/Diode Snubber

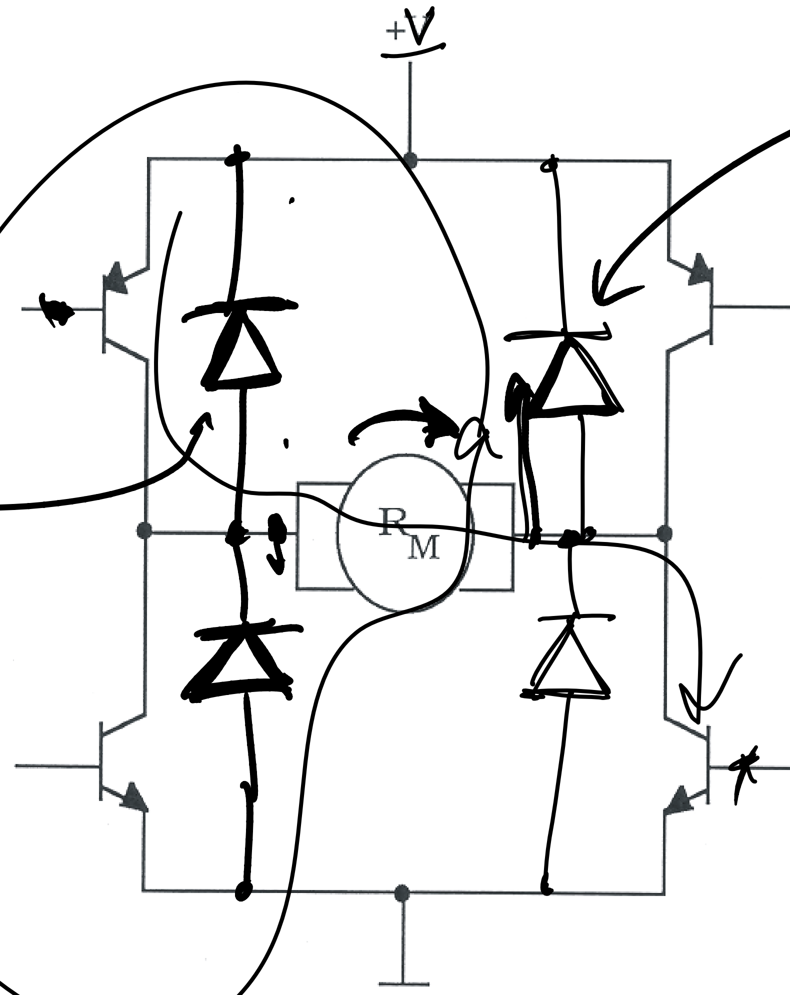


Where to put the diodes?

Peak current I_{stall}

$$\boxed{E = \left(\frac{1}{2} I^2 L\right) f_c}$$

Determines Power Rating of Diode



Fly Back Diodes

want

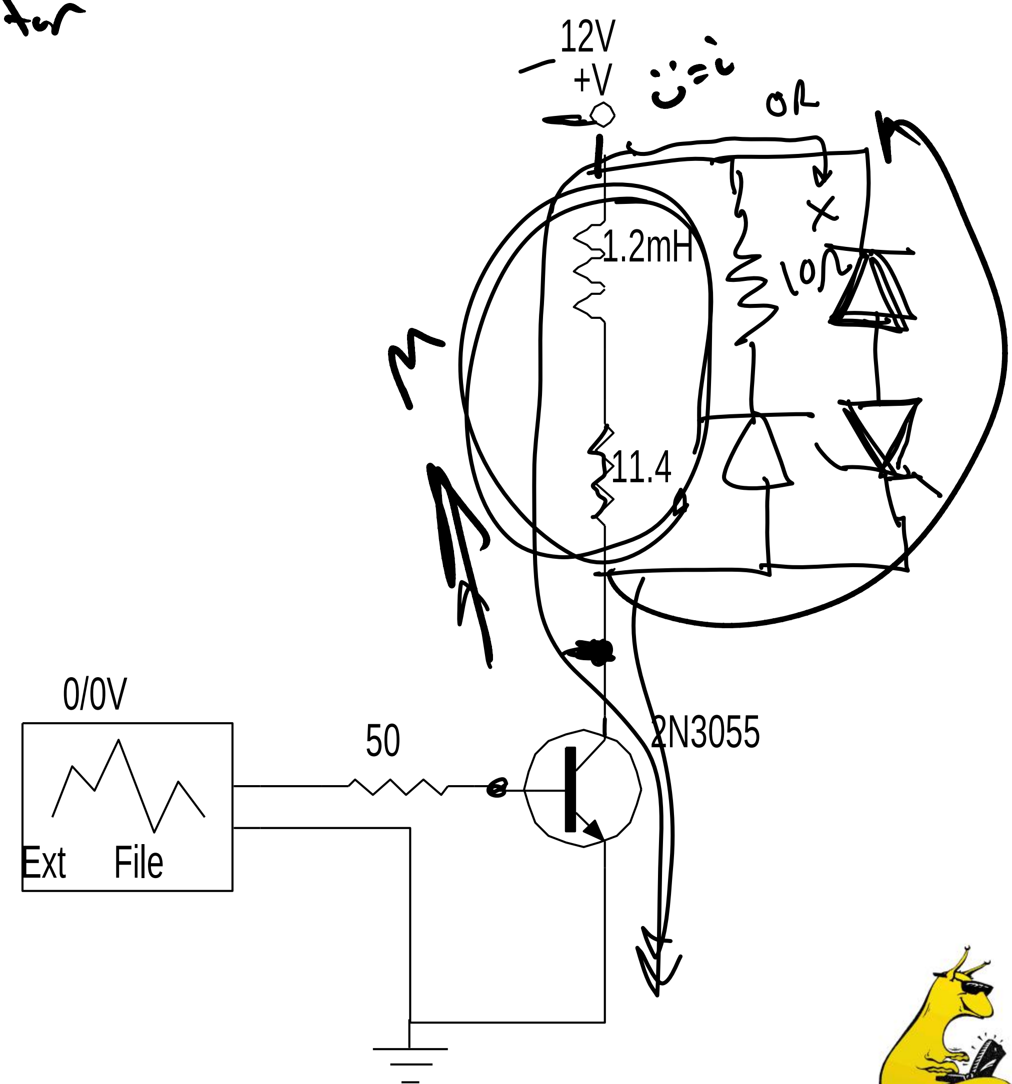
* fast recovery
* high power rating

1/8 watt

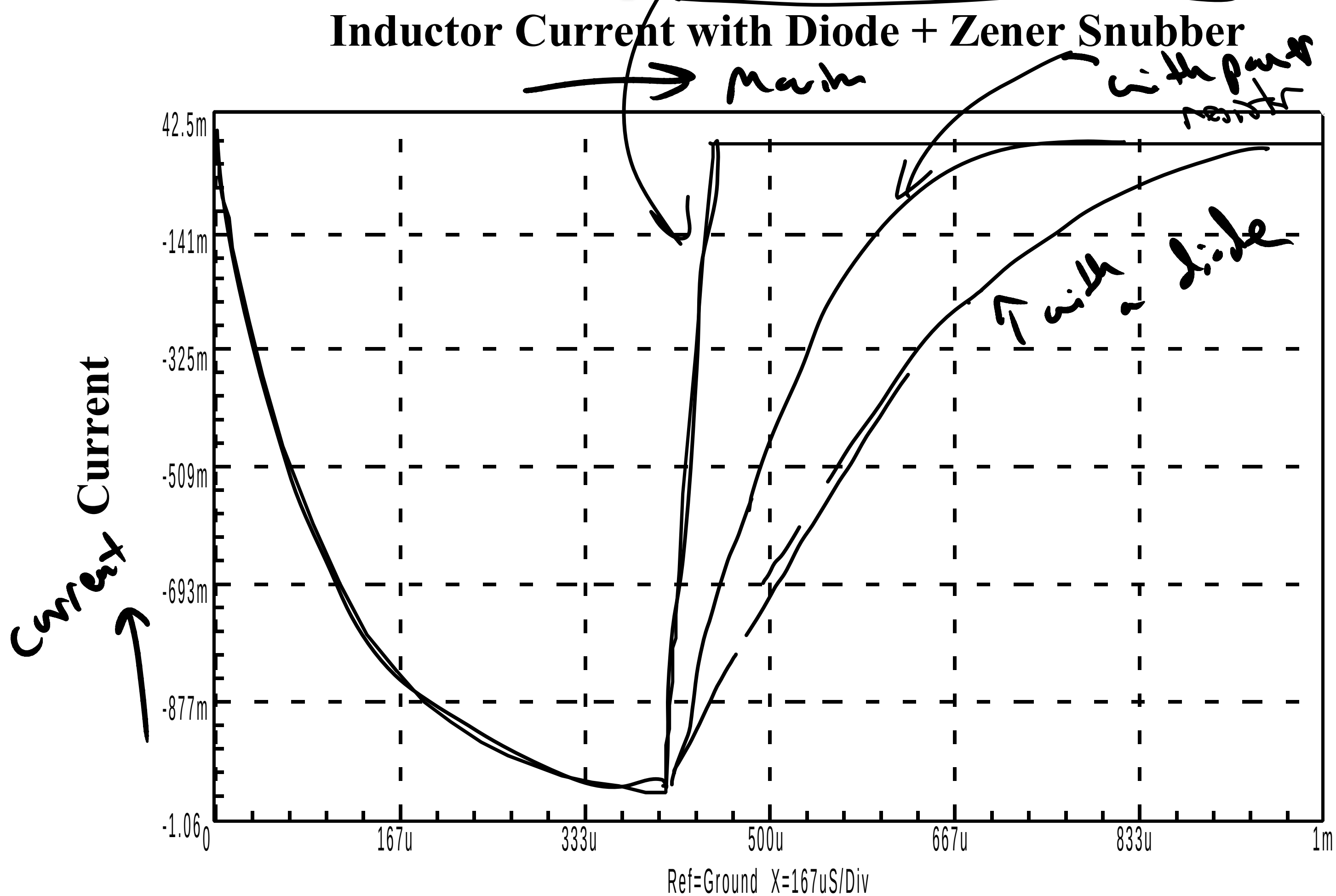
Snubbing: Diode + Zener

1) Diode + power resistor

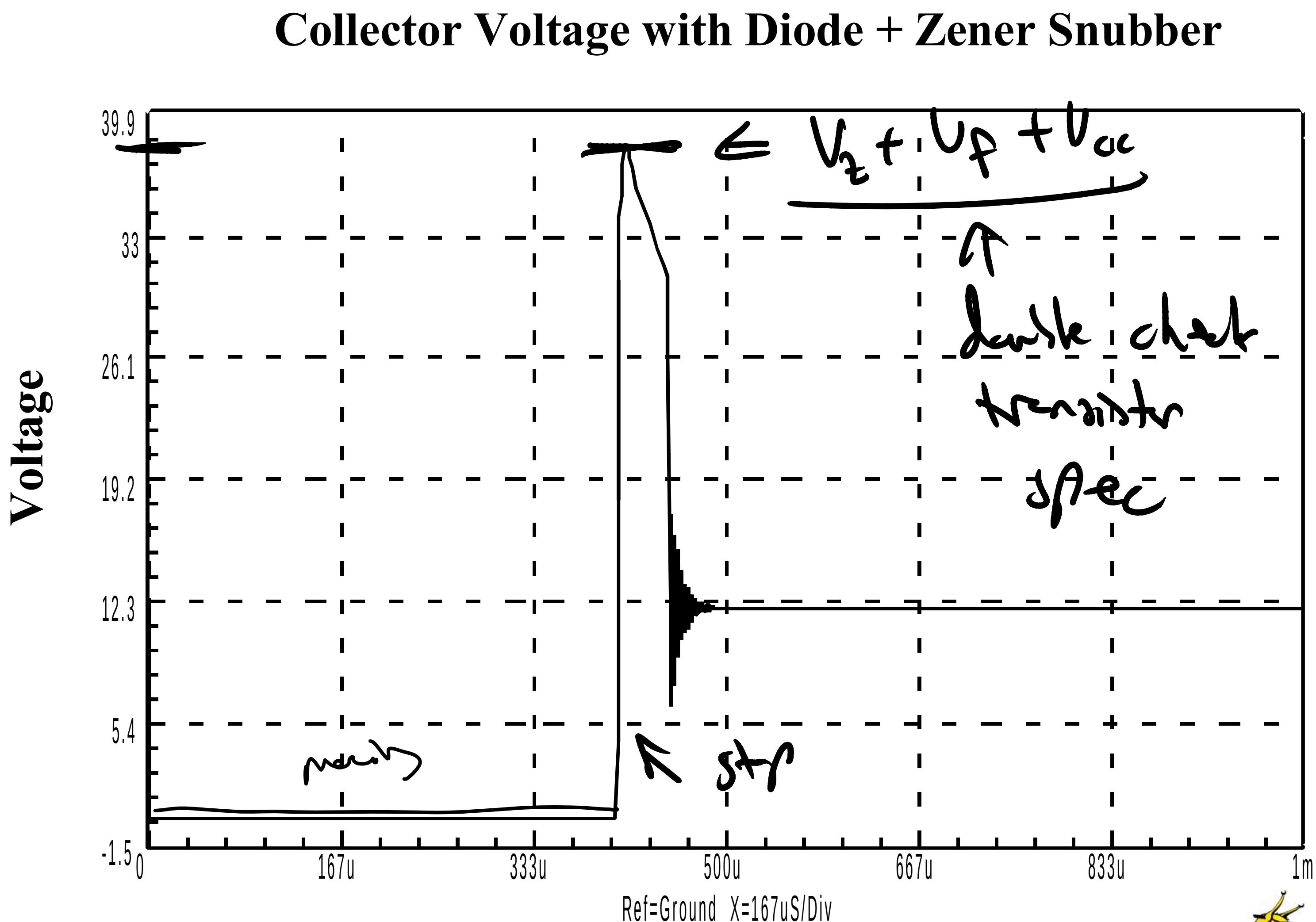
2)



Inductor Current w/ Diode + Zener

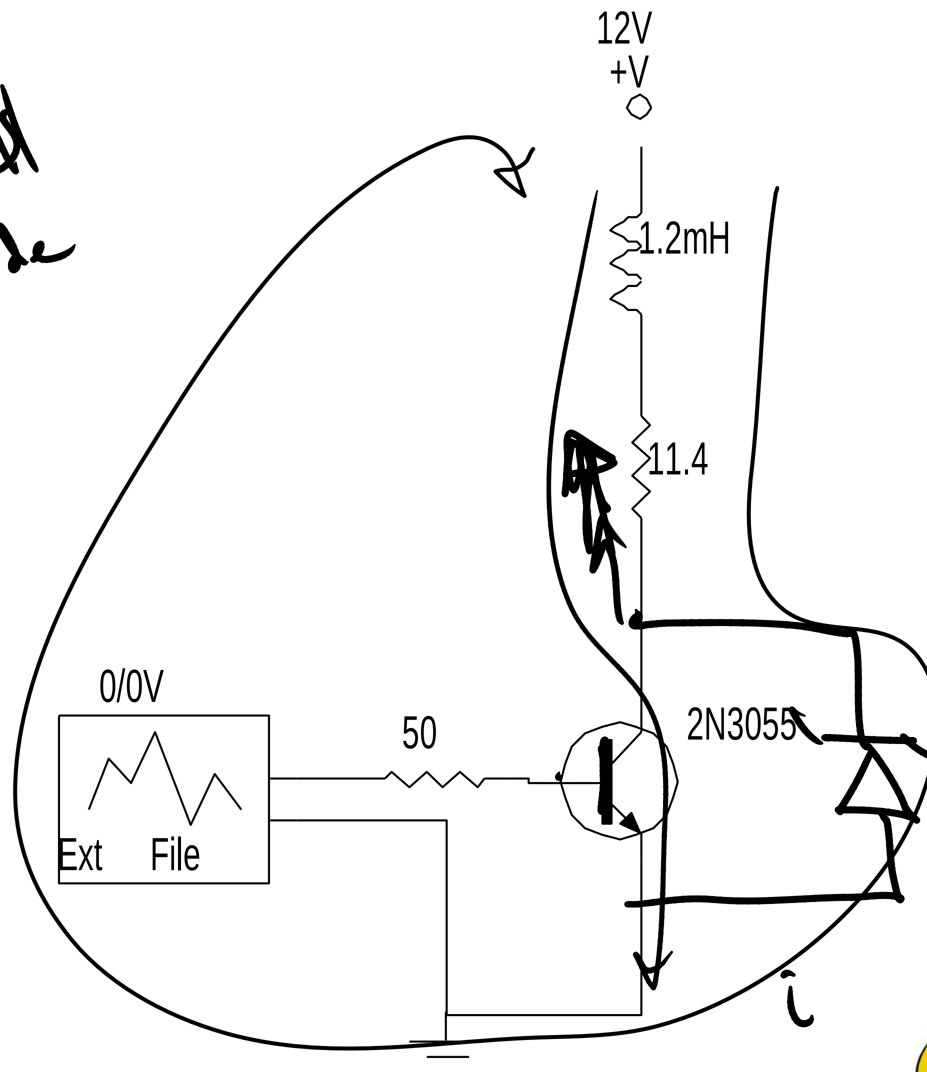


Collector Voltage w/ Diode + Zener



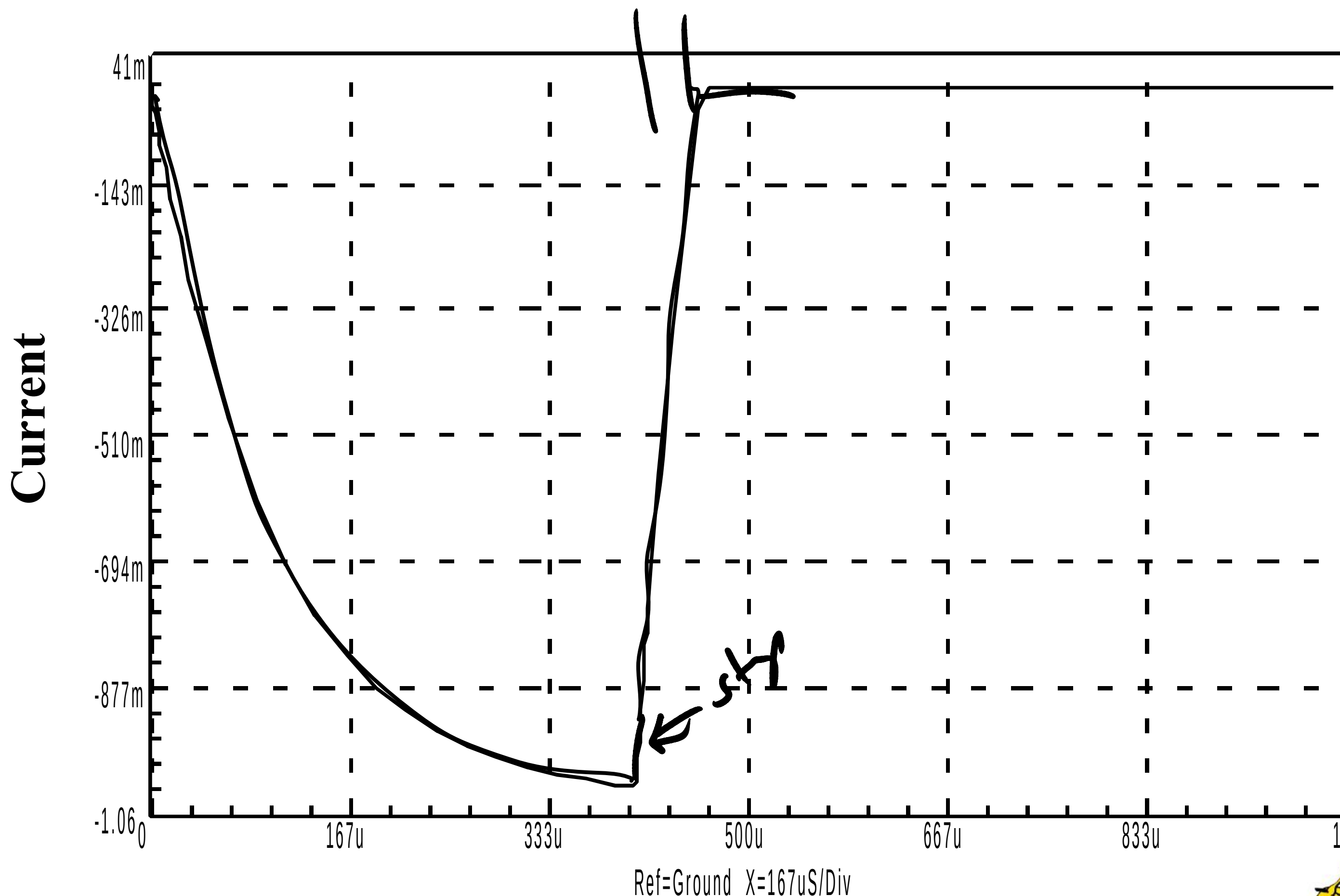
Snubbing: Zener only

Zener
XE more than the diode



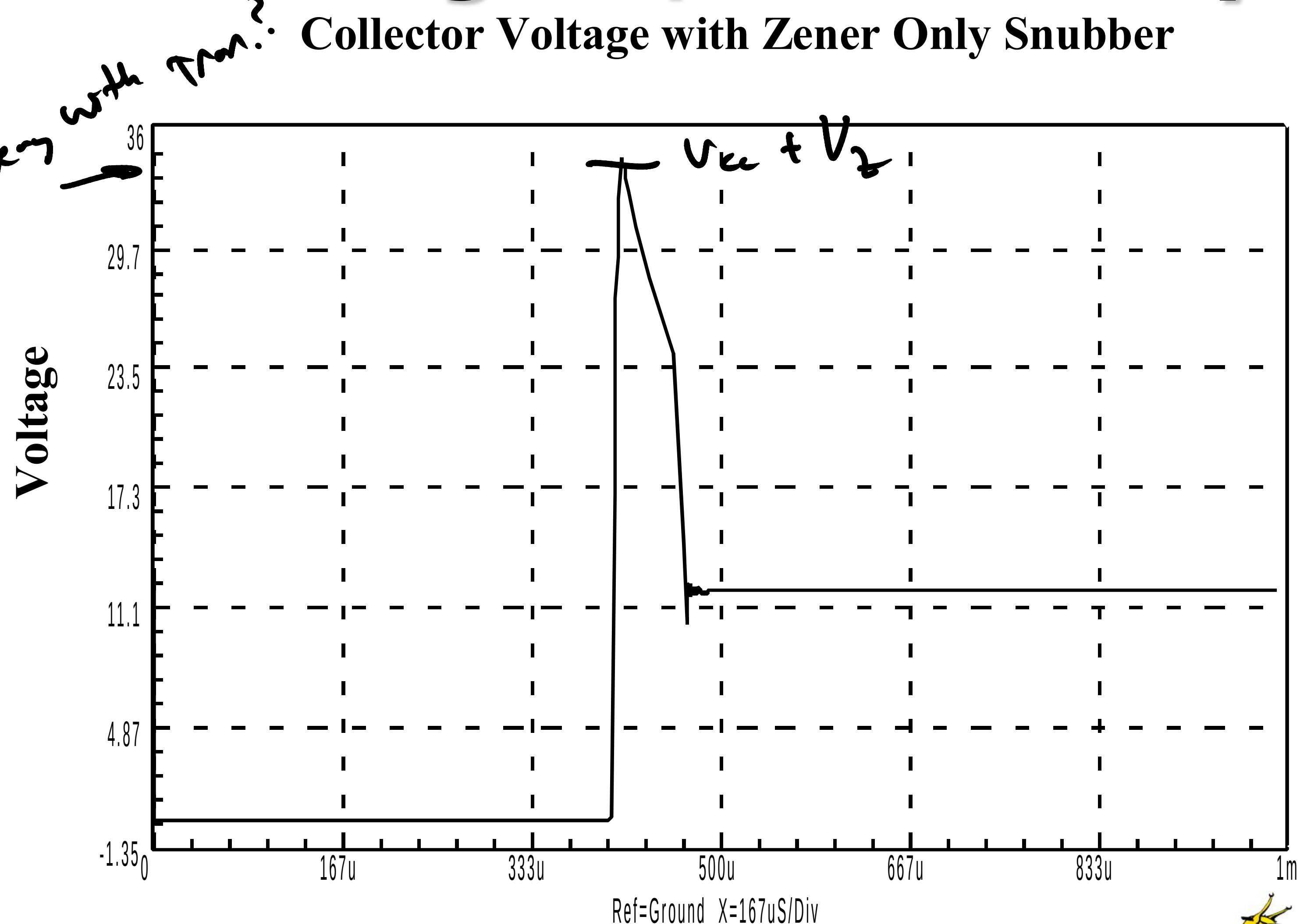
Inductor Current w/ Zener Only

Inductor Current with Zener Only Snubber



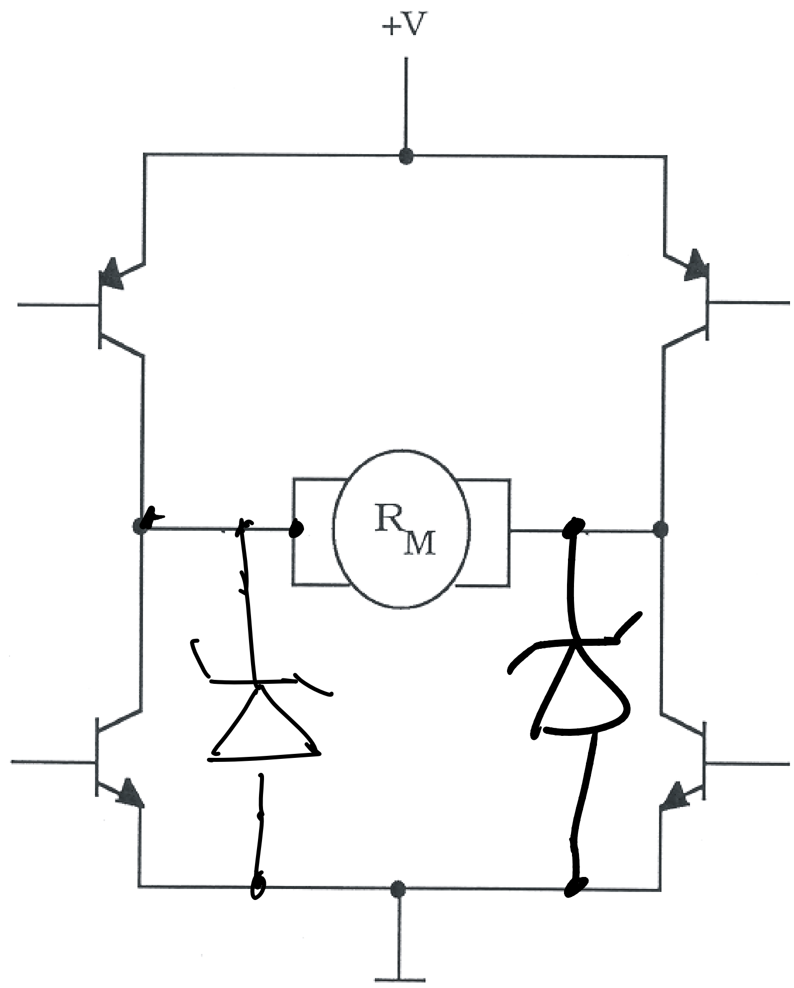
Collector Voltage w/ Zener Only

okay with Tmn?



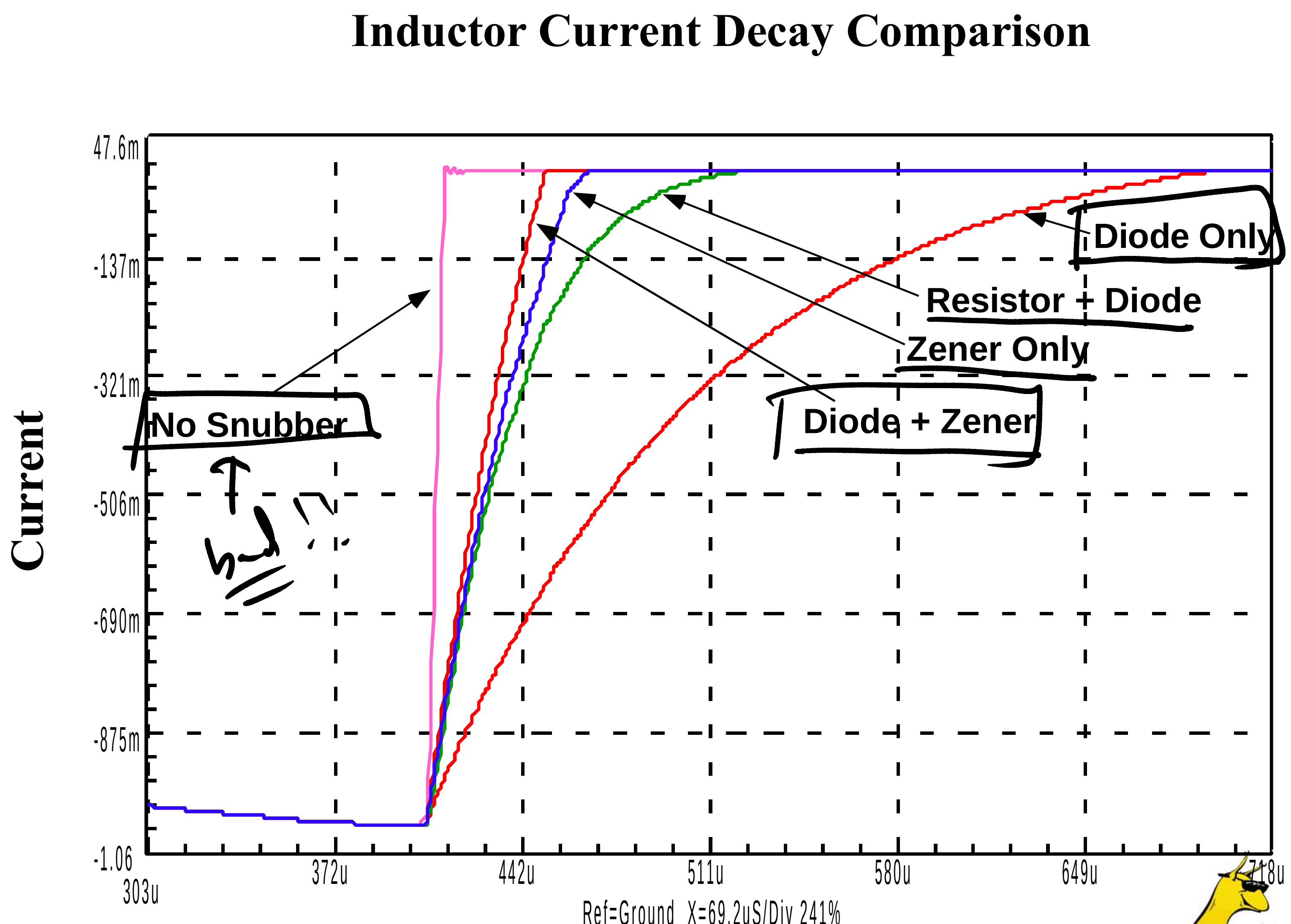
$V_{cc} + V_z$

Where to put the Zeners?



typically
use 4 diodes

Snubbers Compared



Brushless DC Motors

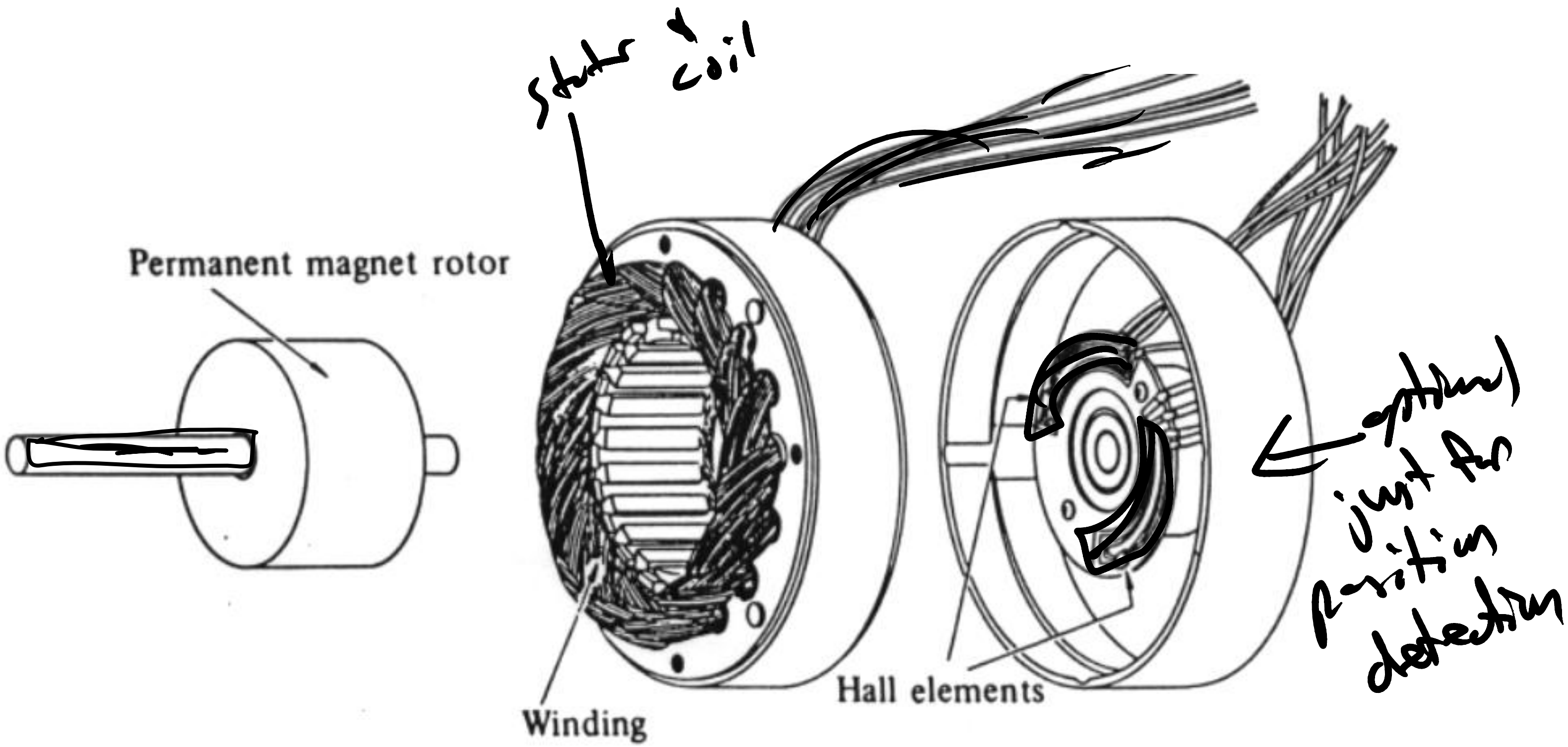
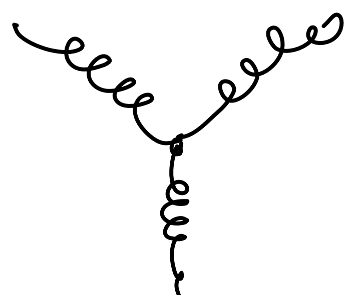
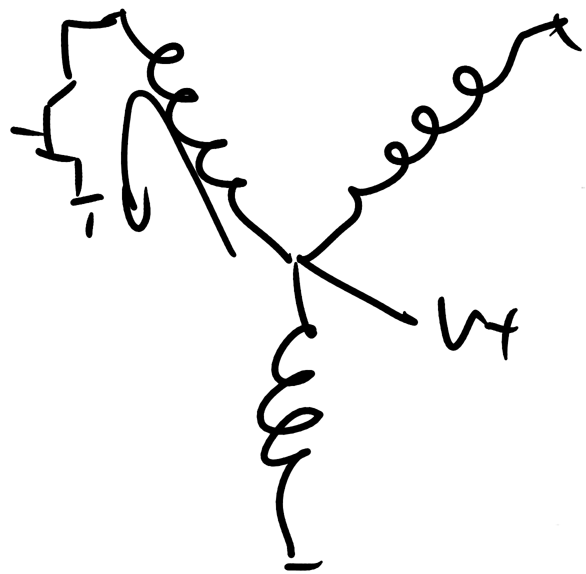
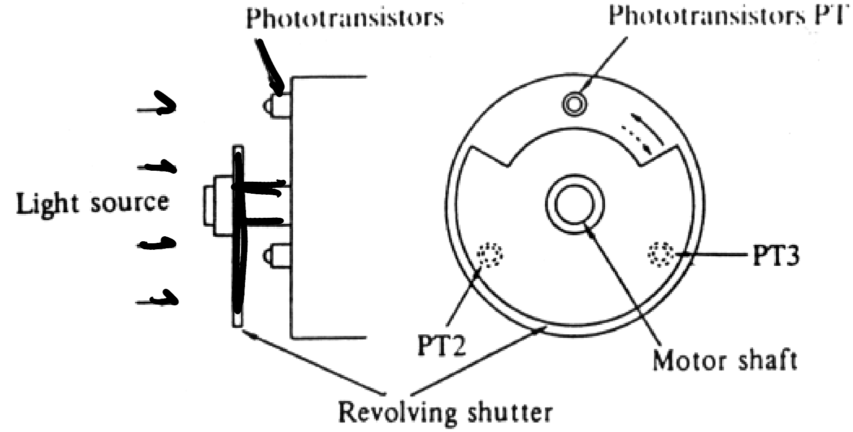


Fig. 4.1. Disassembled view of a brushless DC motor: permanent magnet rotor, winding, and Hall element.



Brushless DC: Commutation





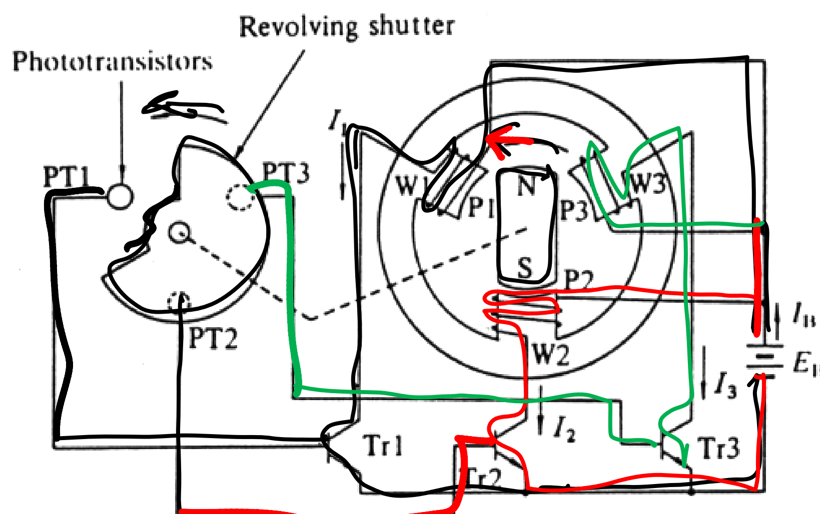
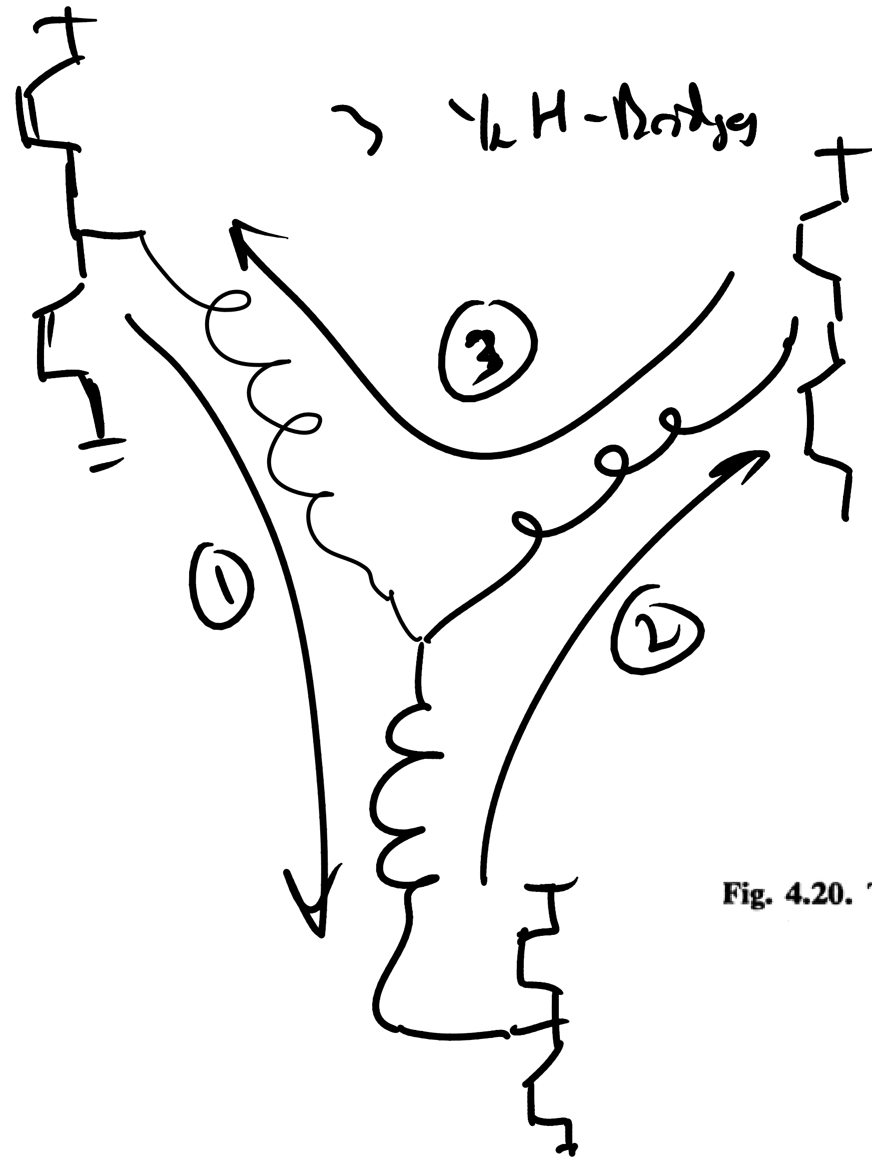


Fig. 4.2. Three-phase unipolar-driven brushless DC motor.

Hall Sensor Based Commutation



3 Hall sensors

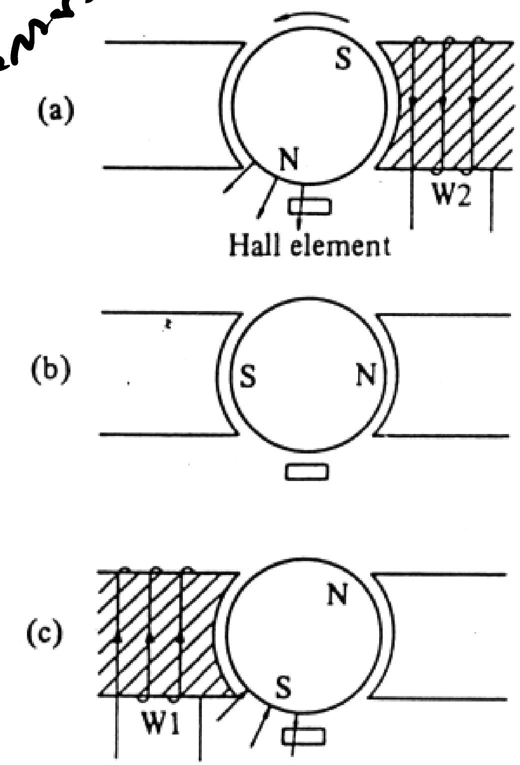


Fig. 4.20. Torque generation, revolution, and switching.

Brushed vs. Brushless

hard to get to for cooling

easy to cool

	Brushed Motor	Brushless Motor
Mechanical Structure	Field Magnets on stator Windings on Rotor	Field Magnets on Rotor Windings on stator
Commutation Method Easy	Mechanical contact between brushes and commutator added friction, brush debris, RFI	Electronic switching using transistors low frequency harmonics due to ripple more complicated to ctrl.
Rotor Position Detection	Automatically detected by brushes F ++	Hall Element, optical encoder, Back EMF
Reversing Method	Reverse terminal voltage	Rearrange logic sequencer
Distinctive Features	Quick response Excellent controllability Current limited by brush/commutator interface Speed limited by brush bounce	Long Lasting Easy or no maintenance Current limited by winding resistance only No fundamental high frequency (speed) limit Usually more efficient than brushed

Questions?