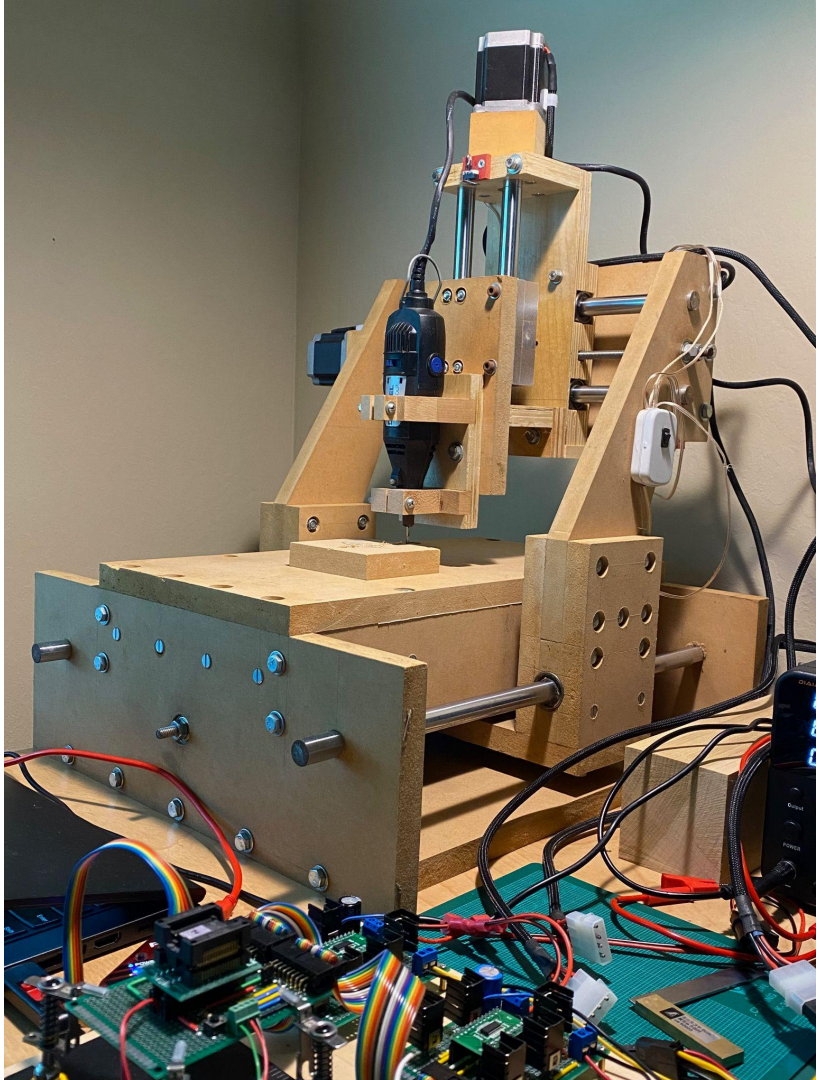
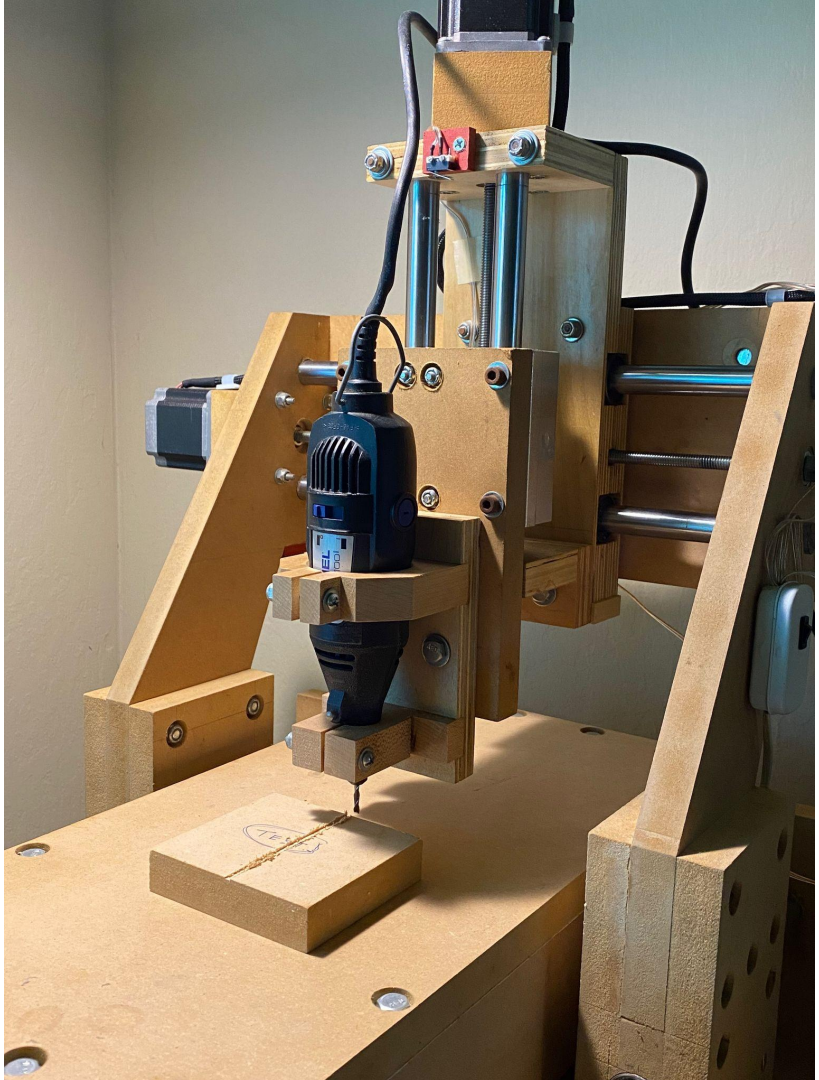
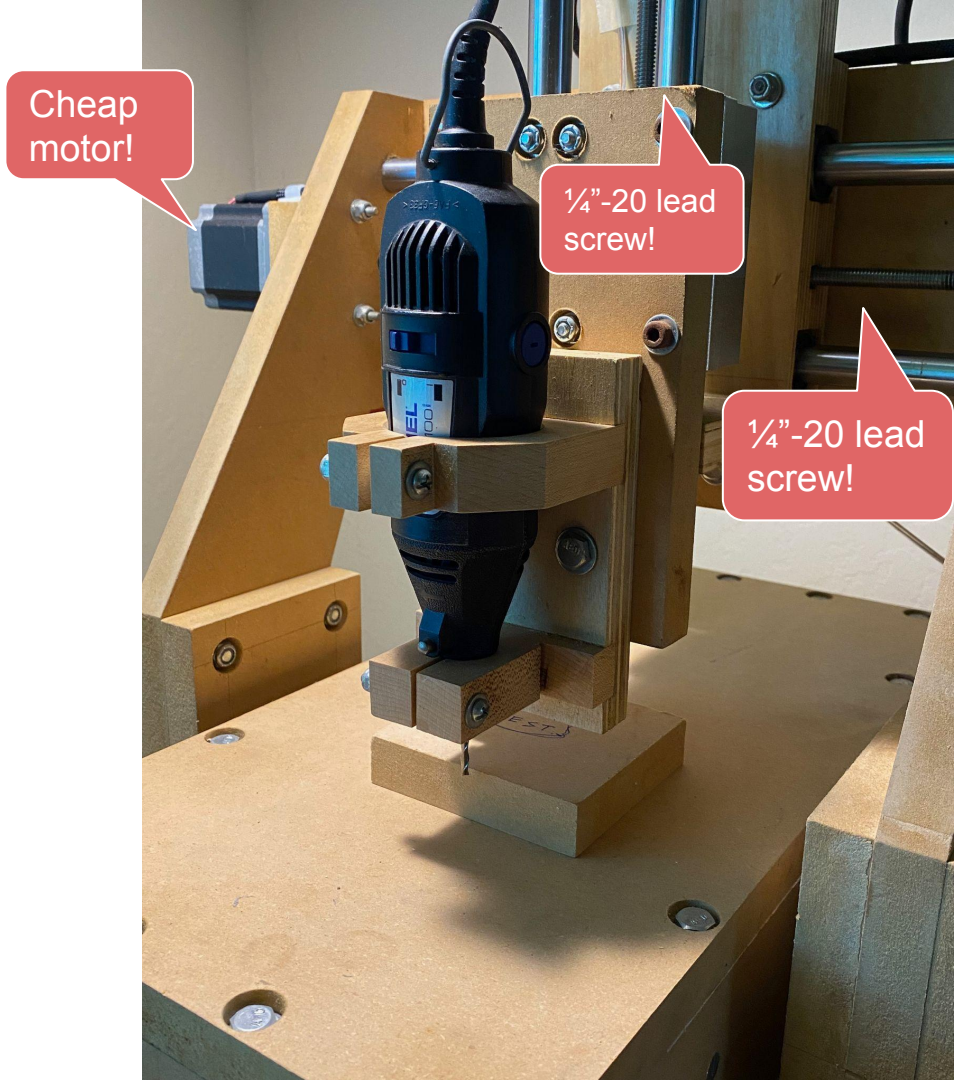
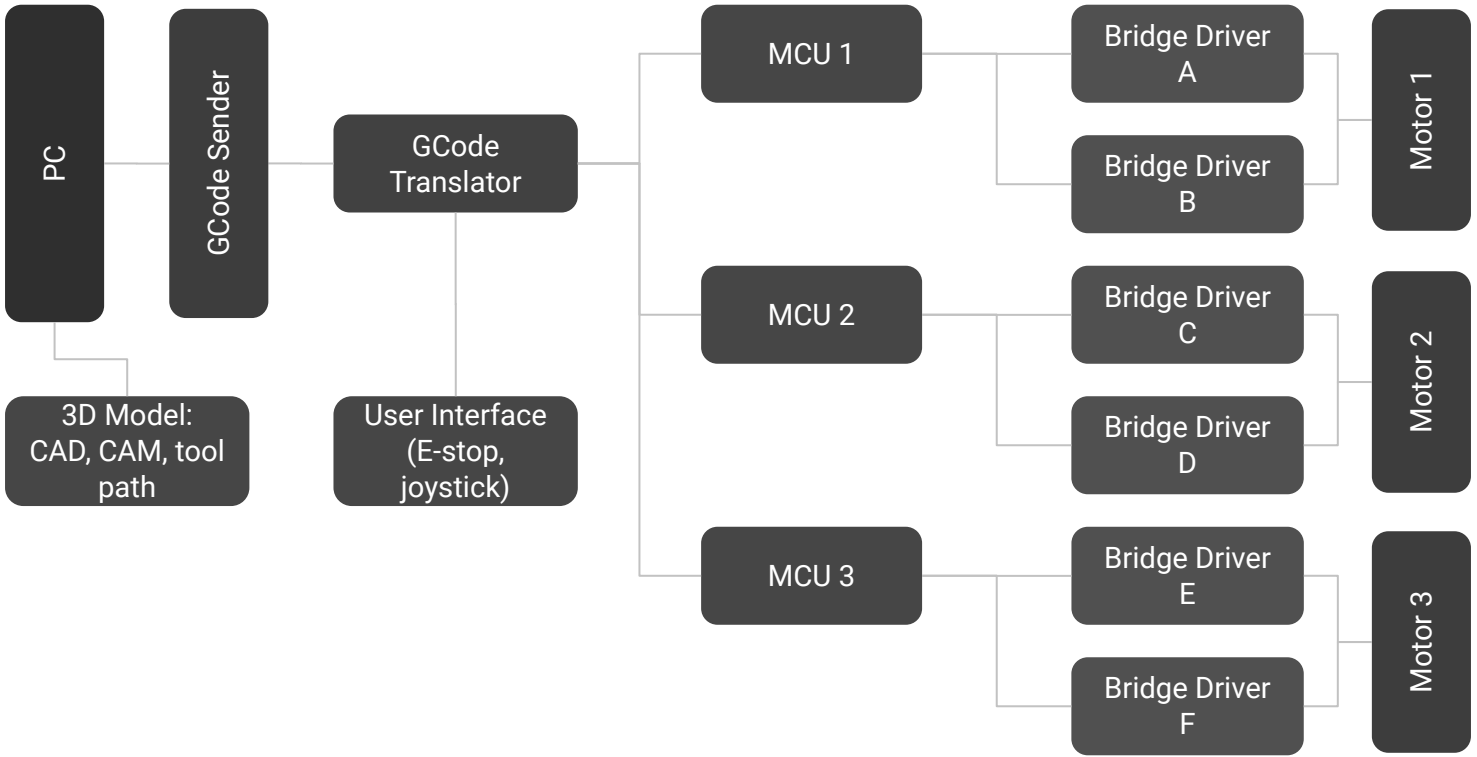
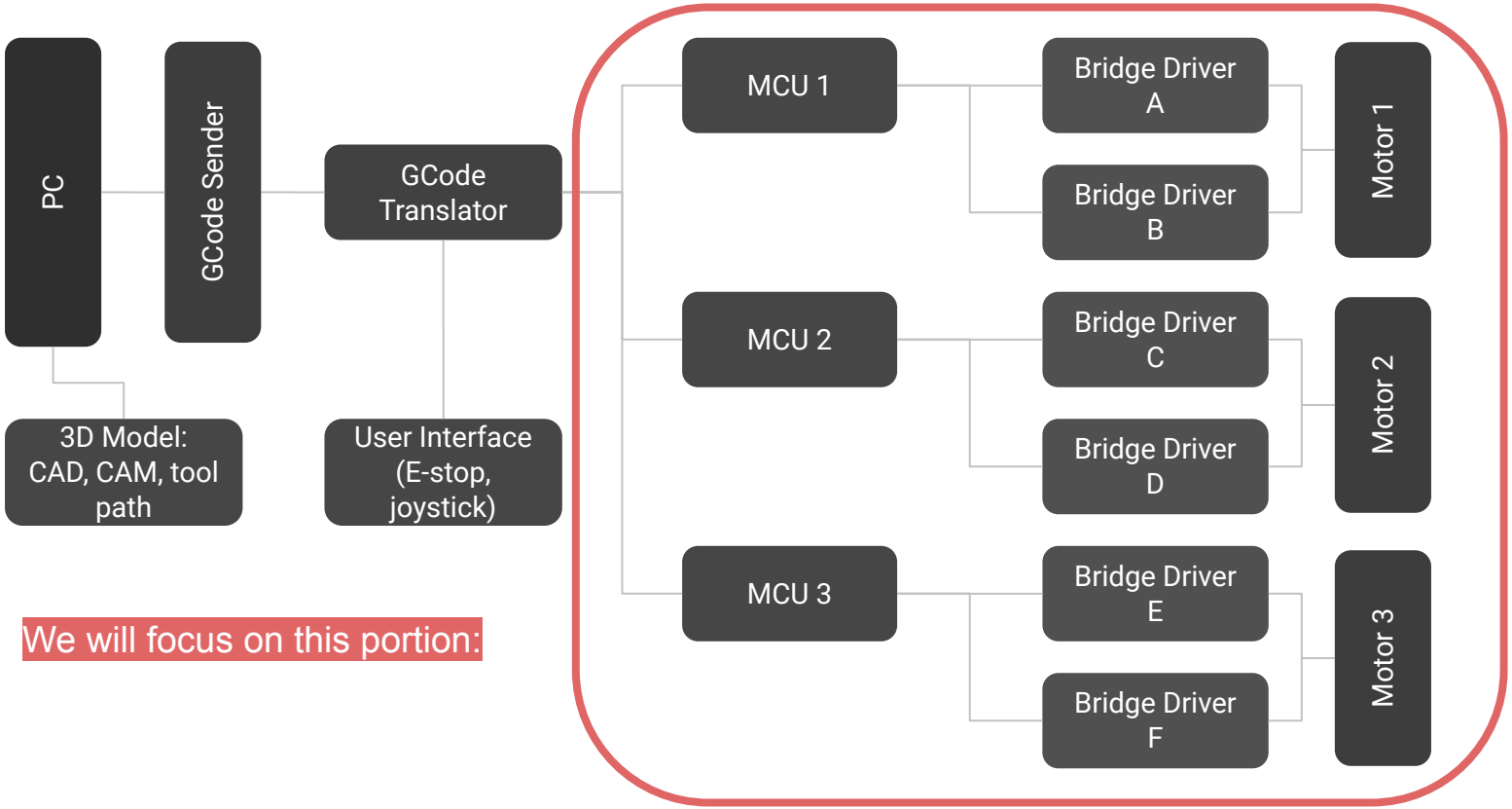


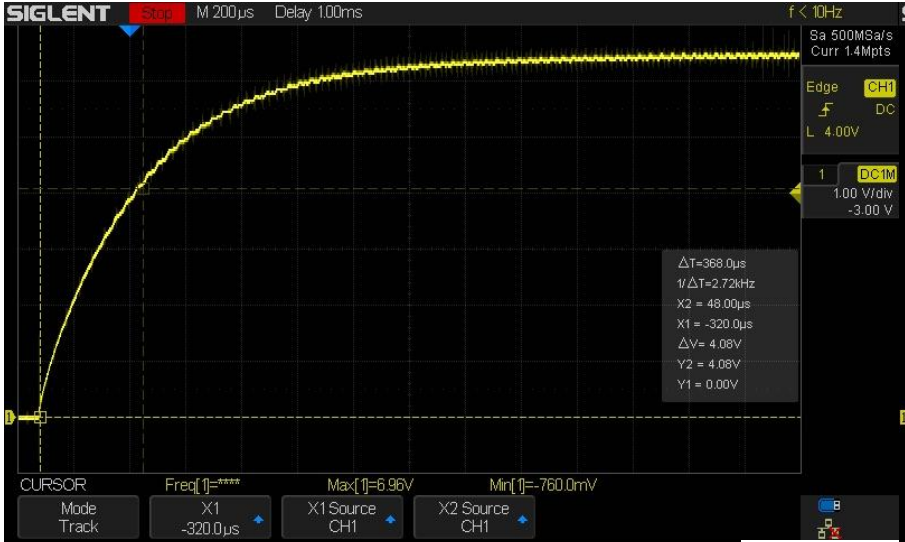



Cheap motor!
¼”-20 lead screw!
¼”-20 lead screw!

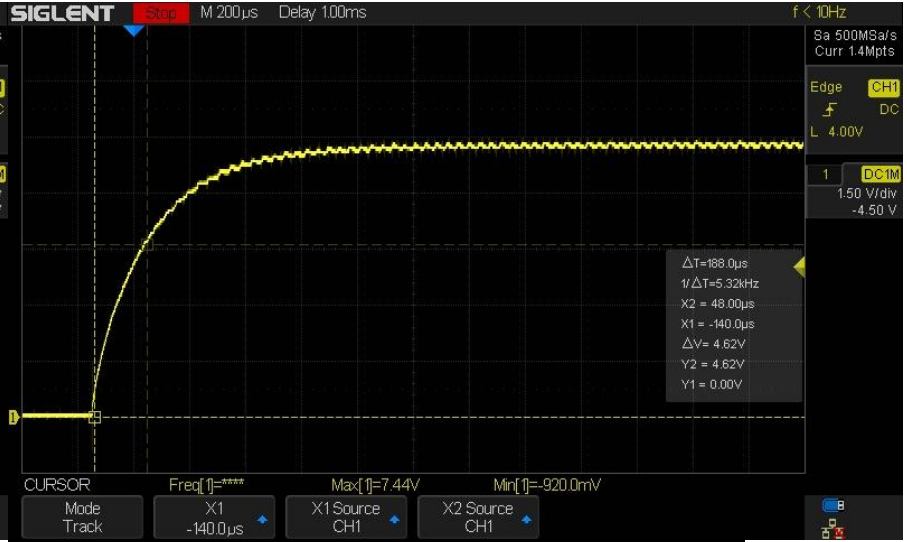

PC
GCode Sender
GCode Translator
3D Model: CAD, CAM, tool path
User Interface (E-stop, joystick)
MCU 1
MCU 2
MCU 3
Bridge Driver A
Bridge Driver B
Bridge Driver C
Bridge Driver D
Bridge Driver E
Bridge Driver F
Motor 1
Motor 2
Motor 3



We will focus on this portion:



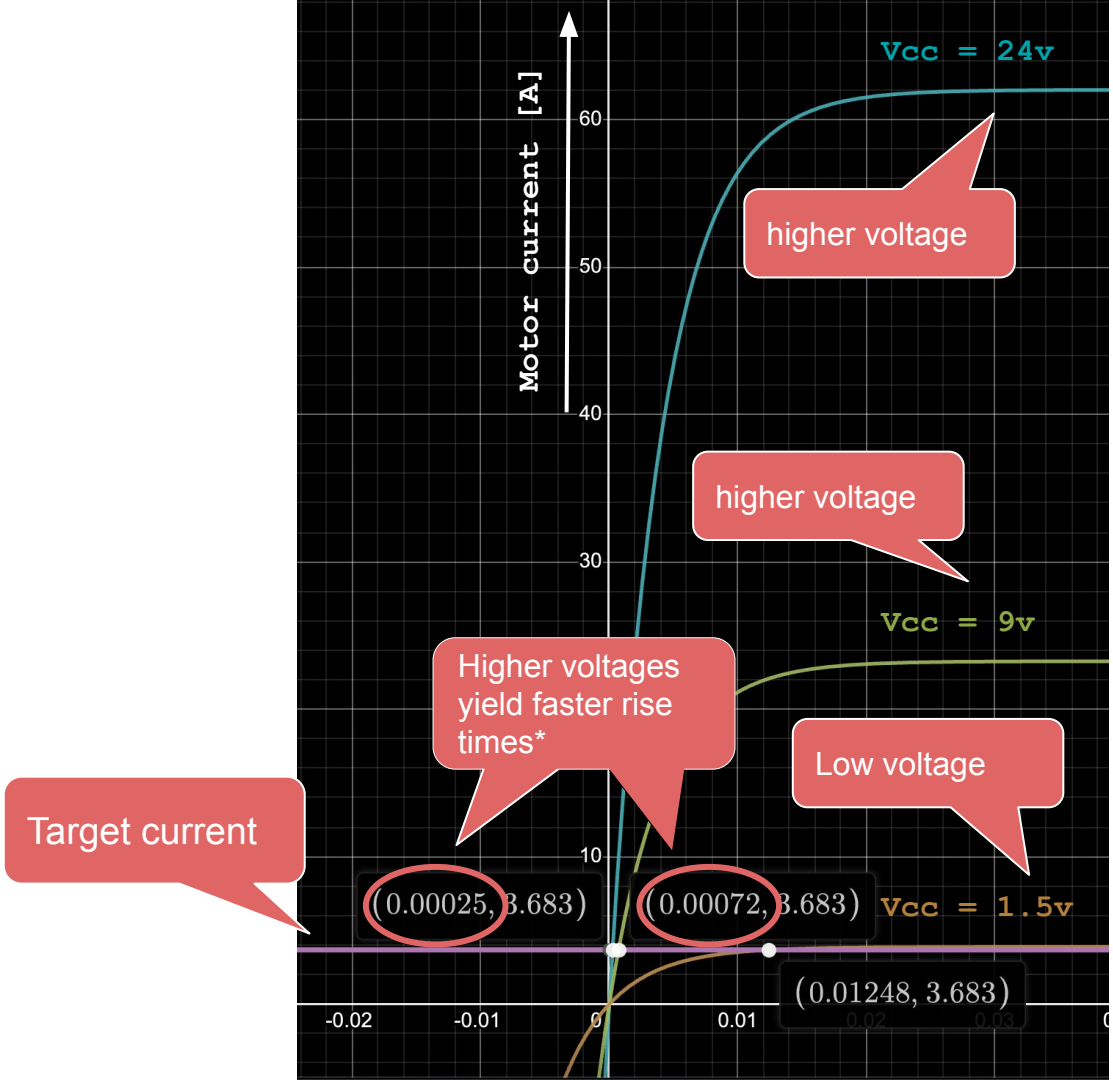
>> tau=368E-6s, R_ext=8.2ohm

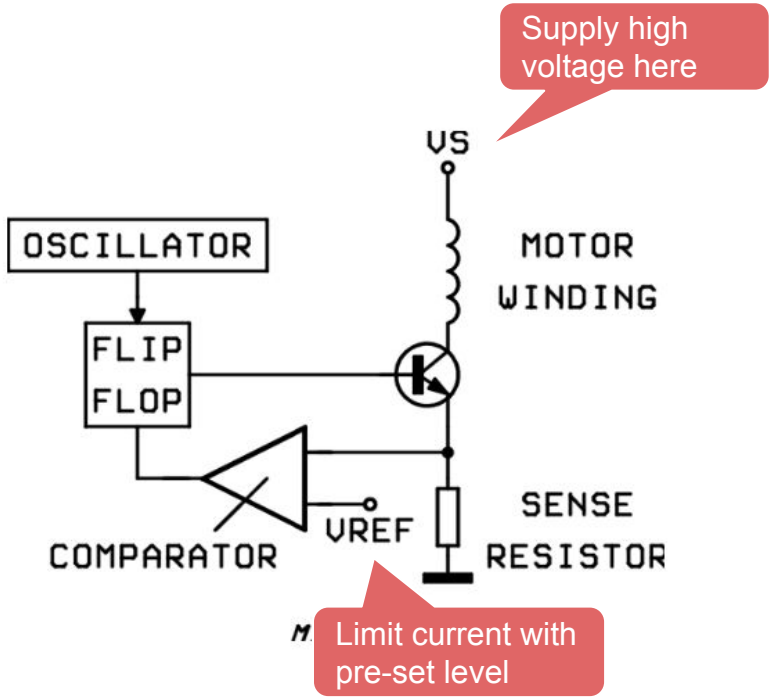


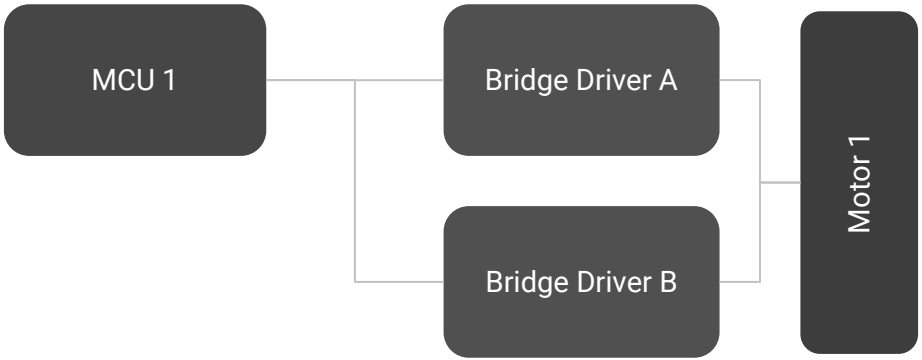
>> tau=168E-6s, R_ext=4ohm

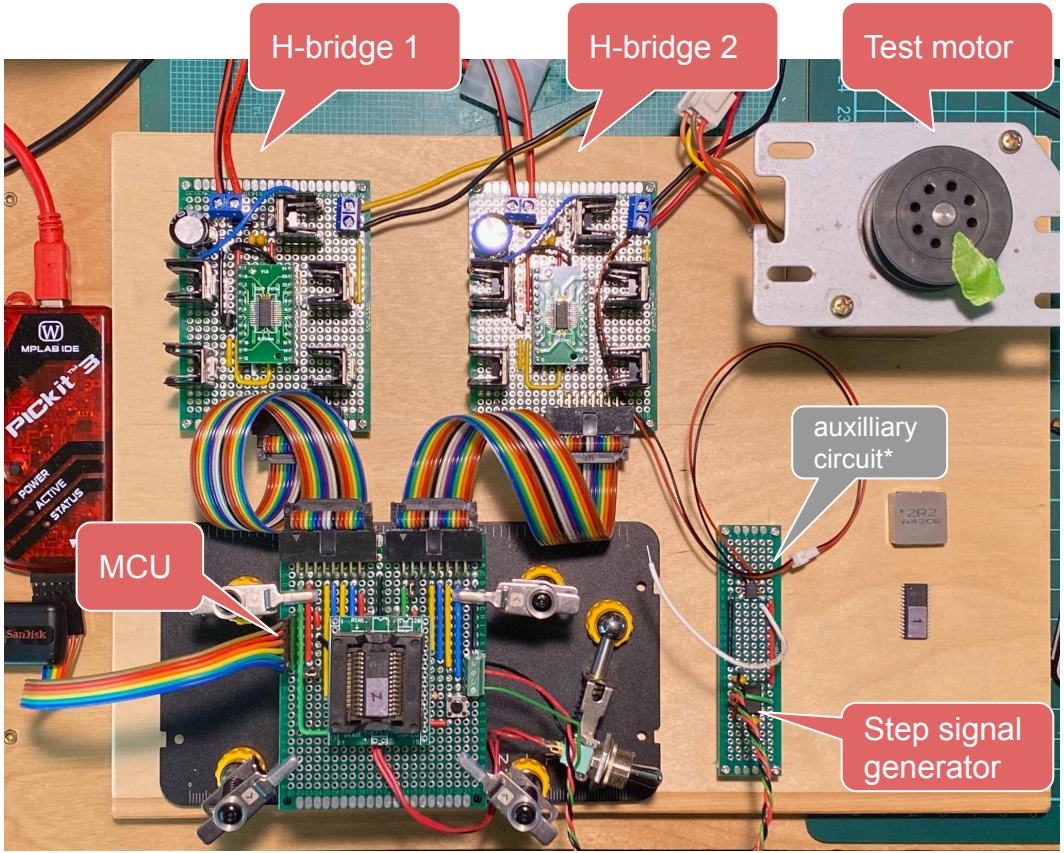
Assume first-order approx.
>>Motor: tau=L_0/(R_0+R_ext)
>> L_0=1.61E-3H, R_0=0.387ohm

Large time constant!!
Tau = L0/R0 = 4.2ms

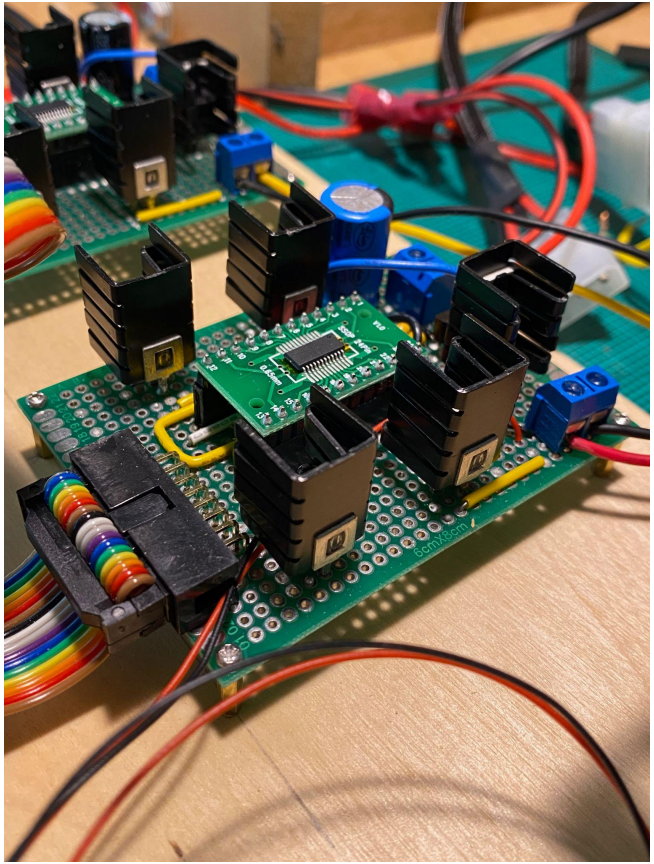

Motor current [A]
60
50
40
30
10
Vcc = 24v
higher voltage
higher voltage
Vcc = 9v
Higher voltages yield faster rise times*
Low voltage
Target current
(0.00025, 3.683)
(0.00072, 3.683)
Vcc = 1.5v
(0.01248, 3.683)
-0.02
-0.01
0
0.01
0.02
0.03

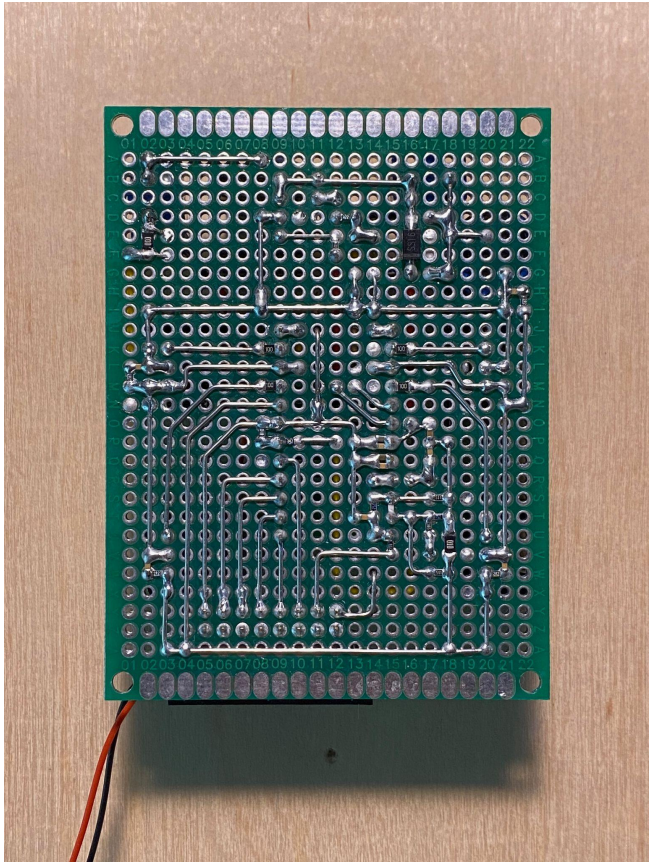

Supply high voltage here
VS
OSCILLATOR
MOTOR WINDING
FLIP FLOP
VREF
SENSE RESISTOR
COMPARATOR
Limit current with pre-set level

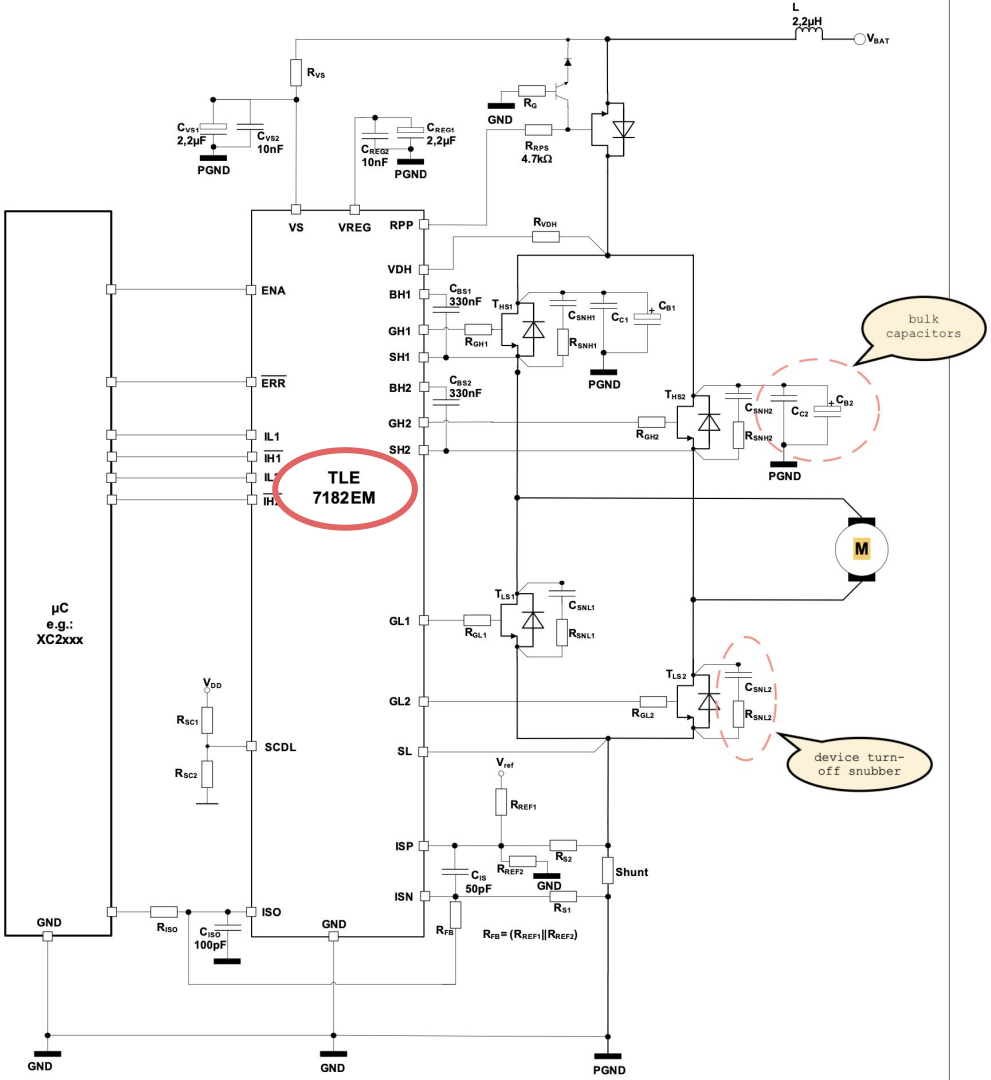

MCU 1
Bridge Driver A
Bridge Driver B
Motor 1

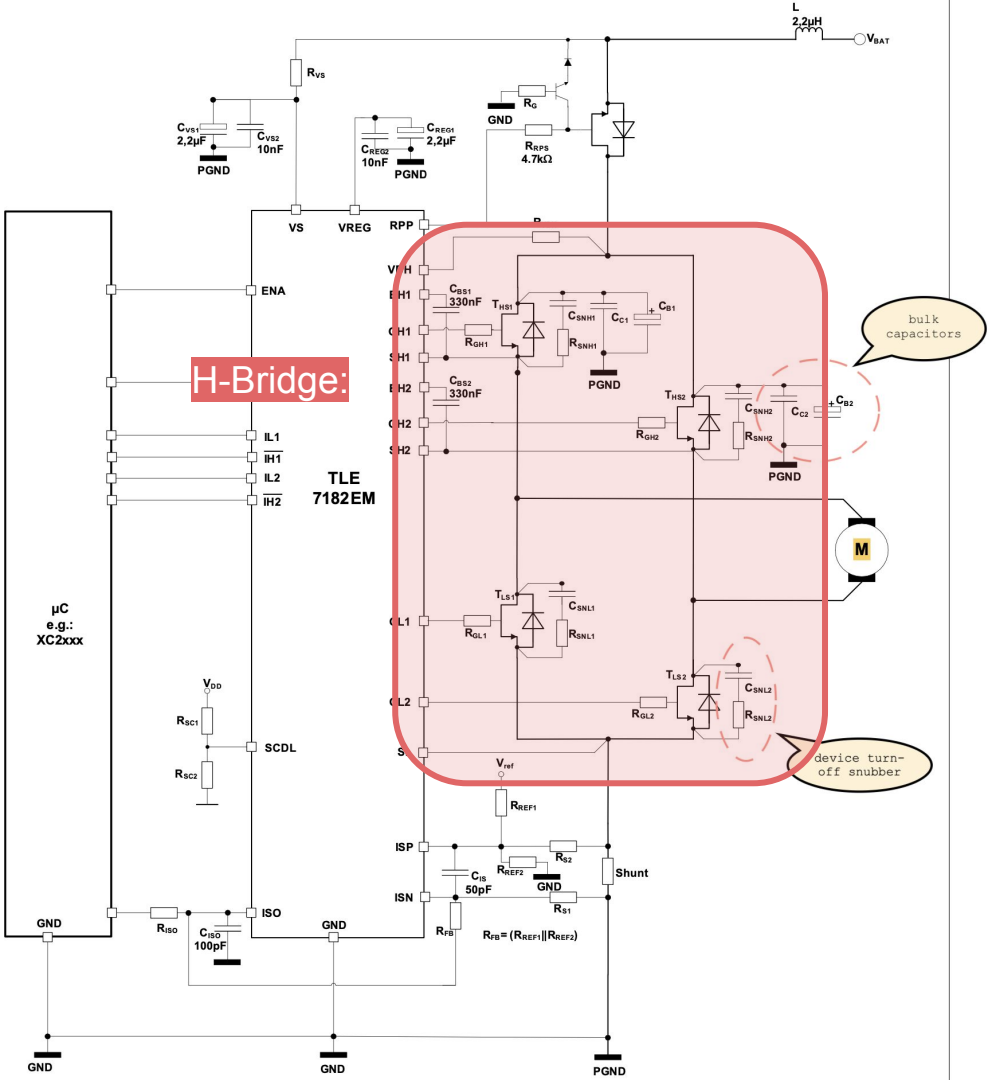


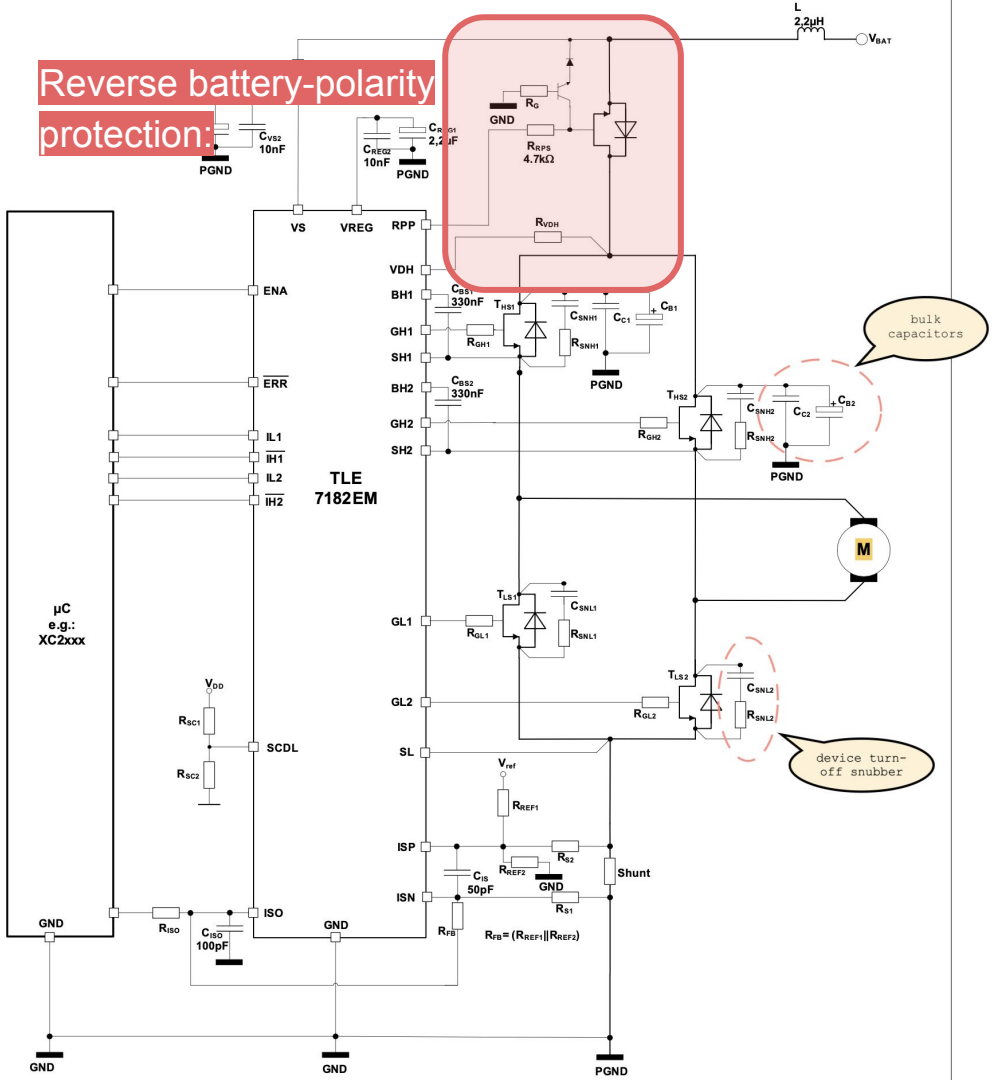
*Discussed later

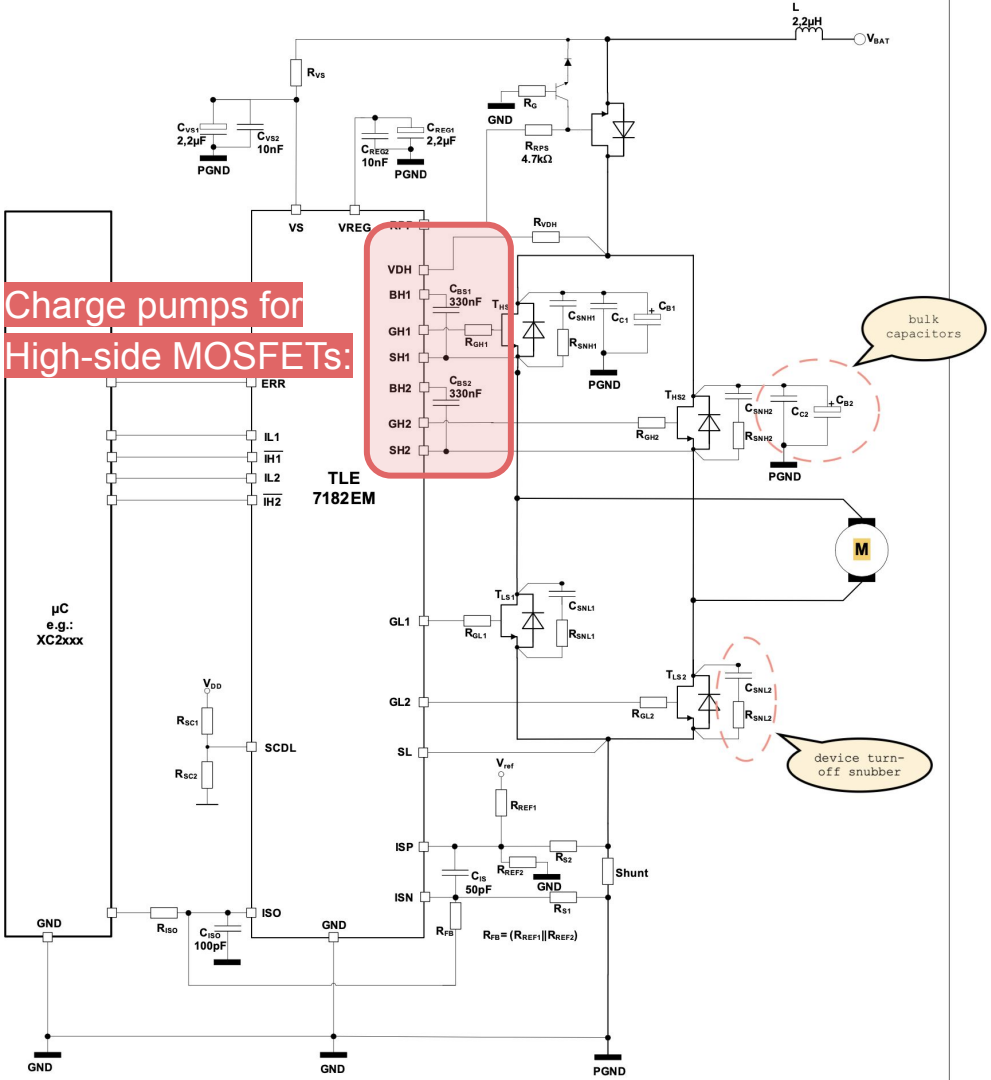


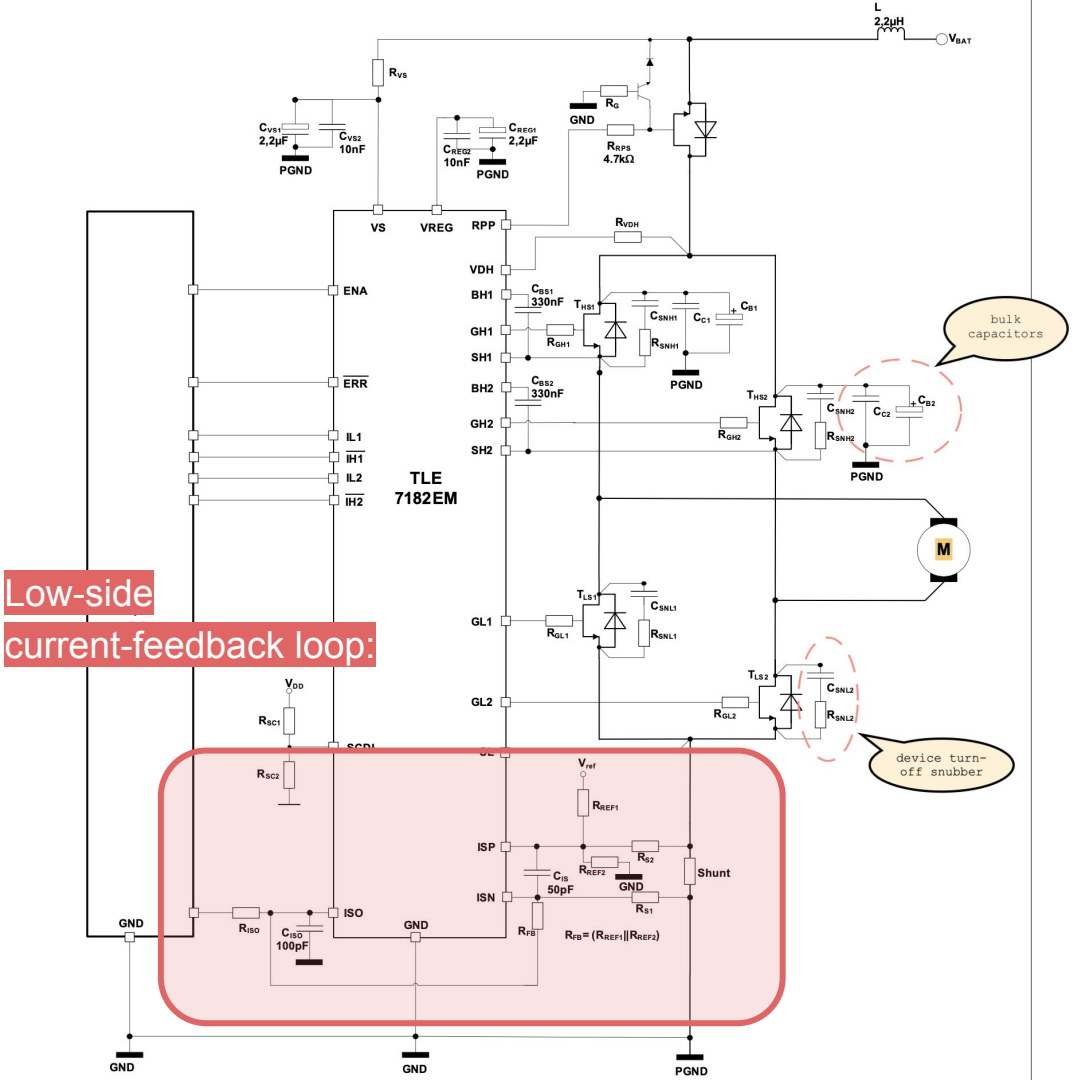


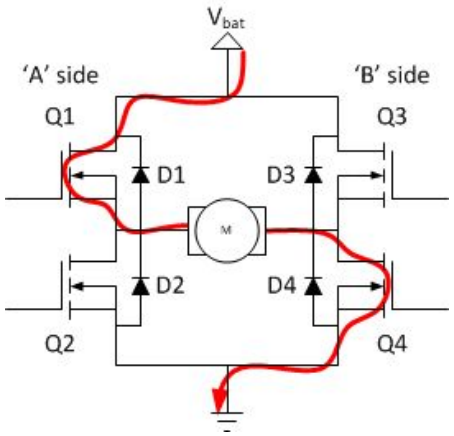

L
2,2µH
VBAT
RVS
CVS1
2,2µF
CVS2
10nF
PGND
CREG2
10nF
CREG1
2,2µF
PGND
RG
GND
RRPS
4.7kΩ
VS
VREG
RPP
RVDH
VDH
BH1
CBS1
330nF
THS1
CSNH1
RSNH1
CC1
CB1
GH1
RGH1
SH1
PGND
BH2
CBS2
330nF
THS2
CSNH2
RSNH2
CC2
CB2
GH2
RGH2
SH2
PGND
bulk
capacitors
ENA
ERR
IL1
IH1
IL2
IH2
TLE
7182EM
M
µC
e.g.:
XC2xxx
GL1
TLS1
RGL1
CSNL1
RSNL1
GL2
TLS2
RGL2
CSNL2
RSNL2
device turn-
off snubber
VDD
RSC1
RSC2
SCDL
SL
Vref
RREF1
ISP
RREF2
RS2
CIS
50pF
GND
Shunt
ISN
RS1
RFB
RFB= (RREF1||RREF2)
GND
RISO
CISO
100pF
ISO
GND
GND
GND
PGND


L
2,2µH
VBAT
RVS
CVS1
2,2µF
CVS2
10nF
PGND
CREG2
10nF
CREG1
2,2µF
PGND
RG
GND
RPPS
4.7kΩ
VS
VREG
RPP
ENA
H-Bridge:
IL1
IH1
IL2
IH2
TLE
7182EM
µC
e.g.:
XC2xxx
VDD
RSC1
SCDL
RSC2
CBS1
330nF
THS1
CSNH1
CC1
CB1
RGH1
RSNH1
PGND
CBS2
330nF
THS2
CSNH2
CC2
CB2
RGH2
RSNH2
PGND
bulk
capacitors
M
TLS1
CSNL1
RGL1
RSNL1
TLS2
CSNL2
RGL2
RSNL2
device turn-
off snubber
Vref
RREF1
ISP
RREF2
RS2
CIS
50pF
GND
Shunt
ISN
RS1
RFB
RFB= (RREF1||RREF2)
GND
RISO
CISO
100pF
ISO
GND
GND
GND
PGND

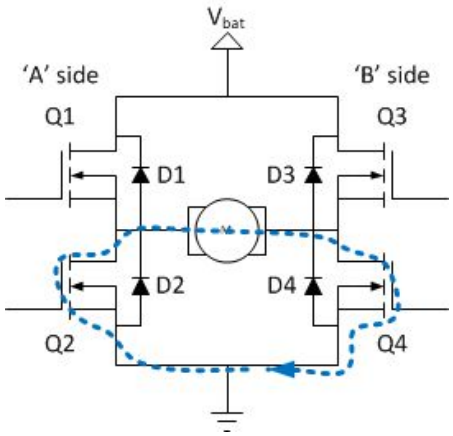

Reverse battery-polarity protection:
L
2.2µH
VBAT
RG
GND
RRPS
4.7kΩ
CVS2
10nF
PGND
CREG2
10nF
CREG1
2.2µF
PGND
RVDH
VS
VREG
RPP
VDH
BH1
GH1
SH1
BH2
GH2
SH2
ENA
ERR
IL1
IH1
IL2
IH2
TLE
7182EM
CBS1
330nF
THS1
CSNH1
RSNH1
CC1
CB1
RGH1
PGND
CBS2
330nF
THS2
CSNH2
RSNH2
CC2
CB2
RGH2
PGND
bulk capacitors
M
µC
e.g.:
XC2xxx
GL1
TLS1
CSNL1
RSNL1
RGL1
GL2
TLS2
CSNL2
RSNL2
RGL2
device turn-off snubber
SL
VDD
RSC1
RSC2
SCDL
Vref
RREF1
ISP
ISN
RREF2
RS2
CIS
50pF
GND
Shunt
RS1
RFB
RFB= (RREF1||RREF2)
ISO
RISO
CISO
100pF
GND
GND
GND
PGND


Charge pumps for
High-side MOSFETs:
TLE
7182EM
µC
e.g.:
XC2xxx
L
2,2µH
VBAT
RVS
CVS1
2,2µF
CVS2
10nF
PGND
CREG2
10nF
CREG1
2,2µF
PGND
RG
GND
RRPS
4.7kΩ
VS
VREG
RVDH
VDH
BH1
GH1
SH1
BH2
GH2
SH2
CBS1
330nF
CBS2
330nF
THS
RGH1
CSNH1
RSNH1
CC1
CB1
PGND
THS2
RGH2
CSNH2
RSNH2
CC2
CB2
PGND
bulk
capacitors
M
ERR
IL1
IH1
IL2
IH2
TLS1
RGL1
CSNL1
RSNL1
GL1
TLS2
RGL2
CSNL2
RSNL2
GL2
device turn-
off snubber
SL
VDD
RSC1
SCDL
RSC2
Vref
RREF1
ISP
RREF2
RS2
CIS
50pF
GND
Shunt
ISN
RS1
RFB
RFB= (RREF1||RREF2)
GND
RISO
ISO
CISO
100pF
GND
GND
GND
PGND


L
2,2µH
VBAT
RVS
CVS1
2,2µF
CVS2
10nF
PGND
CREG2
10nF
CREG1
2,2µF
PGND
RG
GND
RRPS
4.7kΩ
VS
VREG
RPP
RVDH
VDH
ENA
BH1
CBS1
330nF
THS1
CSNH1
CC1
CB1
GH1
RGH1
RSNH1
SH1
PGND
ERR
BH2
CBS2
330nF
THS2
CSNH2
CC2
CB2
GH2
RGH2
RSNH2
IL1
IH1
IL2
IH2
SH2
PGND
bulk
capacitors
TLE
7182EM
M
Low-side
current-feedback loop:
TLS1
CSNL1
GL1
RGL1
RSNL1
TLS2
CSNL2
GL2
RGL2
RSNL2
device turn-
off snubber
VDD
RSC1
SCDL
RSC2
Vref
RREF1
ISP
RREF2
RS2
Shunt
CIS
50pF
GND
ISN
RS1
RFB= (RREF1||RREF2)
GND
RISO
ISO
CISO
100pF
GND
RFB
GND
GND
PGND

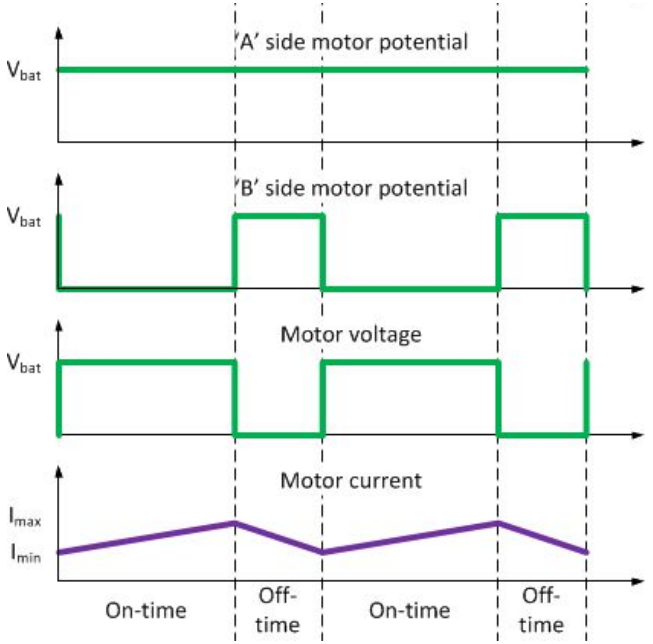


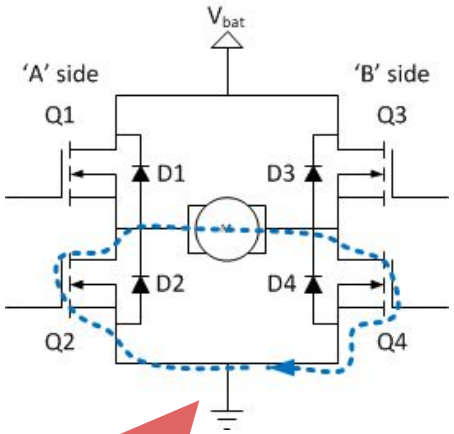
Above: "ON"/forward



Above: "slow-decay"

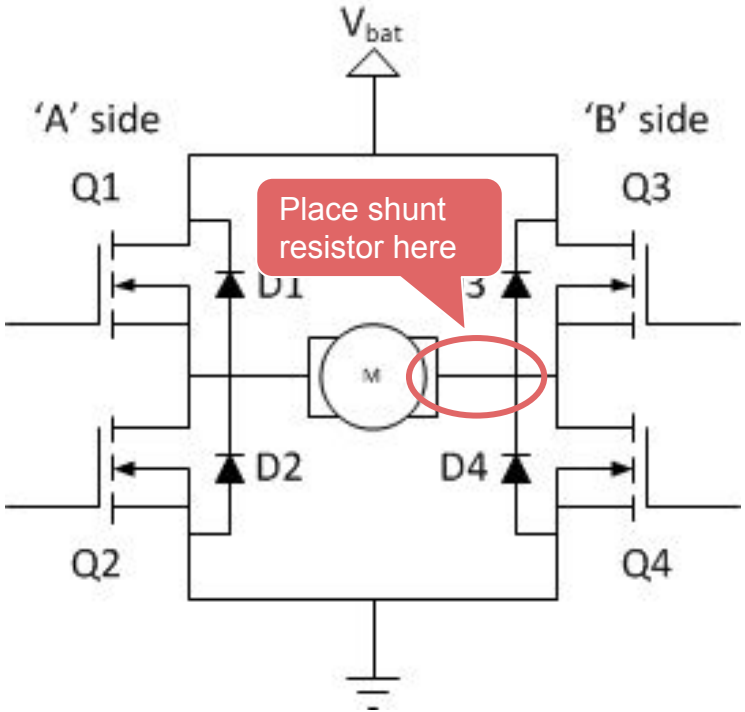
→ "ON" period
→ "OFF" period

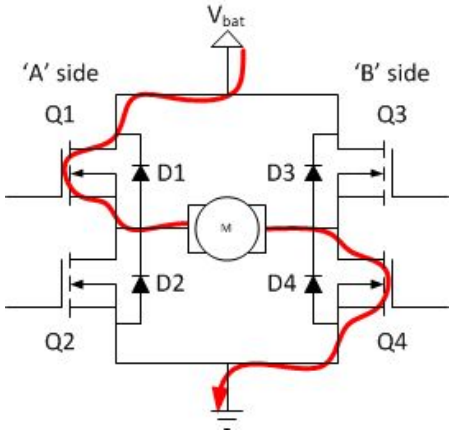




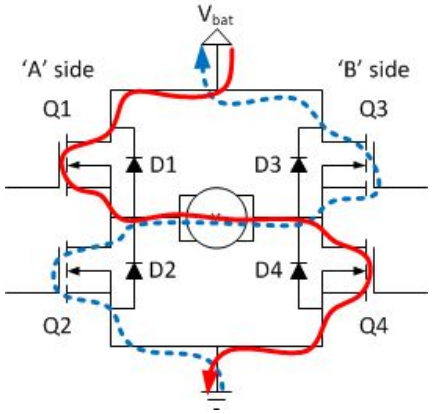
Current does not flow through low-side shunt during off cycle


distortion!
Tek Stop
Phase A Current
STEP
100mV
5.00 V
4.00ms
20.70 %
125MS/s
5M points
84.0mV
2 Nov 2015
16: 54: 30


V_{bat}
'A' side
'B' side
Q1
Q3
Place shunt resistor here
D1
M
D2
D4
Q2
Q4

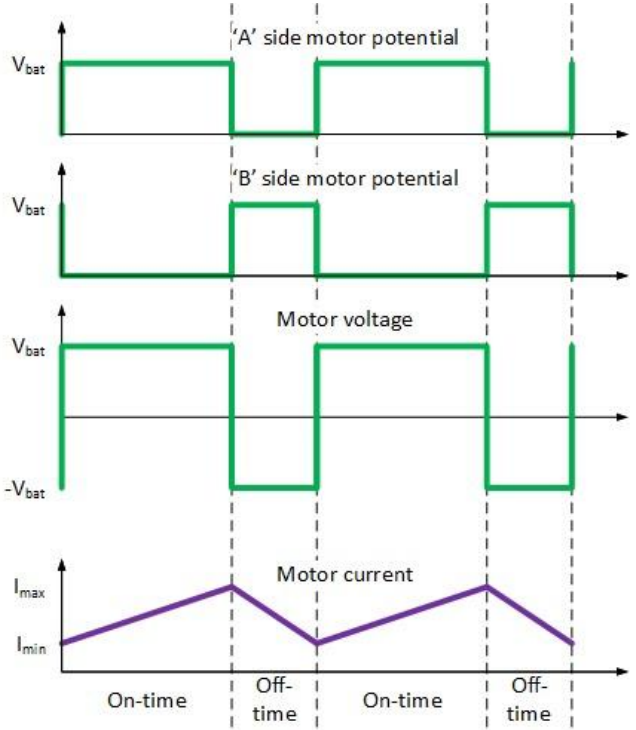


Above: "ON"/forward

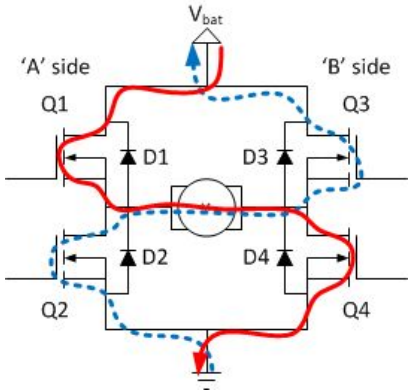


Above: "fast-decay"

→ "ON" period
→ "OFF" period

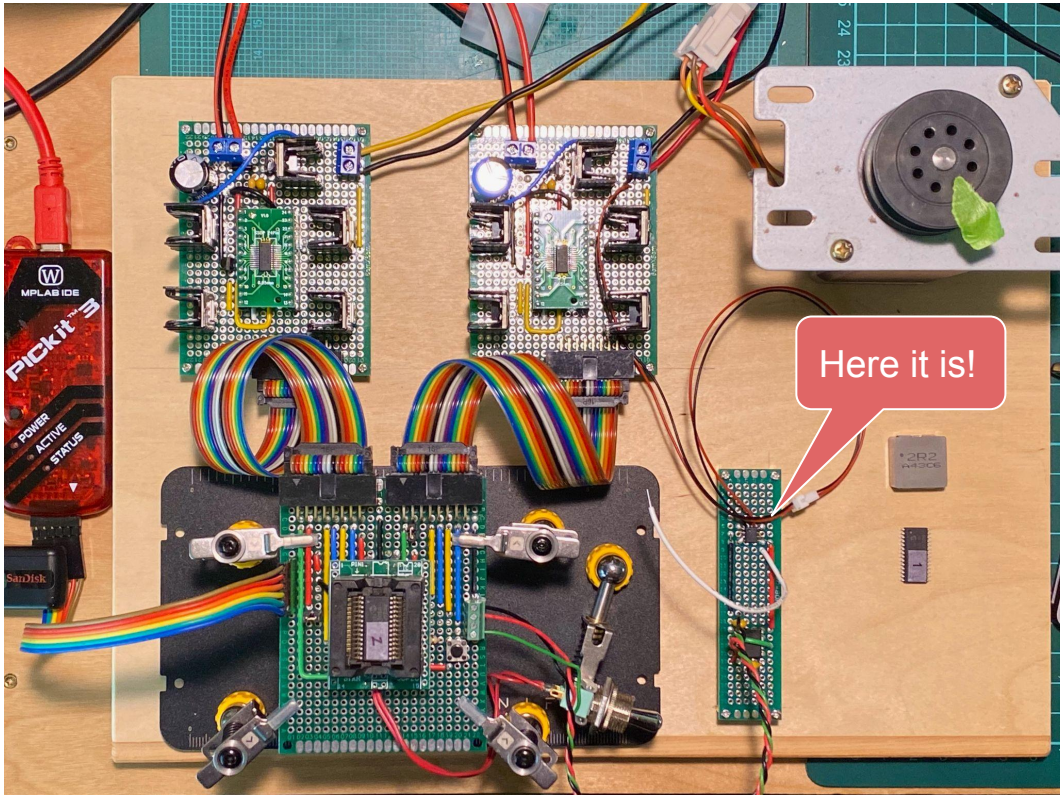


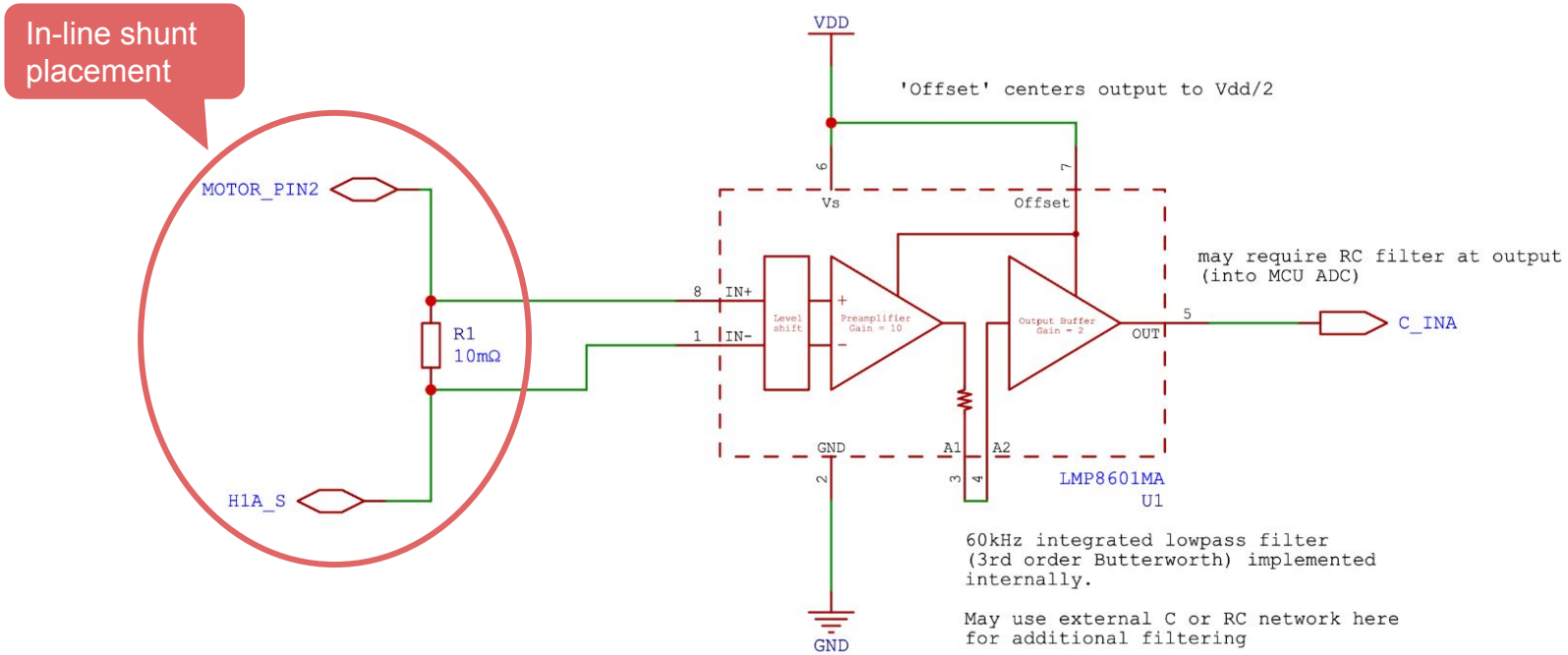
In-line current sensing: Reduced distortion

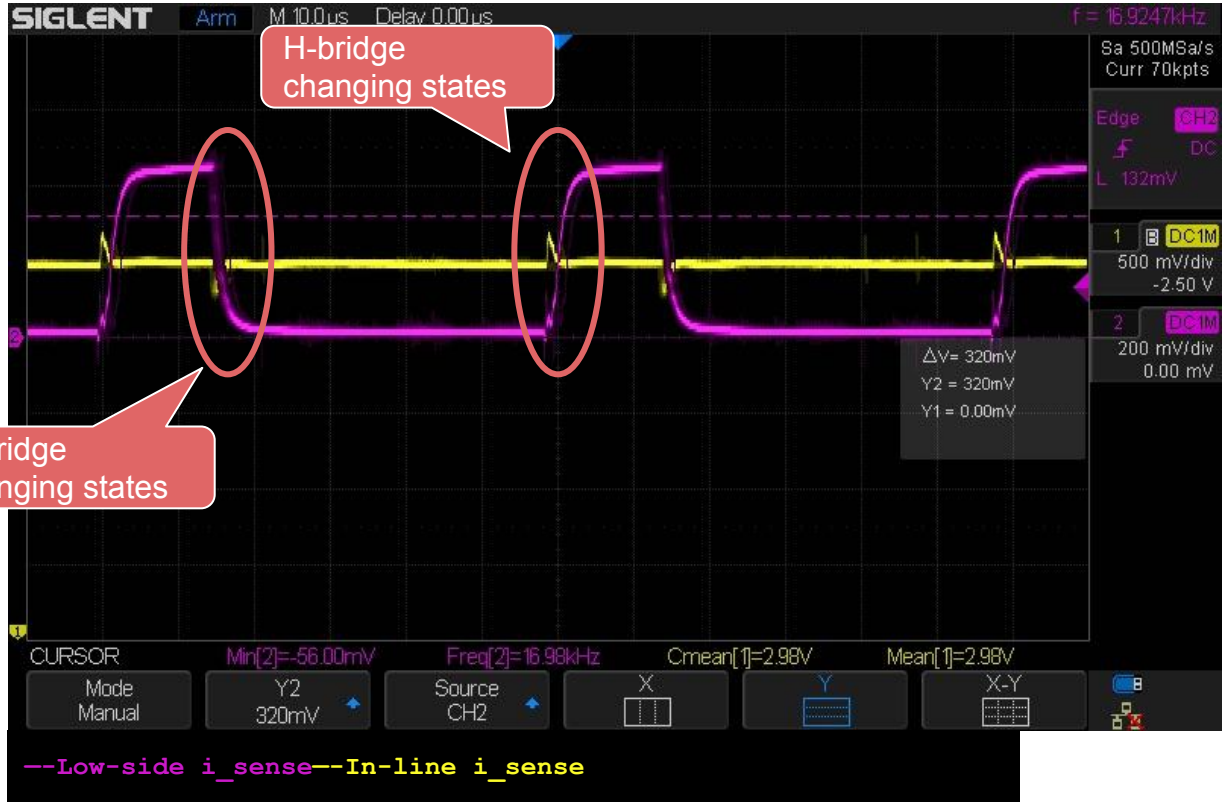


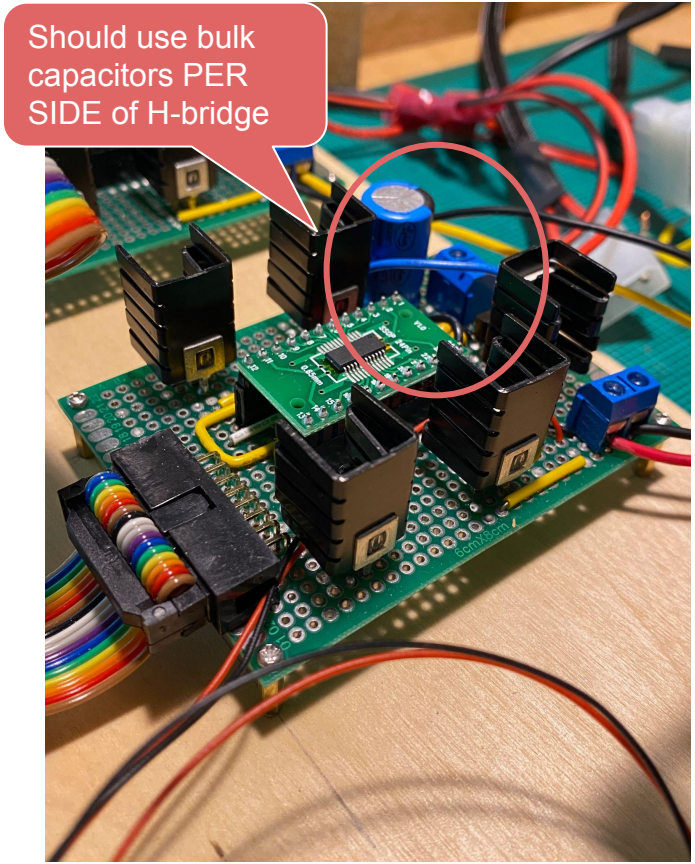
Above: "fast-decay"

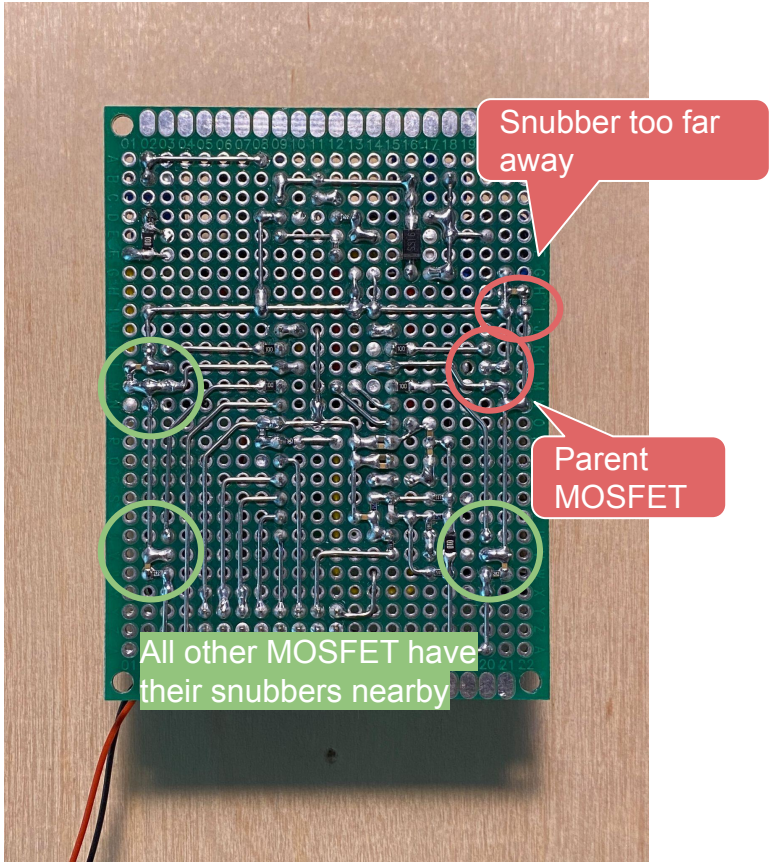
Source:
https://www.eenewseurope.com/en/improving-current-control-for-better-stepper-motor-motion-quality/

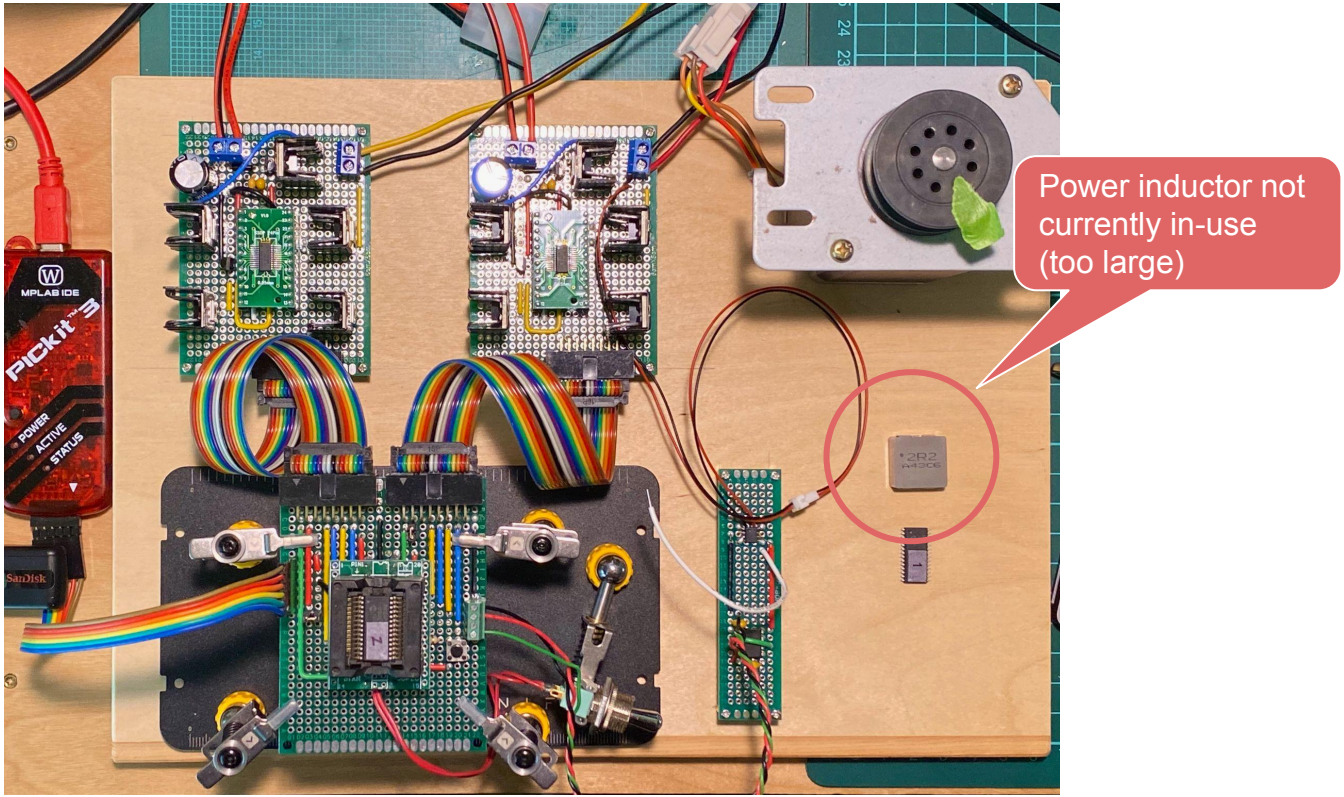

MPLAB IDE
PICkit 3
POWER
ACTIVE
STATUS
SanDisk
Here it is!


In-line shunt placement
MOTOR_PIN2
H1A_S
R1
10mΩ
VDD
'Offset' centers output to Vdd/2
6
Vs
7
Offset
8
IN+
1
IN-
Level shift
Preamplifier Gain = 10
Output Buffer Gain = 2
OUT
5
may require RC filter at output (into MCU ADC)
C_INA
GND
2
A1
3
A2
4
LMP8601MA
U1
GND
60kHz integrated lowpass filter (3rd order Butterworth) implemented internally.
May use external C or RC network here for additional filtering

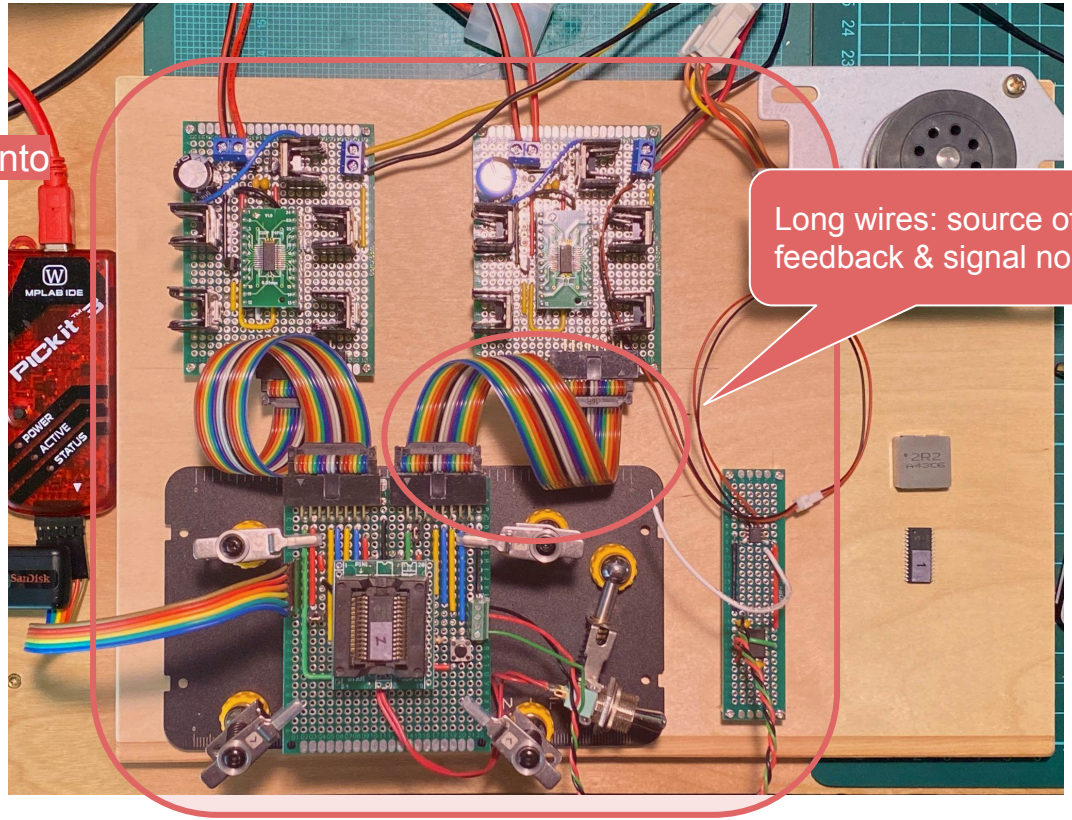

SIGLENT
Arm
M 10.0µs Delay 0.00µs
f = 16.9247kHz
H-bridge changing states
Sa 500MSa/s
Curr 70kpts
Edge CH2
DC
L 132mV
1 B DC1M
500 mV/div
-2.50 V
2 DC1M
200 mV/div
0.00 mV
ΔV= 320mV
Y2 = 320mV
Y1 = 0.00mV
H-bridge changing states
CURSOR
Min[2]=-56.00mV
Freq[2]=16.98kHz
Cmean[1]=2.98V
Mean[1]=2.98V
Mode Manual
Y2 320mV
Source CH2
X
Y
X-Y
--Low-side i_sense--In-line i_sense


Should use bulk capacitors PER SIDE of H-bridge

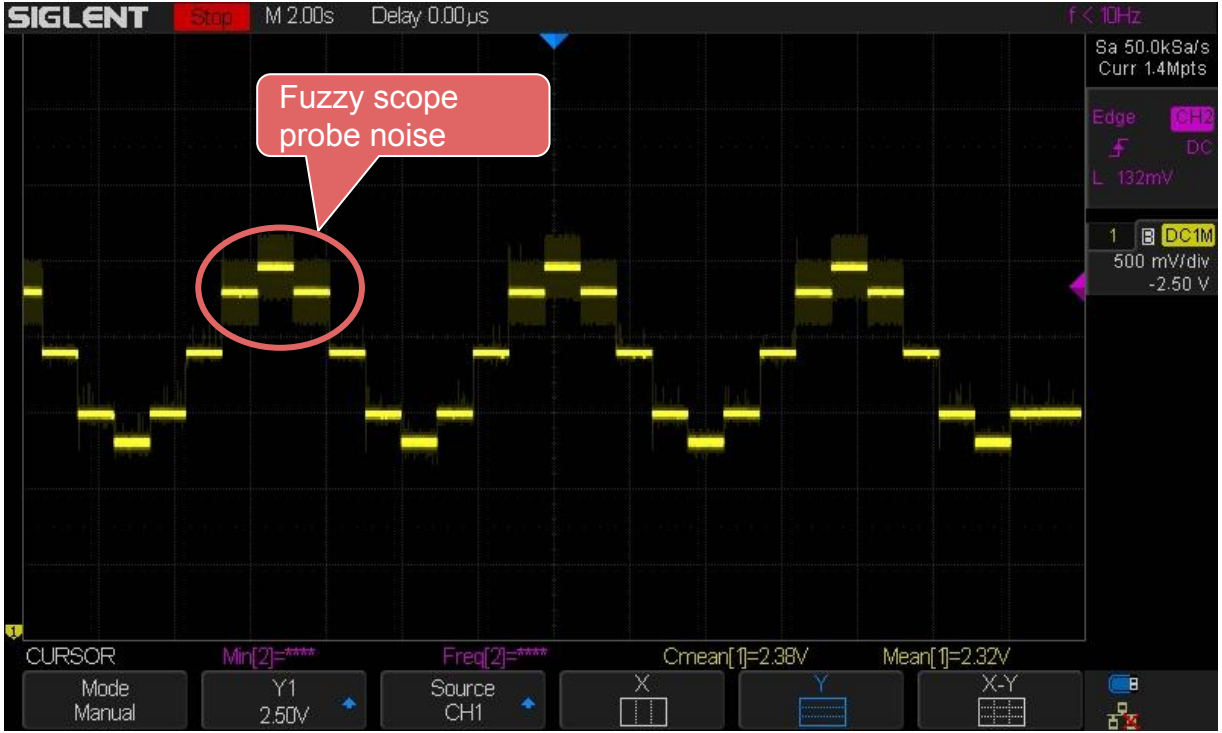

Snubber too far away
Parent MOSFET
All other MOSFET have their snubbers nearby


MPLAB IDE
PICkit 3
POWER
ACTIVE
STATUS
SanDisk
Power inductor not currently in-use (too large)

Consolidate into one board!



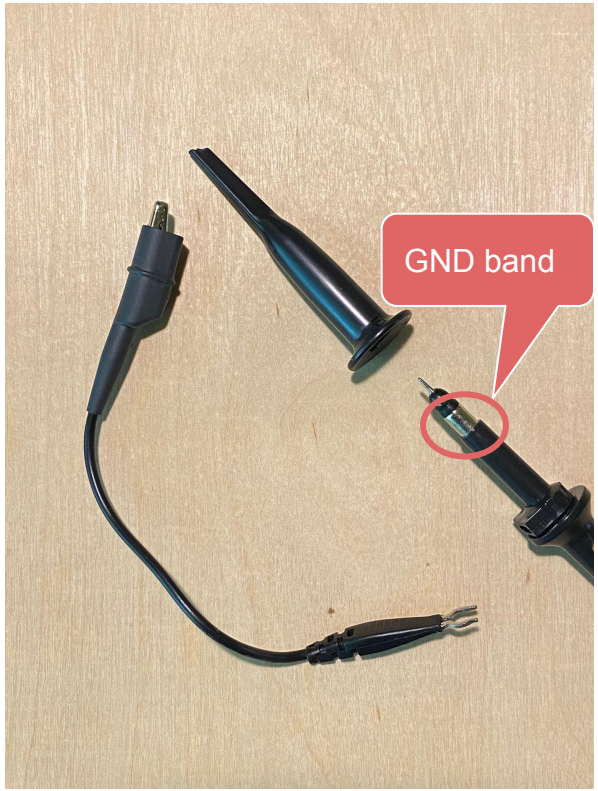
Long wires: source of feedback & signal noise!

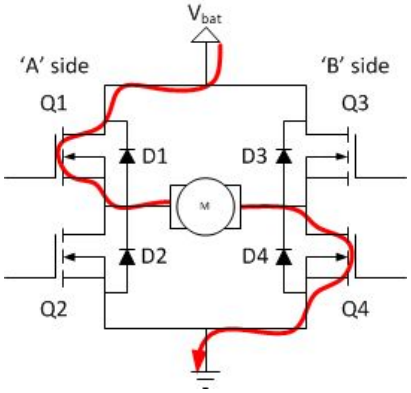

SIGLENT
Stop
M 2.00s
Delay 0.00µs
f < 10Hz
Sa 50.0kSa/s
Curr 1.4Mpts
Edge
CH2
DC
L 132mV
1
B
DC1M
500 mV/div
-2.50 V
Fuzzy scope probe noise
CURSOR
Min[2]=****
Freq[2]=****
Cmean[1]=2.38V
Mean[1]=2.32V
Mode Manual
Y1 2.50V
Source CH1
X
Y
X-Y

--Imotor

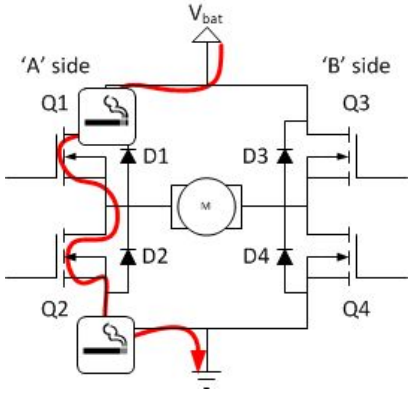

Long ground loop


remove!


GND band

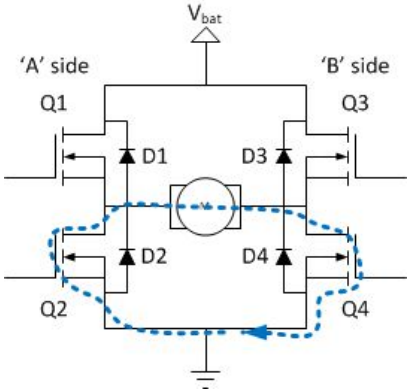


Above: "ON"/forward

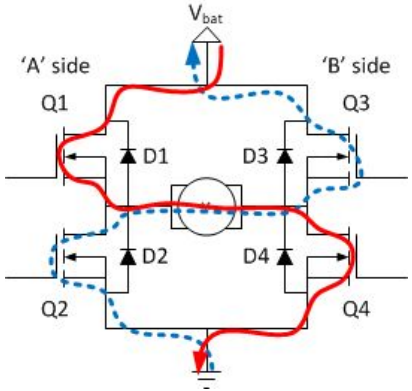


Above: "shoot-through" -PROHIBITED

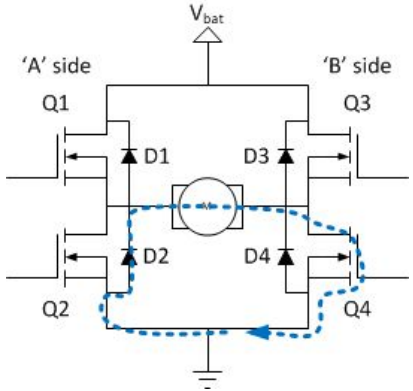
→ "ON" period
→ "OFF" period



Above: "slow-decay"



Above: "fast-decay"



Above: discontinuous current*

H-bridge: MOSFET selection

⑤ Calculated continuous current based on maximum allowable junction temperature. Package limitation current is 75A.

Q_{gd}	Gate-to-Drain (Miller) Charge	—	—	54		V_{GS} = 10V, S
$t_{d(on)}$	Turn-On Delay Time	—	14	—	ns	V_{DD} = 28V
t_r	Rise Time	—	101	—		I_D = 62A
$t_{d(off)}$	Turn-Off Delay Time	—	50	—		R_G = 4.5Ω
t_f	Fall Time	—	65	—		V_{GS} = 10V, Se
						Between lead

Source: IRF3205 datasheet
Note: switching time << motor tau

MOSFET driver output

5.1.11	Output source resistance	R_{Sou}	2	–	13.5	Ω	I_{Load}=-20mA
5.1.12	Output sink resistance	R_{Sink}	2	–	9.0	Ω	I_{Load}=20mA

Source: TLE7182EM datasheet
Remark: MOSFET switch time dominated by driver limitations

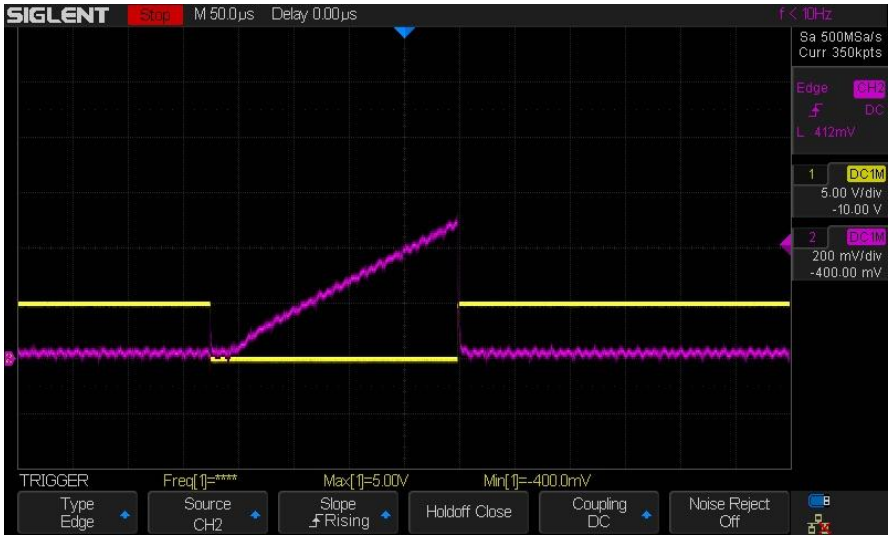
Design Deep Dive: MOSFET selection

- Given V_DD = 24V, Motor_R = 0.387ohm
  - I_max (steady state) = **62A**
- Operating at such high voltages reduces rise time T_rise from **12.4ms → 0.2ms**
  - However, faulty operation could lead to very high currents!

⑤ Calculated continuous current based on maximum allowable junction temperature. Package limitation current is 75A.

Q_{gd}	Gate-to-Drain (Miller) Charge	—	—	54		V_{GS} = 10V, S
$t_{d(on)}$	Turn-On Delay Time	—	14	—	ns	V_{DD} = 28V
t_r	Rise Time	—	101	—		I_D = 62A
$t_{d(off)}$	Turn-Off Delay Time	—	50	—		R_G = 4.5Ω
t_f	Fall Time	—	65	—		V_{GS} = 10V, S

Above: from IRF3205 datasheet
Note: switching time << motor tau

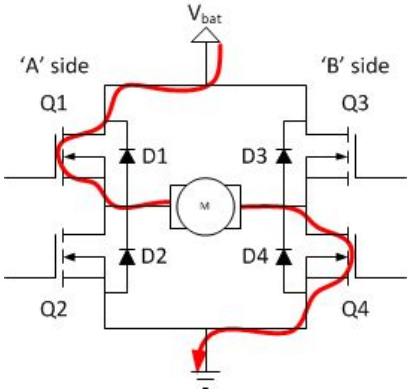


--Motor current, V_DD = 24V

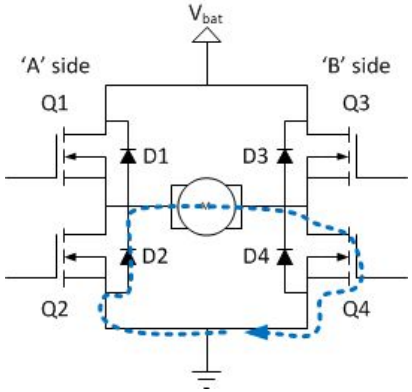
MOSFET driver output

5.1.11	Output source resistance	R_{Sou}	2	–	13.5	Ω	I_{Load}=-20mA
5.1.12	Output sink resistance	R_{Sink}	2	–	9.0	Ω	I_{Load}=20mA

Left: from TLE7182EM datasheet
Remark: MOSFET switch time dominated by driver limitations

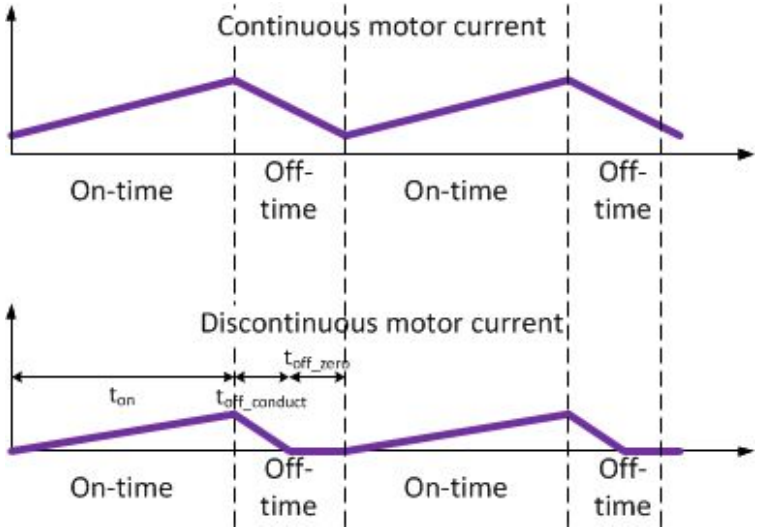


Above: "ON"/forward



Above: discontinuous current flow

→ "ON" period
→ "OFF" period



Above: because of the body diode, motor current is prevented from reversing