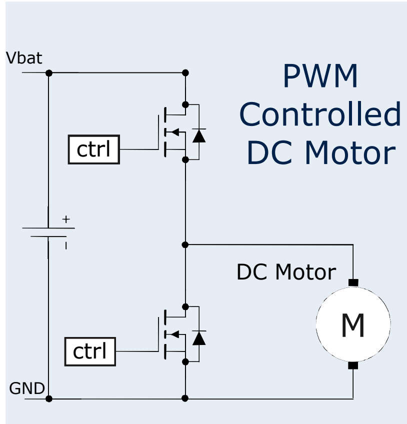
Hardware considerations Electric Power Steering

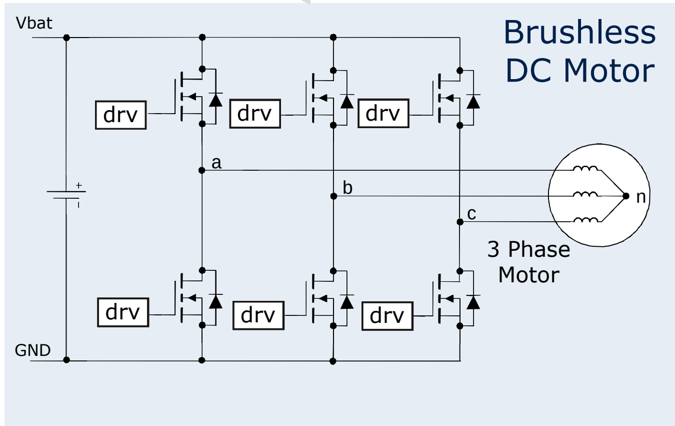
EPS Workshop China

Power on Demand
Electric Power Steering

- Demand oriented torque controlled electric motor
- Reduced Average Power Consumption down to < 50W

Continuously Mechanical Hydraulic Pump



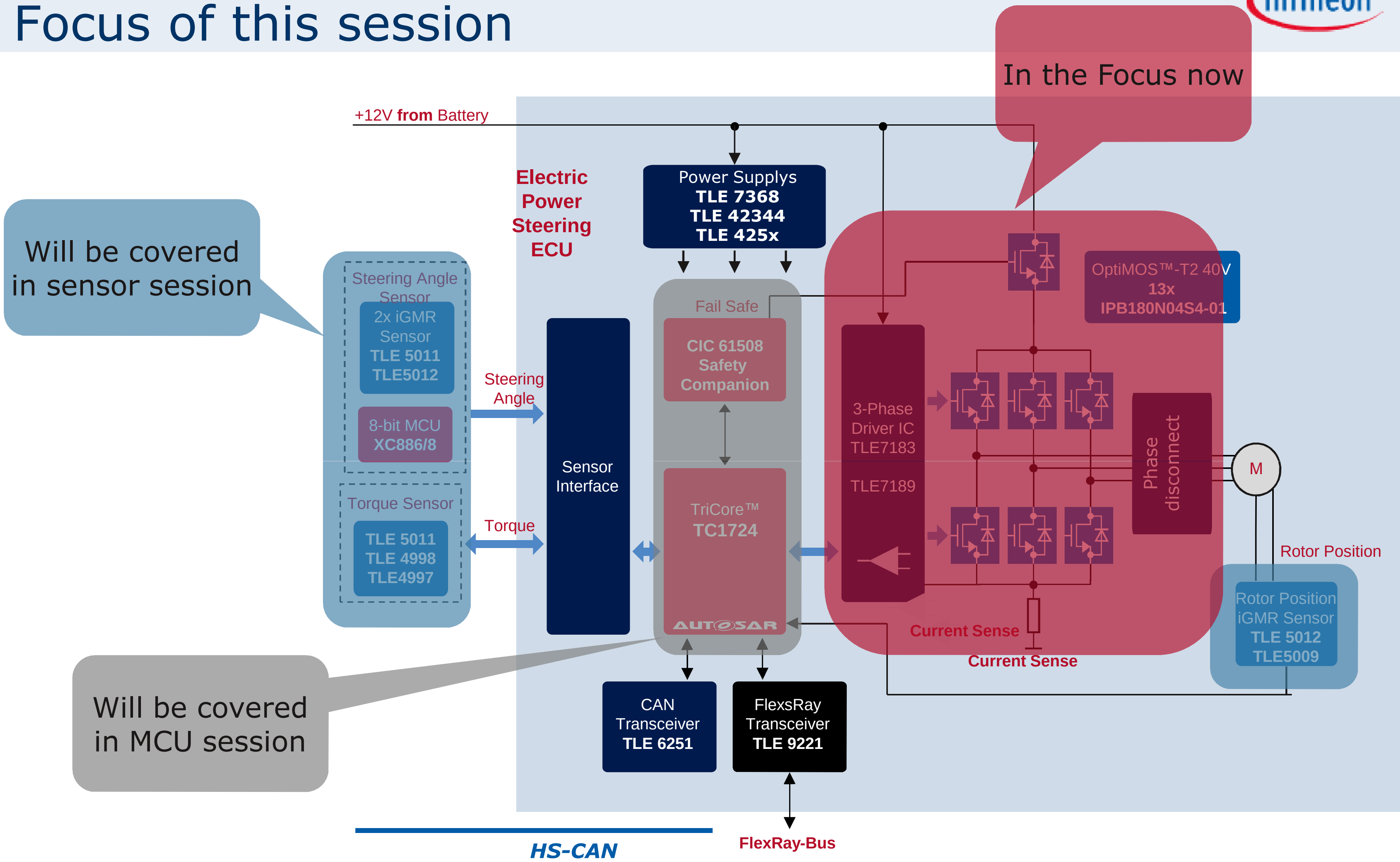


Total Equivalent Electric Power Saving ~ 250 W

Source : ZFLS

CO_2-reduction ~ 5.9 g/km

Electric Power Steering System
Focus of this session



Application requirements Power Steering

- Basic requirements to power stage
  - 3-phase motor drive
  - 100-160A phase current
  - Field oriented control
  - mostly 12V application
  - High functional safety

Drive high currents

Measure current precice

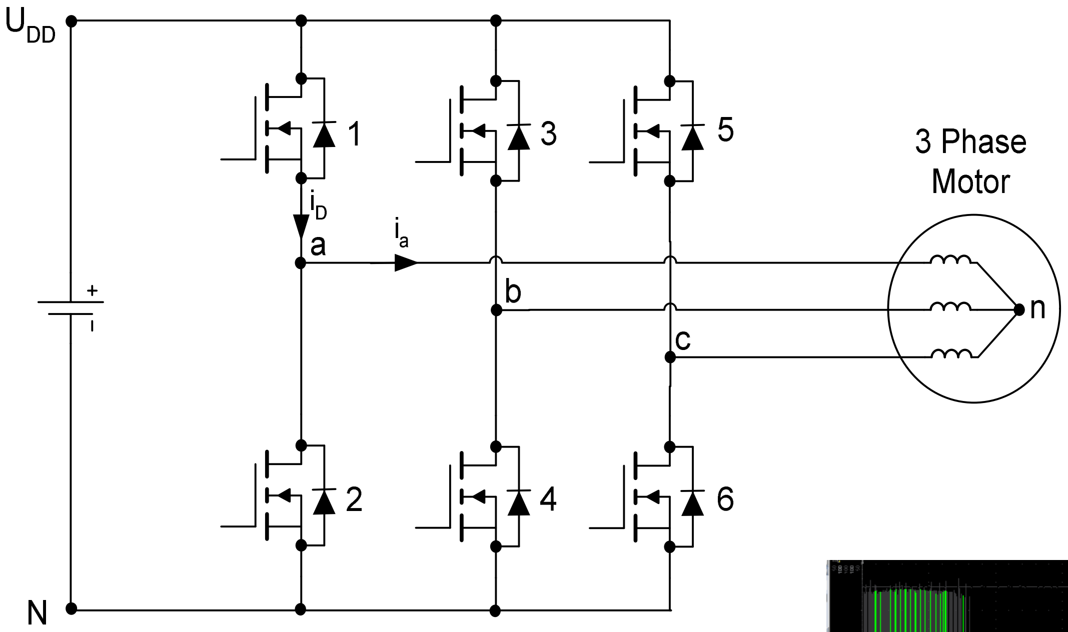
Second switch-off path

- Trends
  - has to work at lower supply voltages
  - (only one shunt for current measurement)
  - increasing accuracy of current measurement
  - highest efficient usage of motor (0...100% duty cycle)
  - fulfill ASIL D safety requirement in application

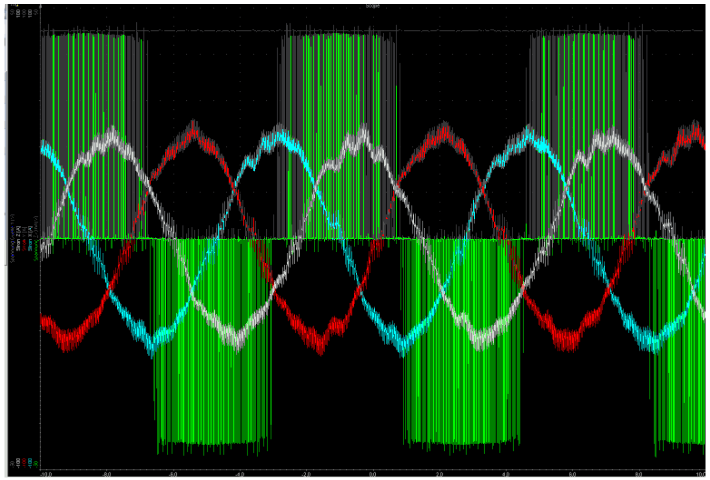
Agenda

- Application requirements EPS (**P**ermanent **M**agnet **S**ynchronous **M**otor)
  - **Driving high currents**
    - Spikes: Why they are harmful
    - Layout recommendations
    - Requirements to MOSFETs and Driver ICs
  - **Measure Current precisely**
    - How many shunts to use?
    - How does it work with one shunt
    - Requirements for driver IC
    - What to consider with IFX OpAmps in driver ICs
  - **Functional Safety: Second switch off path**
    - Star-Point relay vs. MOSFETs

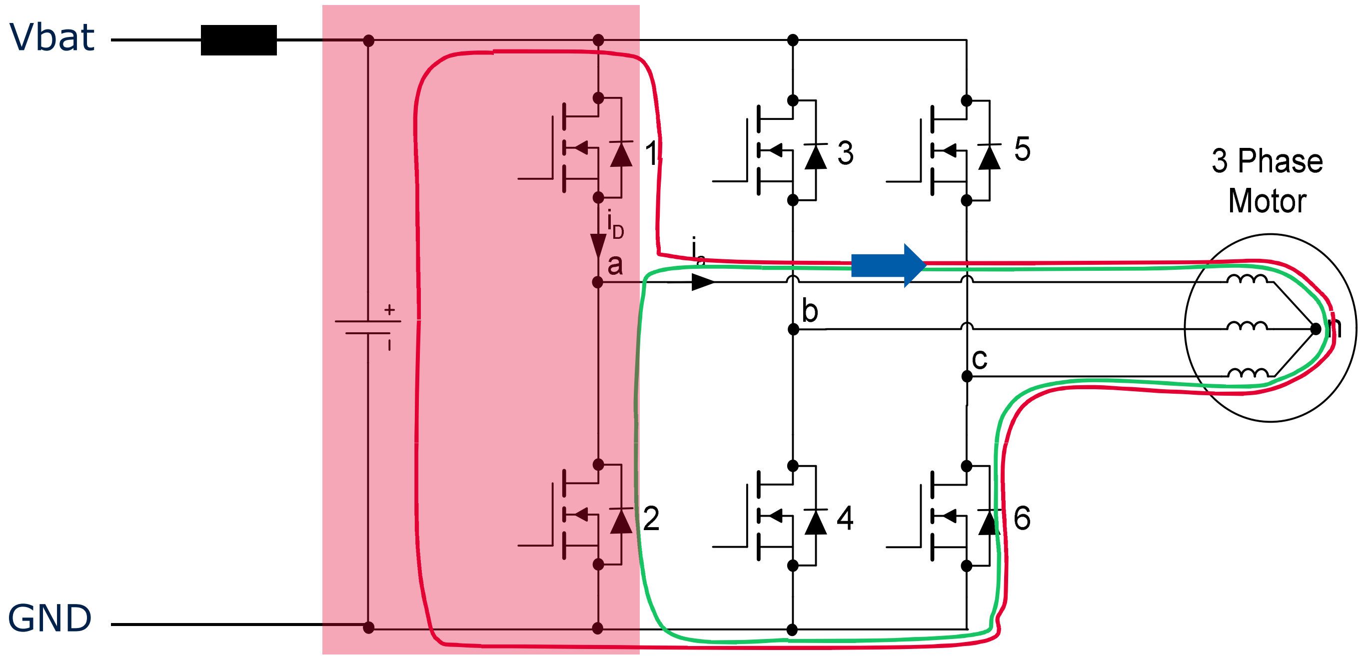
Basic function of each Power Bridge



- **Task of the bridge**
  - Switch voltage at phase
  - Let current commutate
    - Current jumps from LS to HS MOSFET and vice versa

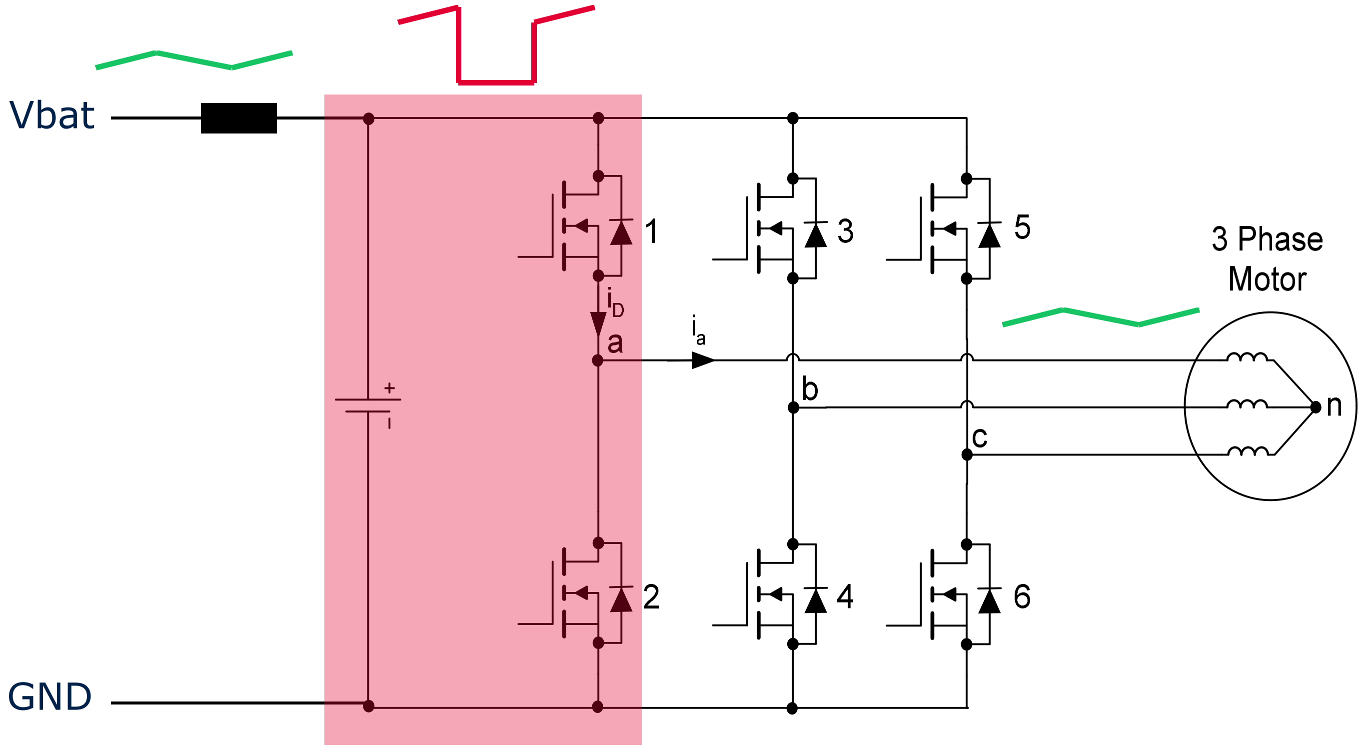


Example MOSFET 1 and 2 switching



- Example: MOSFET 1 and 6 on
  - Switch off 1: Current flow changes
  - Current will be freewheeling in Diode of MOSFET 2

Example MOSFET 1 and 2 switching
Current shape

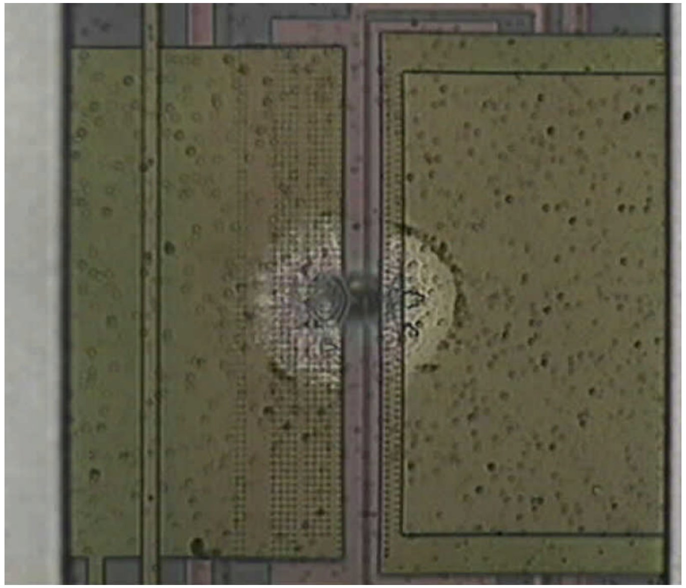


- Current from battery smoothened by inductance of ∏-filter (~µH)
  - ~ 1A/µs
- Current in Motor smoothened by motor inductance (~50µH)
  - ~ 0,2 A/µs
- Current in marked area jumps from 0 to motor current
  - ~ 1000A/µs
  - 10 nH together with 1000A/us are creating 10V Spikes

Why are voltage spikes critical?

- Examples for Problems in Motor drives:
  - Unwanted Short circuit detection (noise)
  - Violation of maximum ratings of the components
  - Electro-magnetic noise

- Consequences
  - Motor does not run reliably
  - Destruction of components
  - Disturbance of analog signals
  - EMC Problems



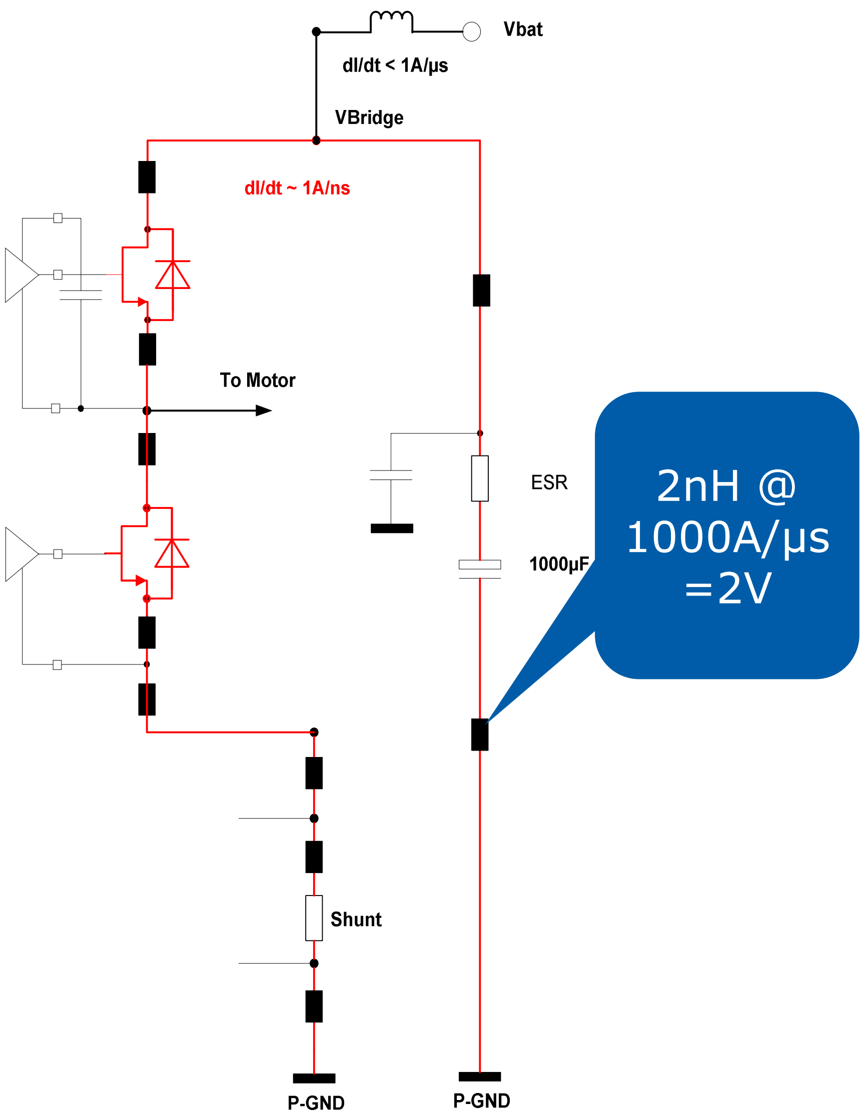
Over and under voltages
Spikes caused by Stray Inductances

Commutations means generating dI/dt in the „red path“

L is the sum of the inductances in the red path.

U is generated by switching off a MOSFET

$$\frac{dI}{dt} = -\frac{U}{L}$$



Over and under voltages
Spikes caused by Stray Inductances

Example 1:

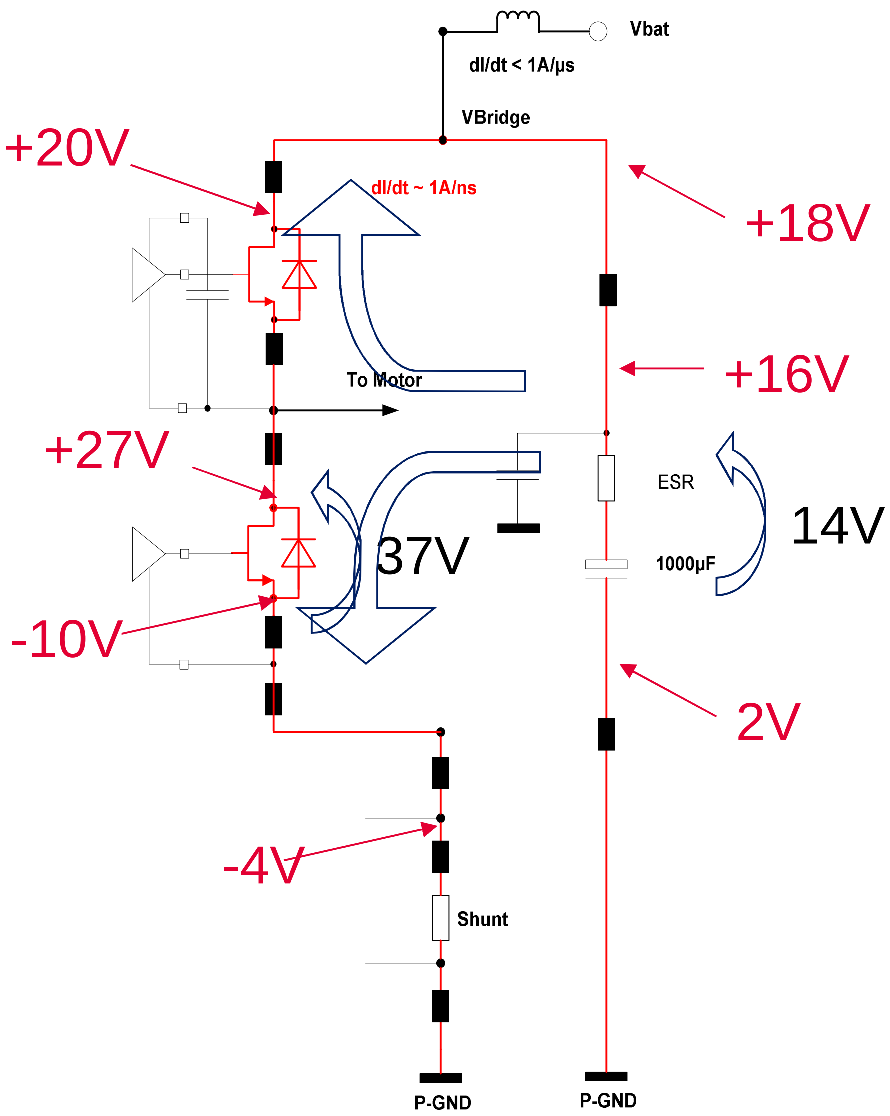
1) Current flows from motor to LS switch
2) LS switch is switched off
3) Current flows over diode of HS switch

Voltages in red are related to GND
Voltages in black are relative voltages

di/dt across stray inductances cause:

- **Over and under voltages**
- **EMC noise**
- **... result in high component costs**

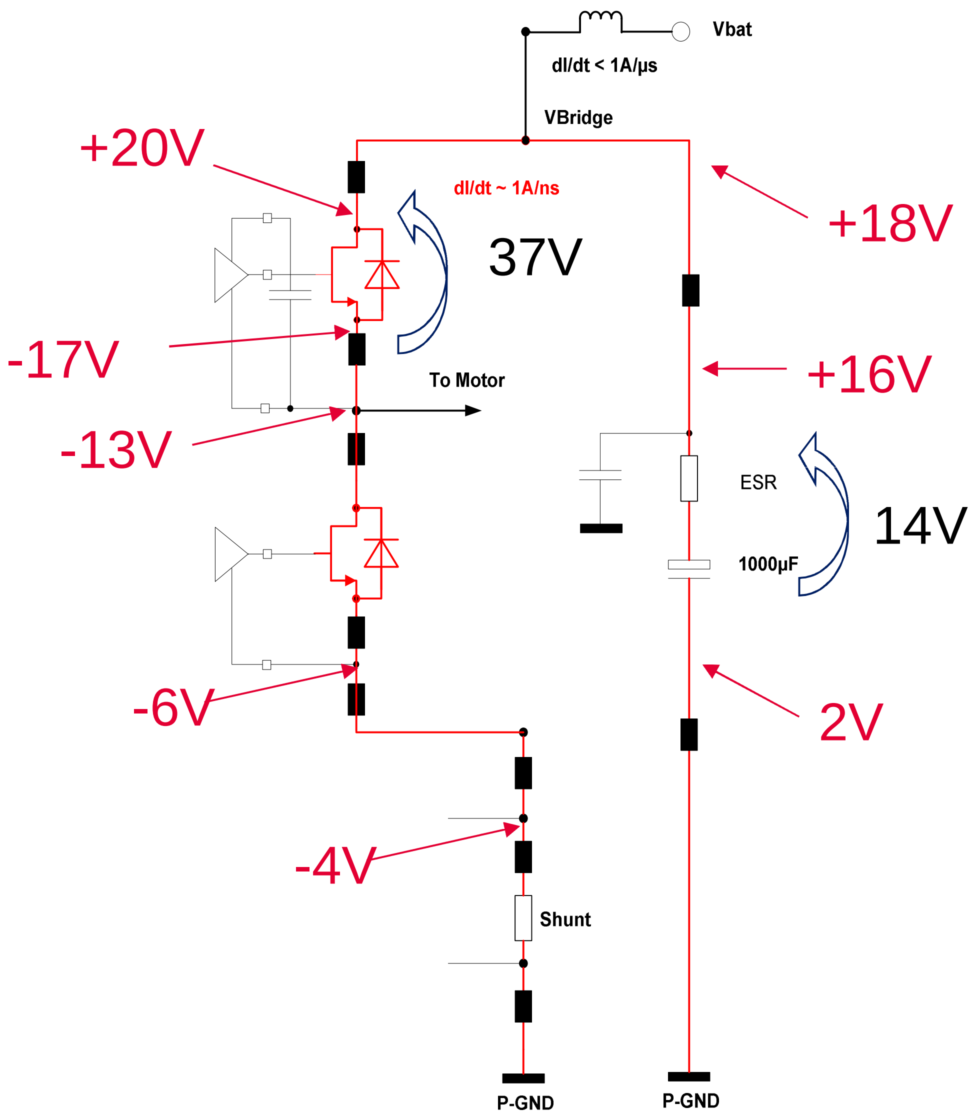
→ keep stray inductances small !!!



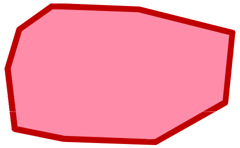
Over and under voltages
Spikes caused by Stray Inductances

Example 2:

1) Current flows from motor to HS switch
2) HS switch is switched off
3) Current flows over diode of LS switch



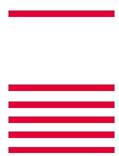
Over and under voltages
Spikes caused by Stray Inductances

- How to identify stray inductivities
  - Find out the current path on the PCB
  - Investigate the Area which is created by this path
    - Not so good 
    - better 
- The smaller the area – the better
  - No long distances !!

What can be done to avoid stray inductivities?

- Place all components in the red area close together
  - HS + LS MOSFET
  - DC Link capacitor (Elko + ceramic cap)
  - Shunt

- Avoid thin connections
  - Parallel wires have lower inductance as a single wire

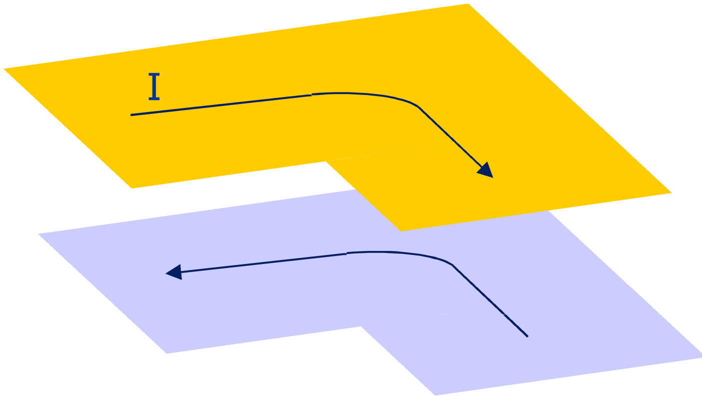


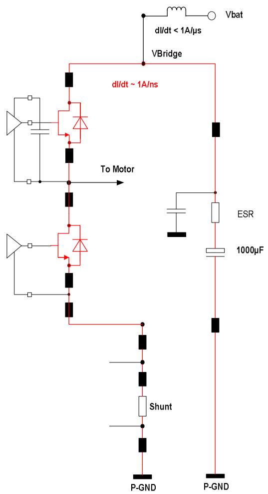
- If possible:
  - Optimize each half-bridge for itself
  - One cap per half-bridge needed

Reducing stray inductances and ohmic resistances

More possibilities

- Use of GND and VBB planes
- “guided” current flow





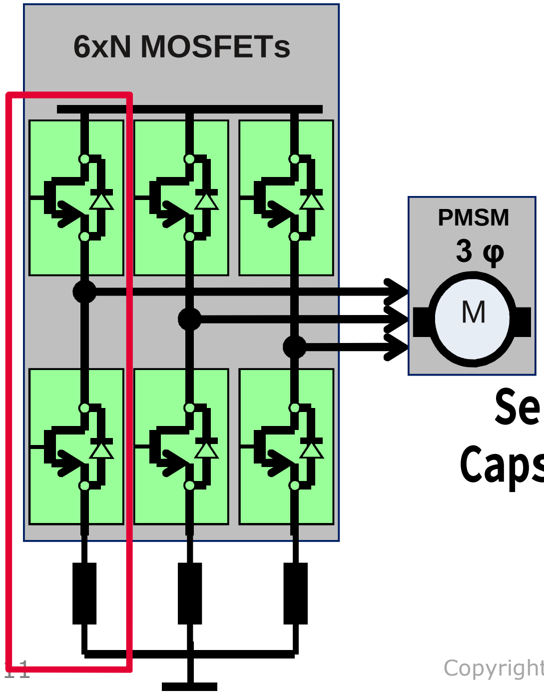
Generated electro-magnetic field compensate in some distance

Planes add “capacitance” all over the current path = smoothens over and under voltages

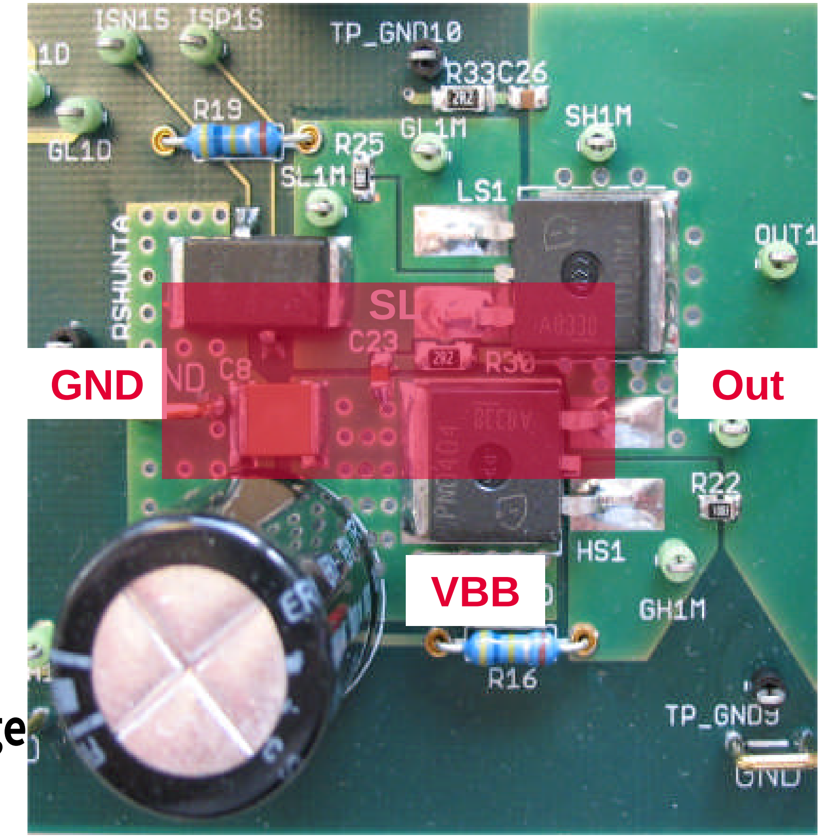
Reducing stray inductances and ohmic resistances

Example 1: Optimized Half Bridge = 3 shunts

- Minimize the distances in the red path
- Use LOW ESR / low ESL capacitors
- Avoid vias (resistance)

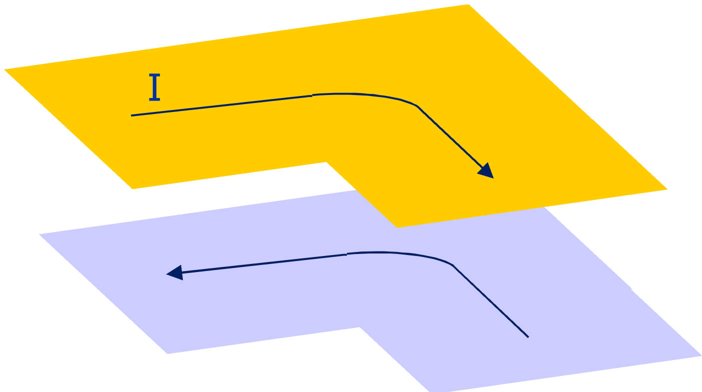


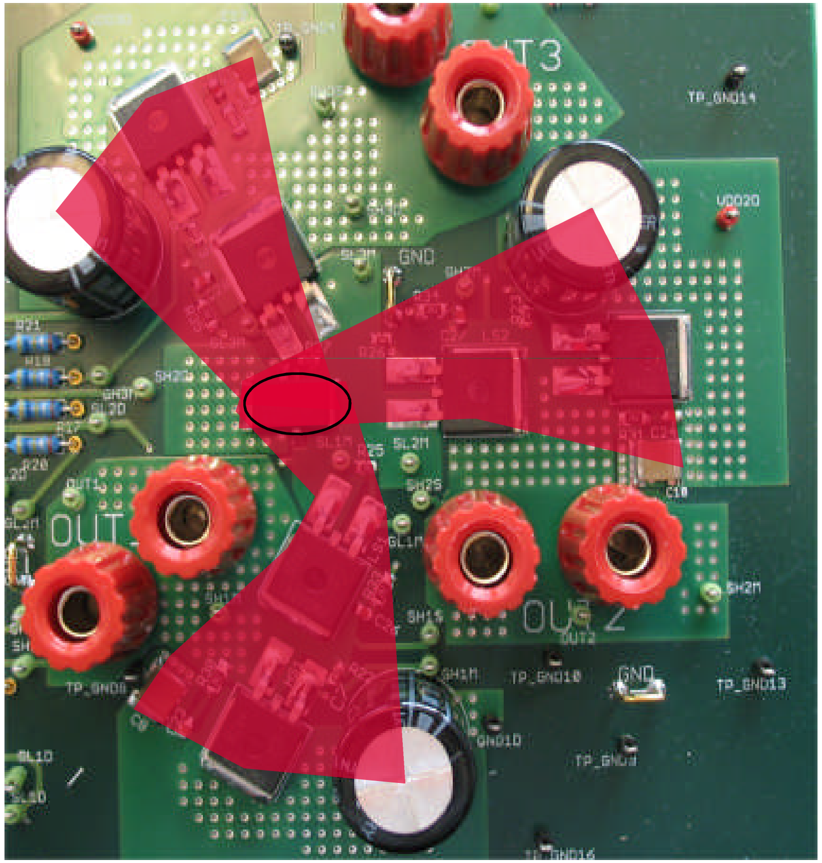
Separate DC-link Caps per half-bridge



Example with common shunt

- Use of GND and VBB planes
- Current flows back from shunt to capacitor through GND plane

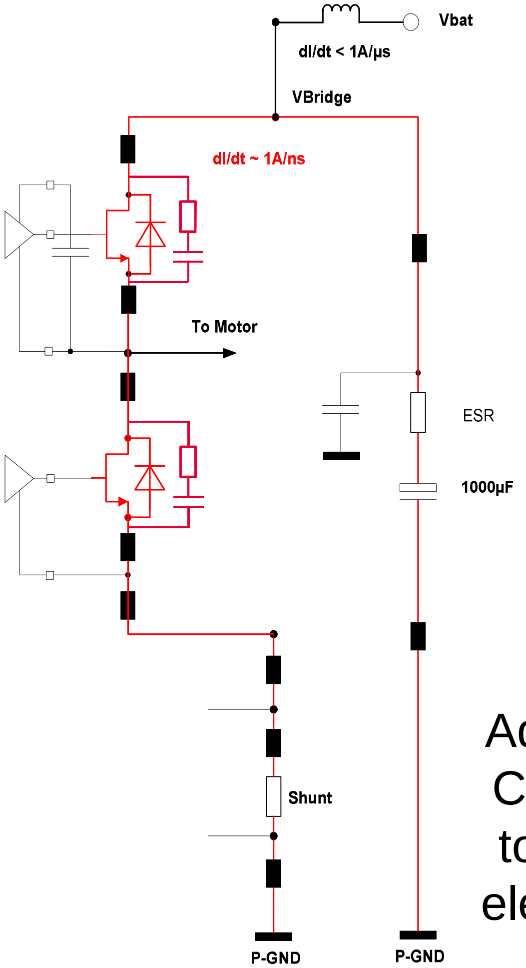




GND and VBB planes are good heat sinks as well !

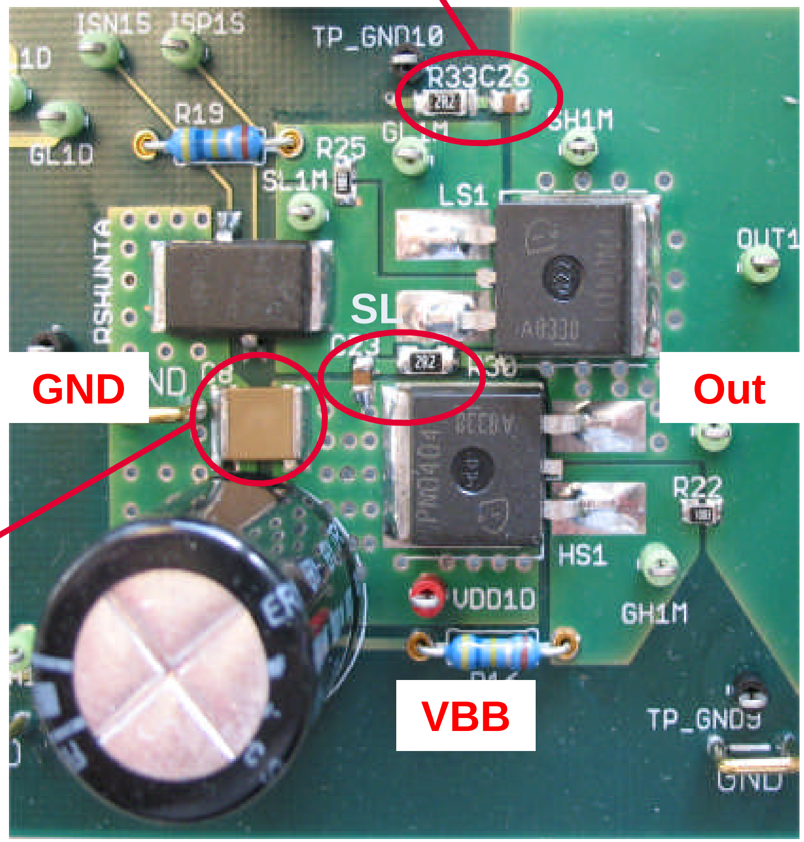
Further noise reduction

Some possibilities



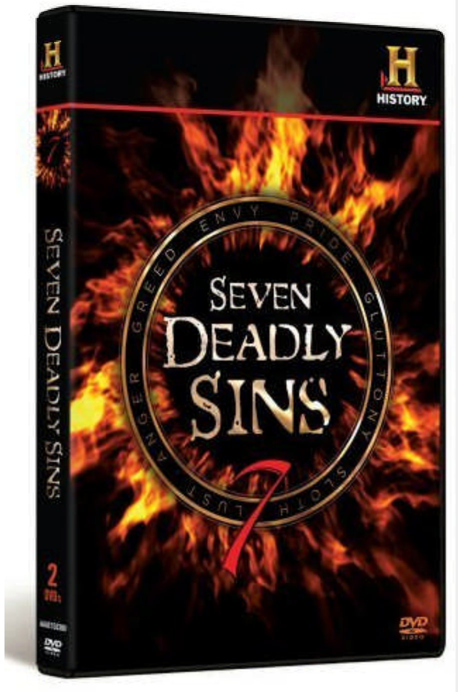
Add a snubber circuit to each MOSFET

Add ceramic C in parallel to the large electrolytic C



The Seven Deadly Sins

1. Place MOSFETs far from each other
2. Use Elko with high ESR and ESL
3. Forget to place ceramic caps in parallel
4. Place Elko or ceramic cap far from MOSFETs
5. Use thin connections
6. Forget that shunt is part of the critical path
7. Optimize the wrong paths (battery or motor connection)



Additional effects leading to over and under voltages:

- **Stray inductances**
  Over and under voltages (L x di/dt)
  Power dissipation

√

- **Ohmic parasitics**
  Over and under voltages
  Power dissipation

Normally OK

- **Snappy diodes of MOSFETs**
  High dI/dt
  Over and under voltages
  EMC noise

Choice of MOSFETs

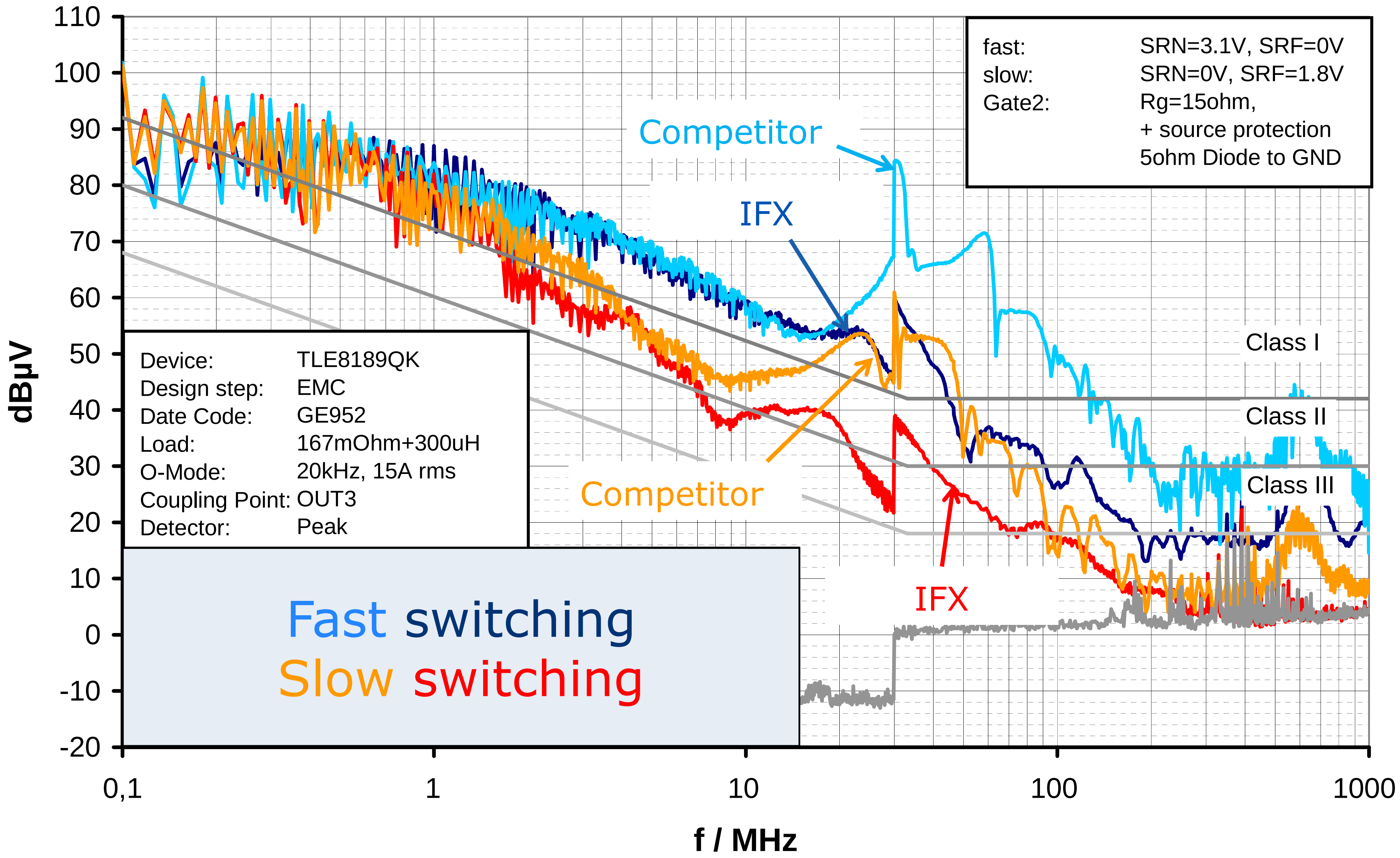
- **Use MOSFETs with a soft recovery behavior (not snappy)**

- **Problem: Specifications of MOSFETs do not provide this information (Qrr and trr are only indications)**

- **Proposal: Test your choice of MOSFETs in EMC tests to see the difference**

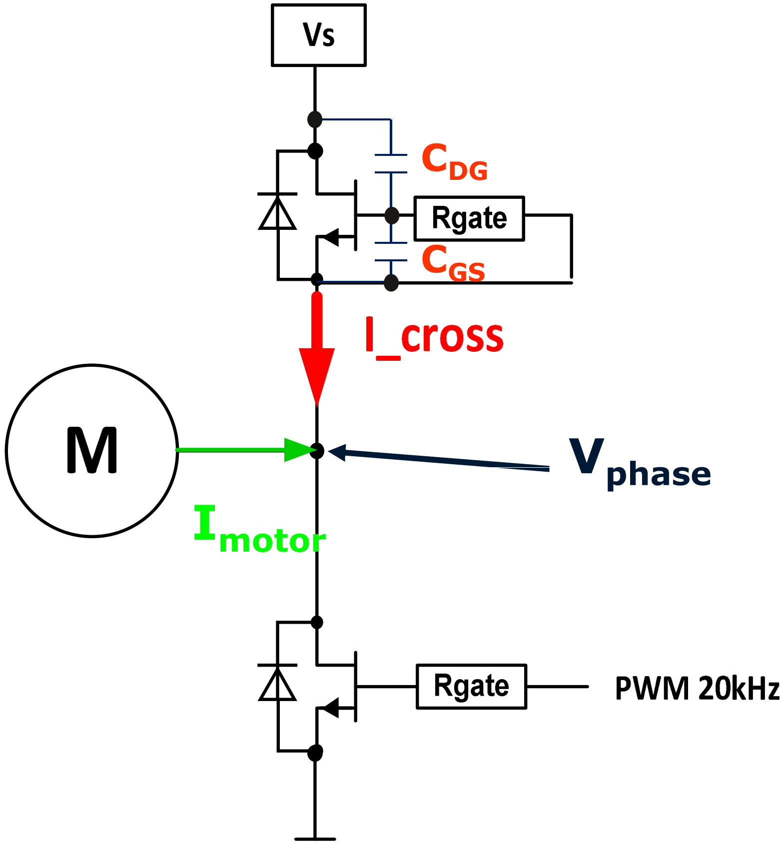
- **IFX MOSFETs (OptiMOS™-T) get usually good feedback !**

EMC characteristics results
comparison OptiMOS™-T2 MOSFET vs competitor



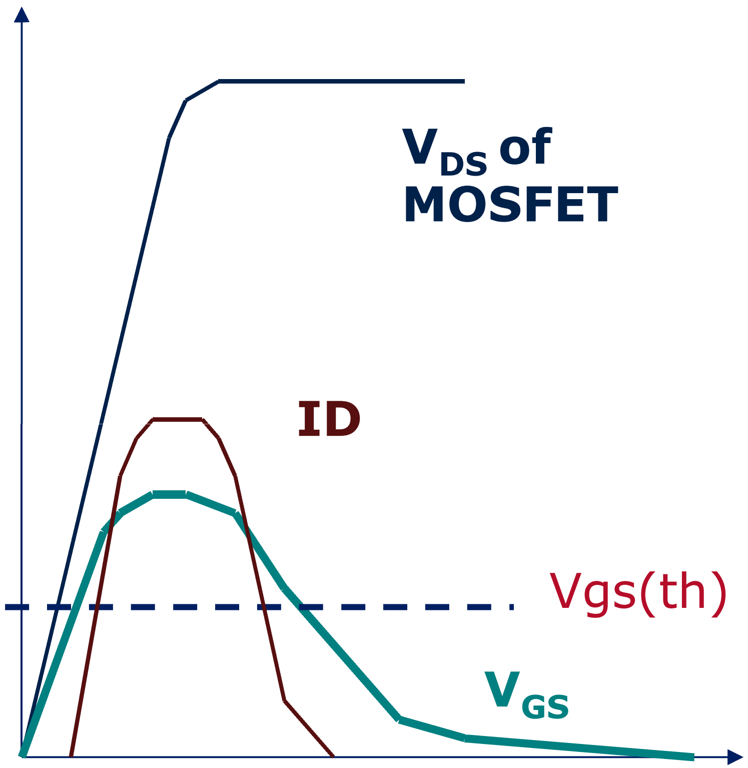
Cross Current in MOSFET Inverter

- PWM in an MOSFET inverter
  - Low side MOSFET is switched ON ➔ VDS of HS2 rises fast
  - C_{DG} and C_{GS} act as capacitive voltage divider
  - Rising VGS caused by C_{DG} and C_{GS}
  - High side MOSFET switches “on” a bit
  - I_cross might flow



Cross Current in MOSFET Inverter

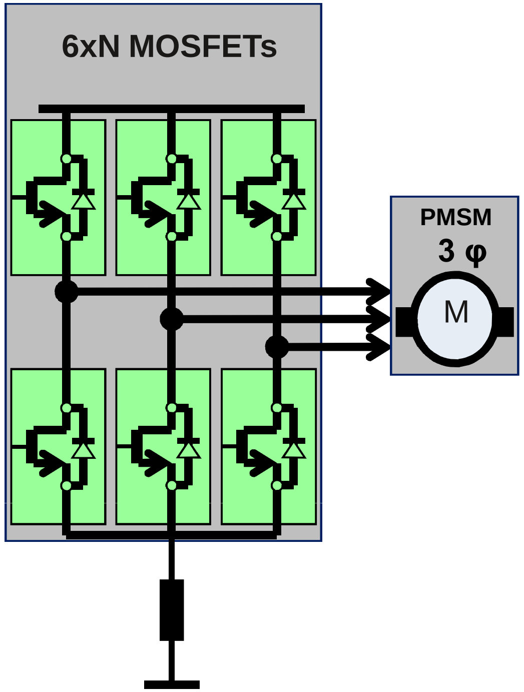
$$V_{GS} \approx \frac{V_{DS}}{\left(\frac{C_{GS}}{C_{GD}}\right)}$$



- If V_{GS} exceeds Vgs(th) ➔ current will flow across the entire bridge leg ➔ Cross Current
- The higher C_{GS} / C_{DG} the less cross current
- C_{GS} / C_{DG} of OptiMOS™-T2 is 8x higher than competition

Application requirements Power Steering

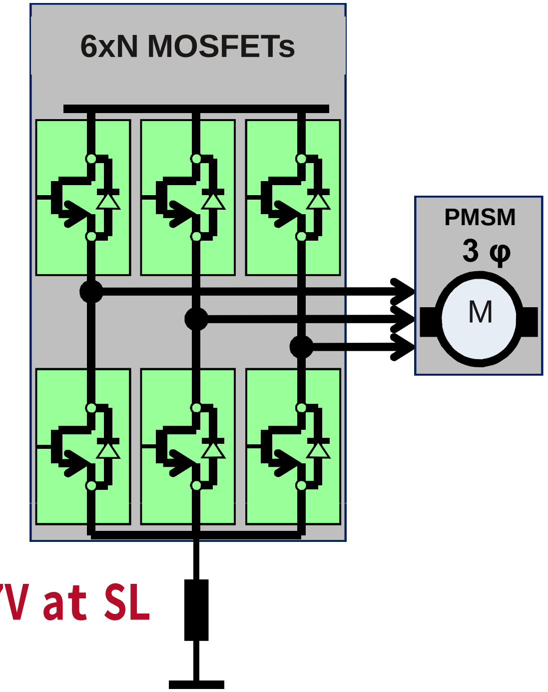
- **160A B6-Bridge**
  - Between 1-2mOhm MOSFET
  - 40V Normal Level (Vgs(th)>2.5V)
  - high current rating package
  - Low gate charge
  - automotive qualified
  - Low feedback of VDS to VGS



IPB180N04S3-02 or IPB180N04-00

e.g.	IPB180N04-00	
RDSon	0,98mΩ max @ RT	
Idrain	180A	720A peak !!
RthJC	0,5 K/W	good cooling
Qgtot	220 nC	low gate charge
Qgd	29 nC	low feedback to gate!
Qrr	132nC	good EMC behavior

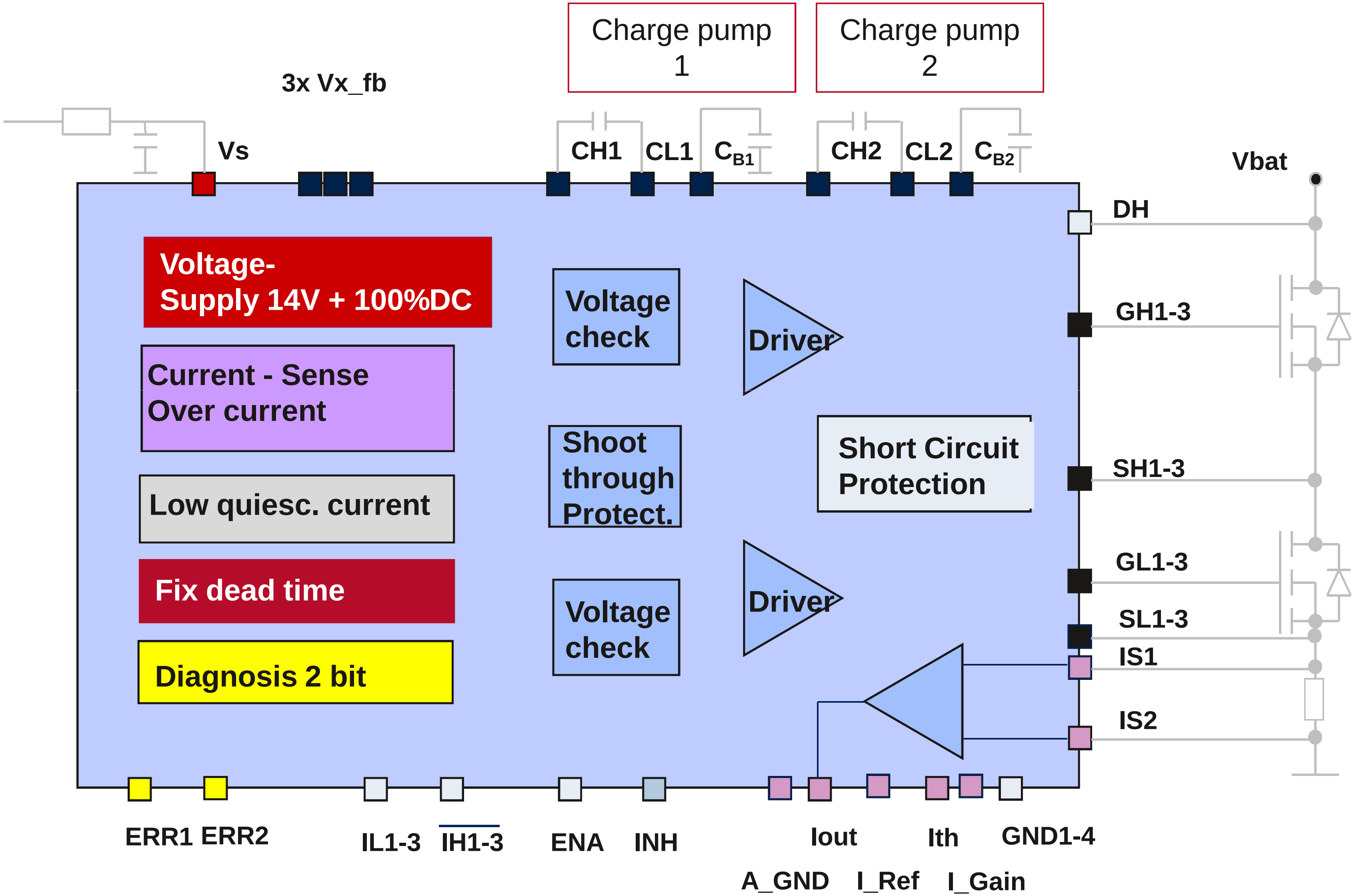
Application requirements Power Steering



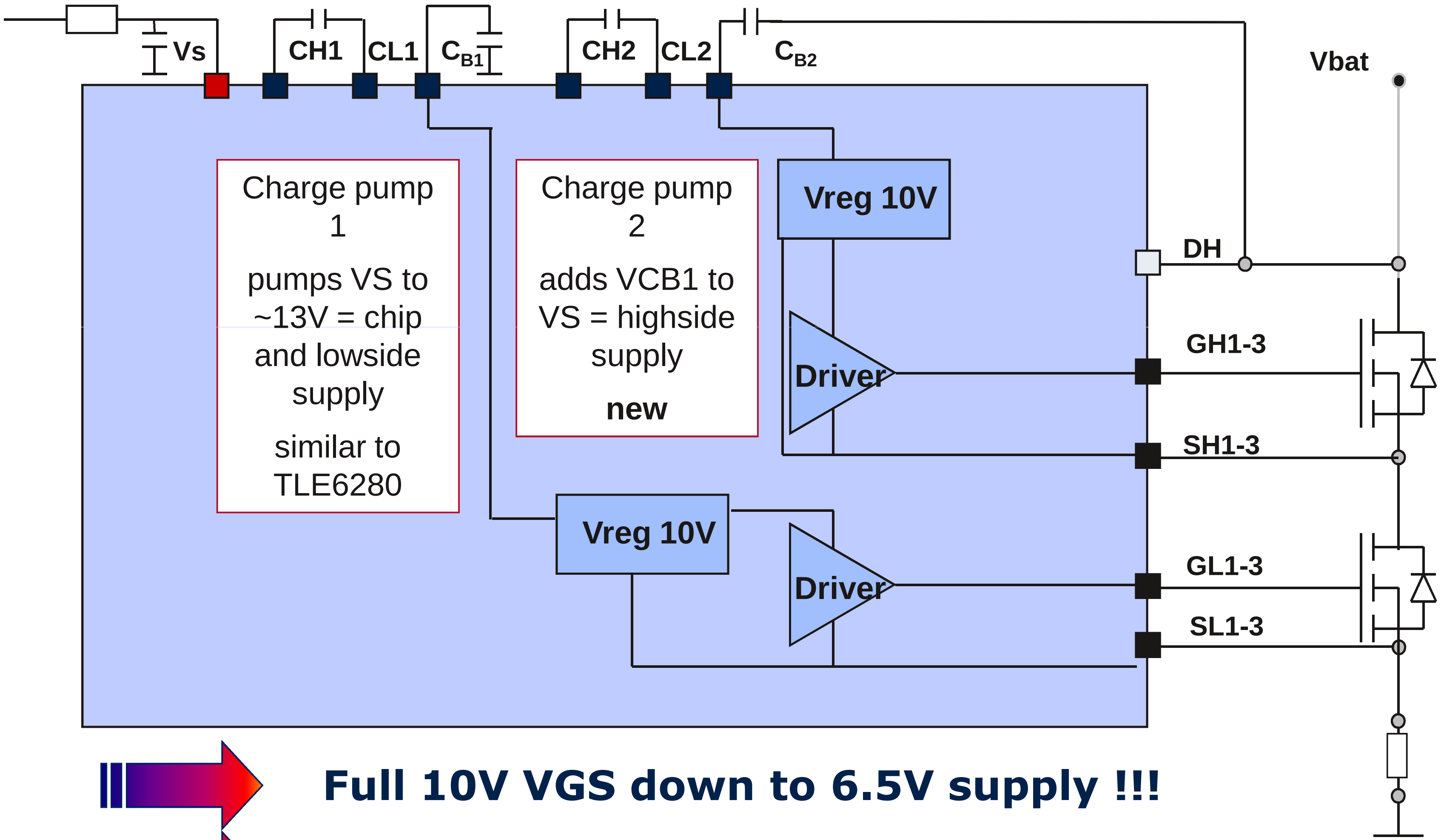
- **160A B6-Bridge ->Diver Requirements**
  - powerful output stage up to 1.5A
  - Robust to positive and negative spikes +/-7V at SL
  - Separate Source connections 4
  - Floating output stages 4

TLE7183 / 89 / 85 / 84

TLE7183 3-Phase Driver IC for 12V



TLE718x 3-Phase Driver IC for 12V



Full 10V VGS down to 6.5V supply !!!

0 – 100% without limits

TLE718x
Gate voltages at low supply voltages

For internal use only!

<u>Conditions:</u>

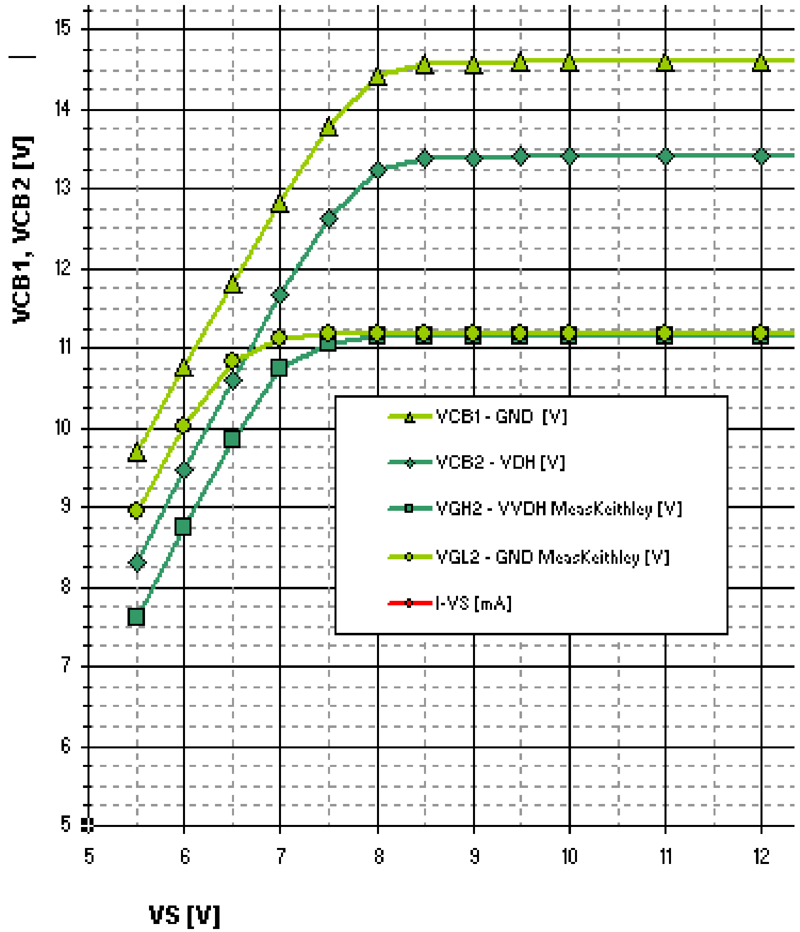
V_S = 5.5 ... 12 V

Q_G = 130 nC

f = 20 kHz

(Max. UV limit on CB1: 8.3 V)

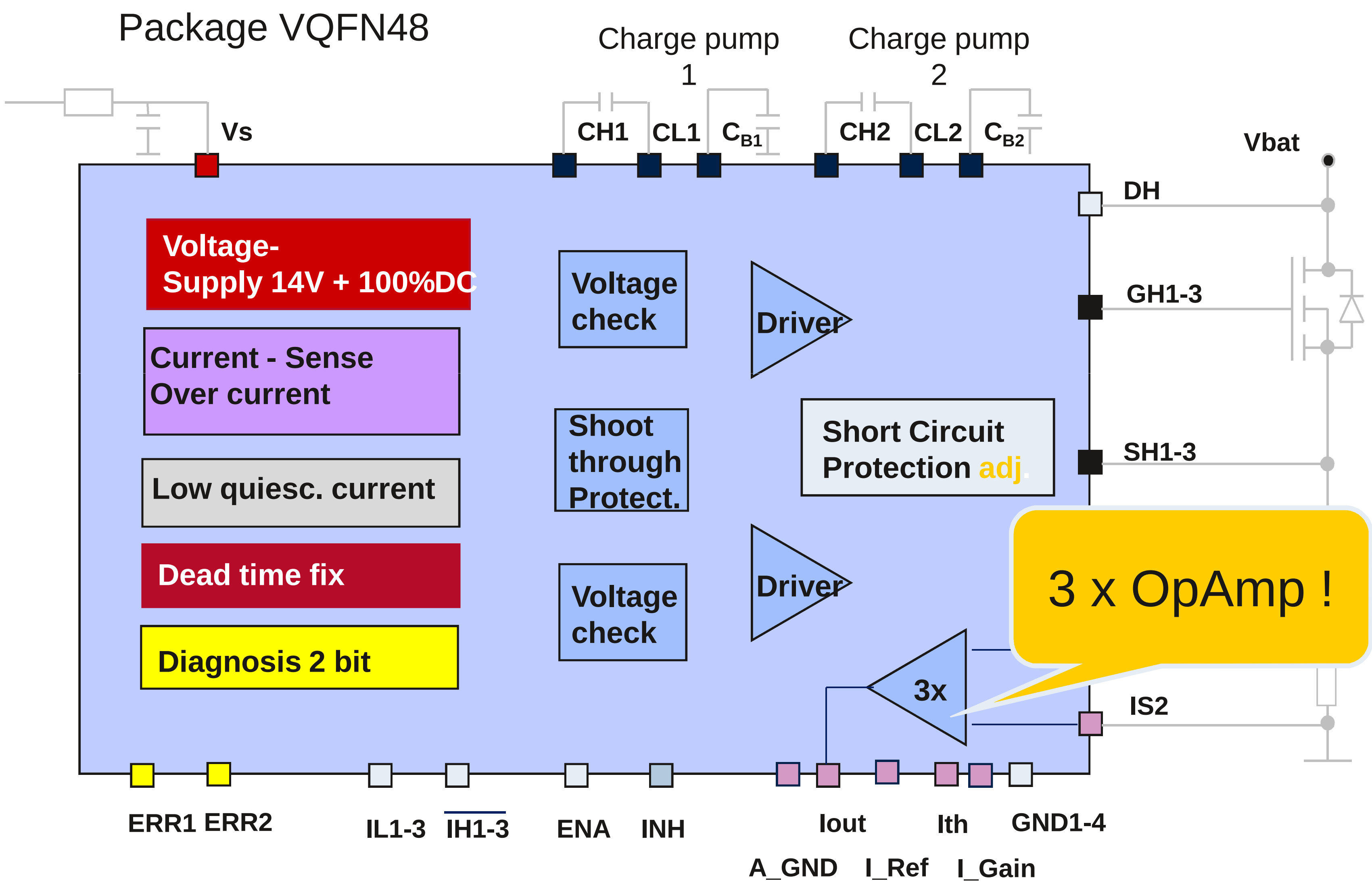
0...100% duty cycle



full supply voltage reaches motor

highest efficient usage of motor (costs + space)

TLE7189
3-Phase Driver IC for 12V



TLE7185
Simplified 3-phase driver IC

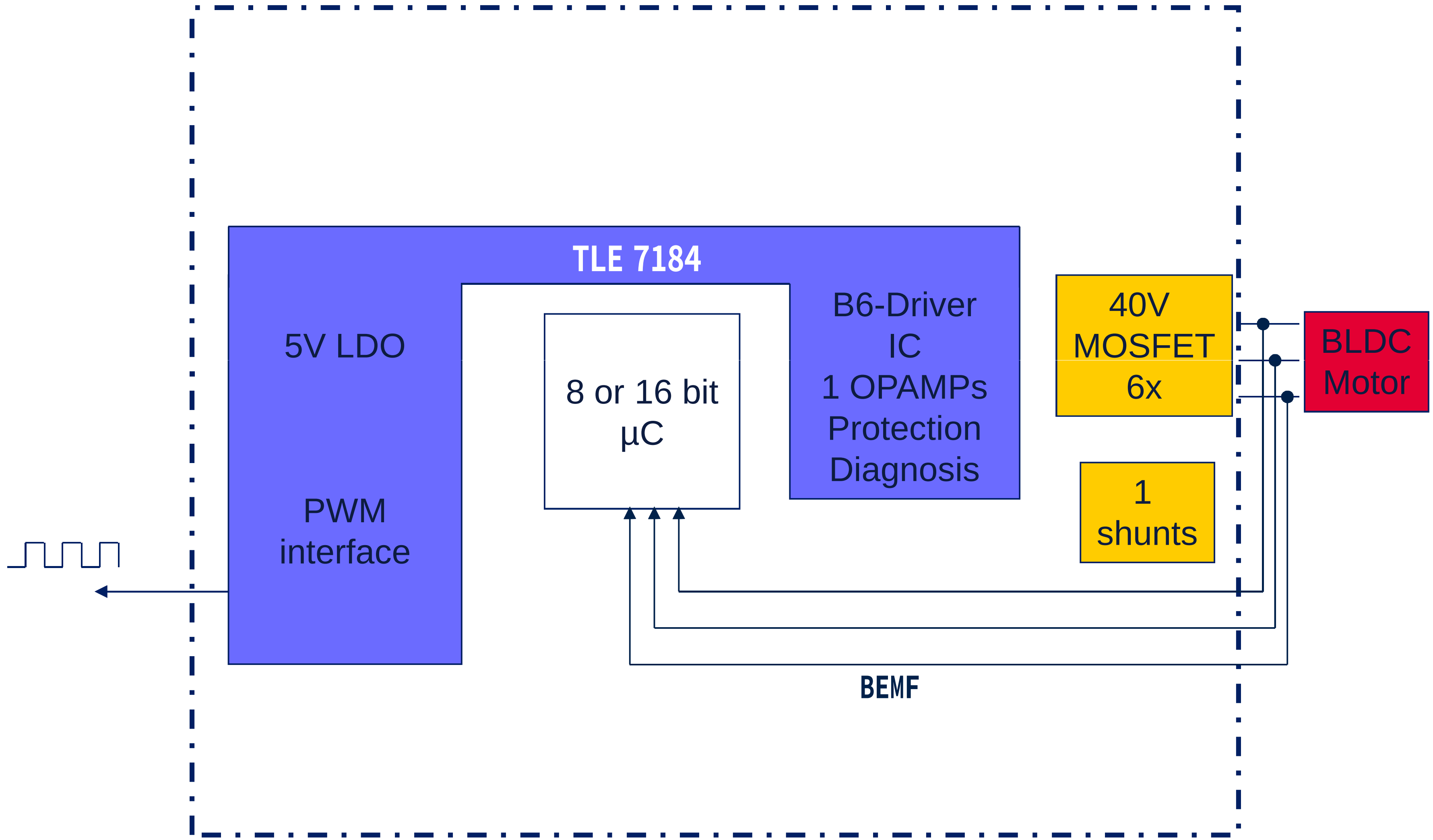
low cost

- Features
  - B6 MOS Bridge driver
    - ~10 Ohm output stages for MOSFETs up to 100A (300mA Gate current)
    - 0-95% duty cycle (bootstrap principle)
    - Adj. Short circuit detection level 0.3-2V
    - Adj. Dead time
    - Low quiescent current mode 20uA
    - 2 bit diagnostic
    - Separate Source pin for each MOSFET
    - Functional range 5.5 to 33V
  - Charge pump to boost the supply voltage
  - P-DSO36-Exposed pad allows TA up to 140°C

Optimized for applications running at 5.5V supply

BLDC Drive for Fans and pumps (and EPS) TLE7184

In Production



BLDC Drives
ASSP- Approach TLE7184

low cost

- Features
  - B6 MOS Bridge driver
    - ~10 Ohm output stages for MOSFETs up to 100A
    - Works down to 7V
    - OpAmp (UGBW 20Mhz / <1.5mV)
    - 0-94% duty cycle (bootstrap principle)
    - Protection functions
  - 5 or 3.3V 70mA LDO to support 8 and 16bit uCs
  - PWM interface
  - Precise analog and digital temperature sense
  - Specific Logic
  - VDH switch (disconnects circuit from battery – sleep mode)

Simplified ECU for BLDC Motors

Lowest cost approach for EPS

Agenda

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    - Spikes: Why they are harmful
    - Layout recommendations
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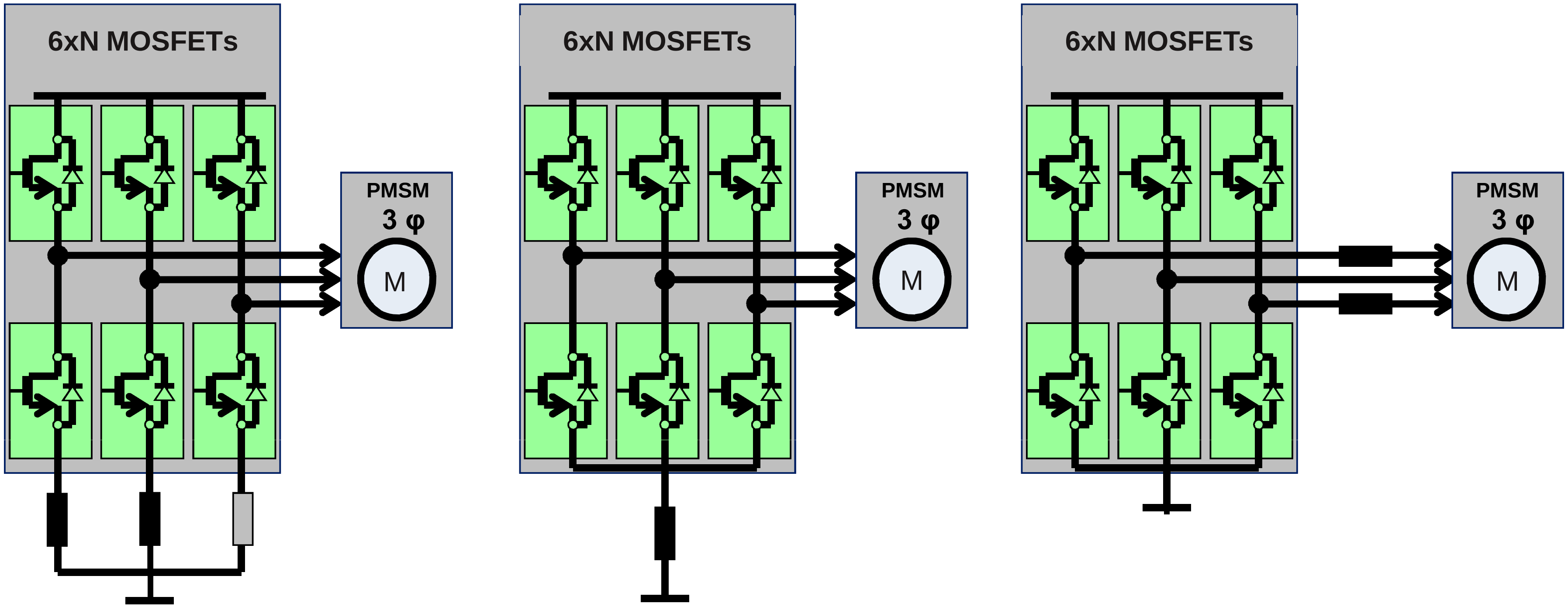
  - Measure Current precisely
    - How many shunts to use?
    - How does it work with one shunt
    - Requirements for driver IC
    - What to consider with IFX OpAmps in driver ICs
  - Functional Safety: Second switch off path
    - Star-Point relay vs. MOSFETs

Application trends
Current measurement



- Options
  - 2 or 3 shunts at the Source of the MOSFETs
  - Single shunt in common GND
  - 2 shunts in phase
  - …

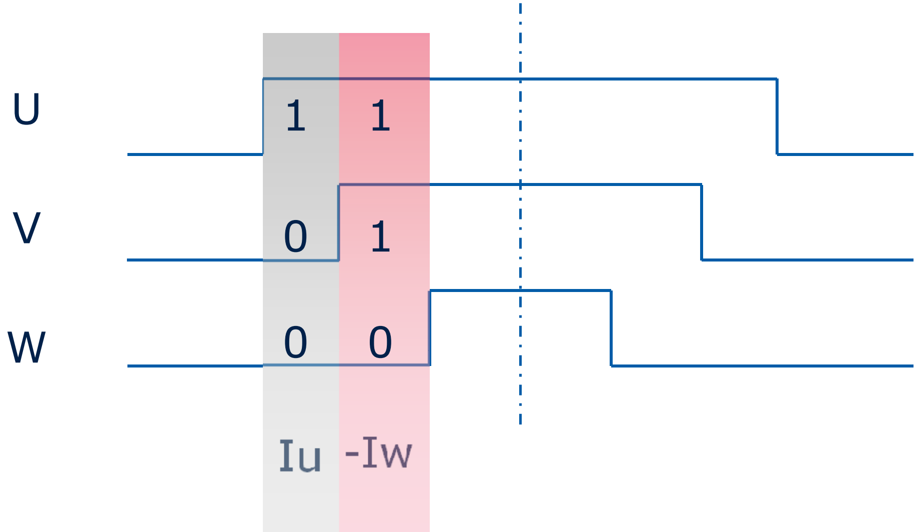
Bridge Driver ICs -Electric Power Steering Features overview

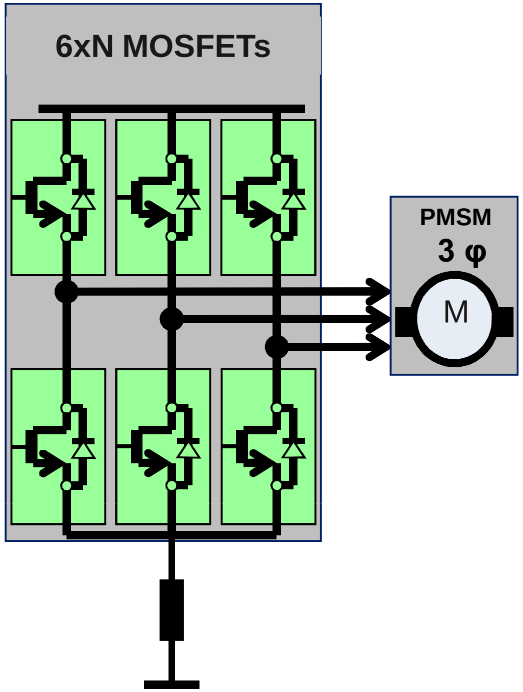
Shunt configurations	**2 shunts @ Sources of low side MOSFETS**	**3 shunts @ Sources of low side MOSFETS**	**1 shunt in common GND**	**2 shunts in the phase connections**
Costs	O	-	+	-
Power Dissipations	-	--	+	--
Space	-	--	+	-
Easy to measure	+	++	O	- (common mode)
Redundancy	-	Yes	-	-
Verification of measurement	against motor model	directly	against motor model	against motor model
Supported by IFX driver ICs	TLE7189	TLE7189	TLE7183 / 84 / 86	No

- Europe : 1 shunt in GND / 2 shunts @ source
- Japan: Often 3 shunts in GND

How to measure with 1 shunt
Short times to measure

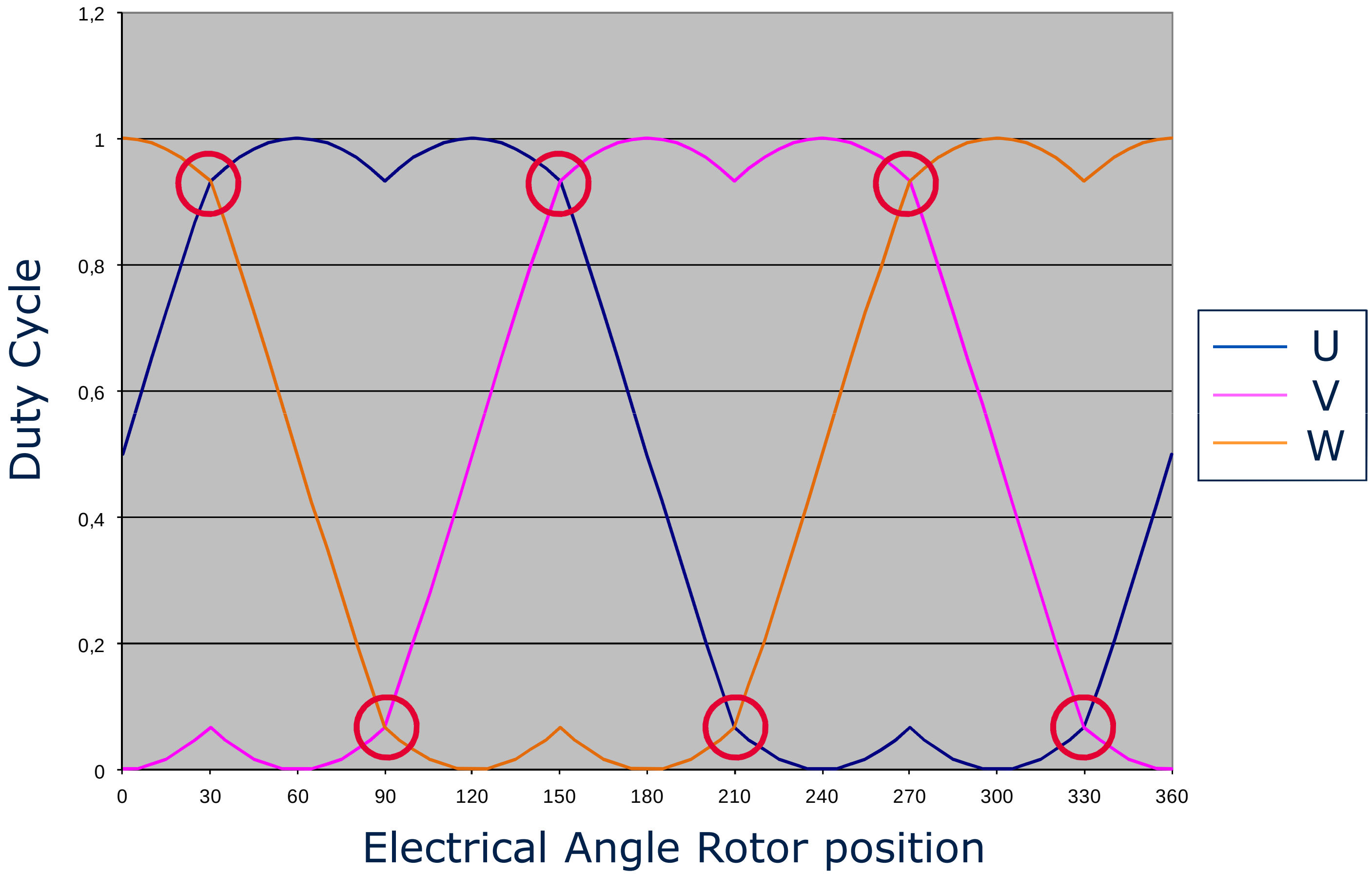
- Example center aligned PWM





- 2 phase currents can be measured
- 3rd phase current can be calculated

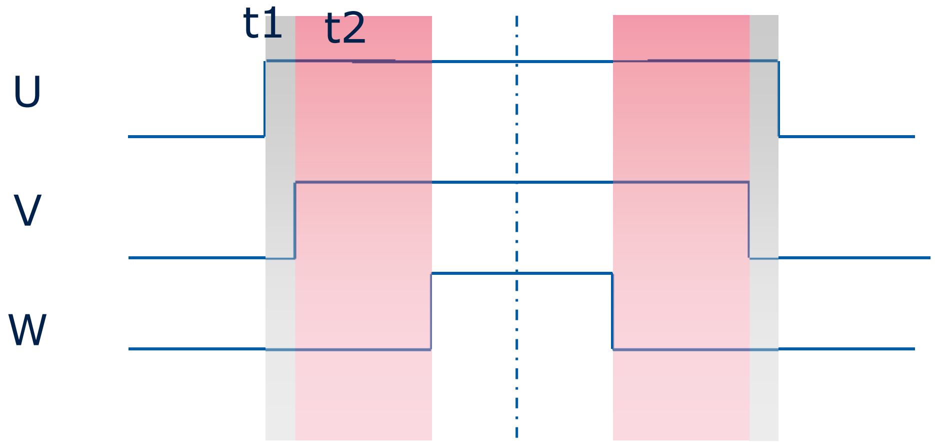
How to measure with 1 shunt
Problem Zones @ space vector modulation



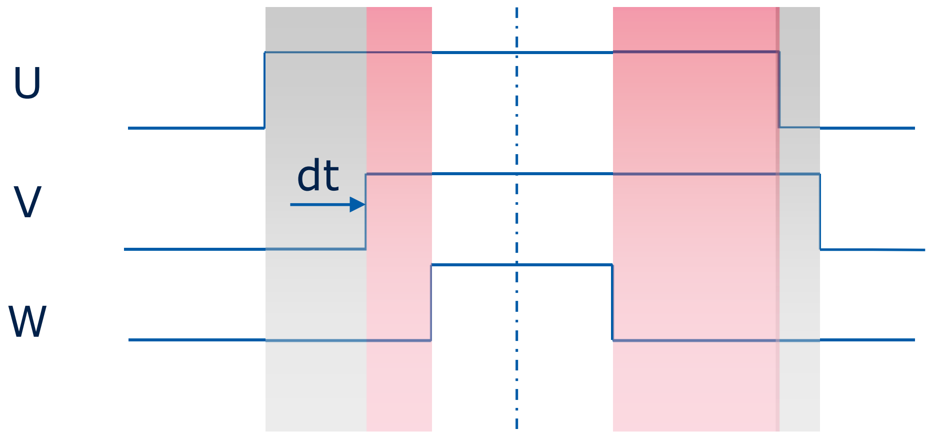
- Only one current can be measured

Work around
Short times to measure

- t1 is too short do measure current -> dt helps



$$2*t_1*\begin{pmatrix}1\\0\\0\end{pmatrix}+(2*t_2)*\begin{pmatrix}1\\1\\0\end{pmatrix}=\begin{pmatrix}2*t_1+2*t_2\\2*t_2\\0\end{pmatrix}$$



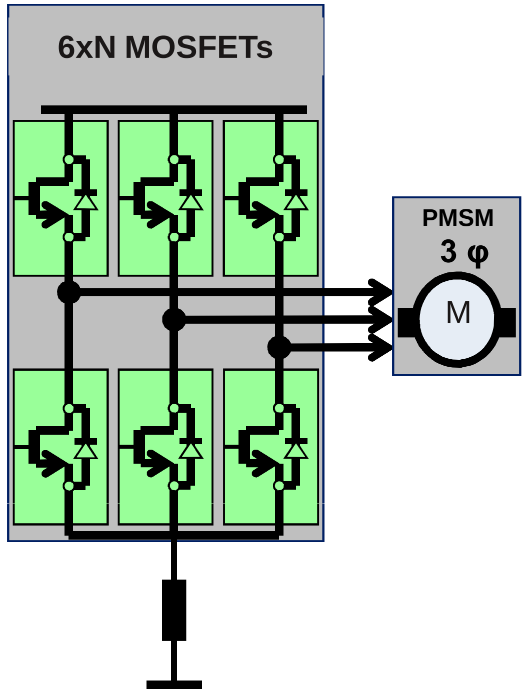
$$(t_1+dt)*\begin{pmatrix}1\\0\\0\end{pmatrix}+(t_2-dt)*\begin{pmatrix}1\\1\\0\end{pmatrix}+(t_2+t_1)*\begin{pmatrix}1\\1\\0\end{pmatrix}+(dt-t_1)*\begin{pmatrix}0\\1\\0\end{pmatrix}=$$

$$\begin{pmatrix}t_1+dt+t_2-dt+t_2+t_1\\t_2-dt+t_2+t_1+dt-t_1\\0\end{pmatrix}=\begin{pmatrix}2*t_1+2*t_2\\2*t_2\\0\end{pmatrix}$$

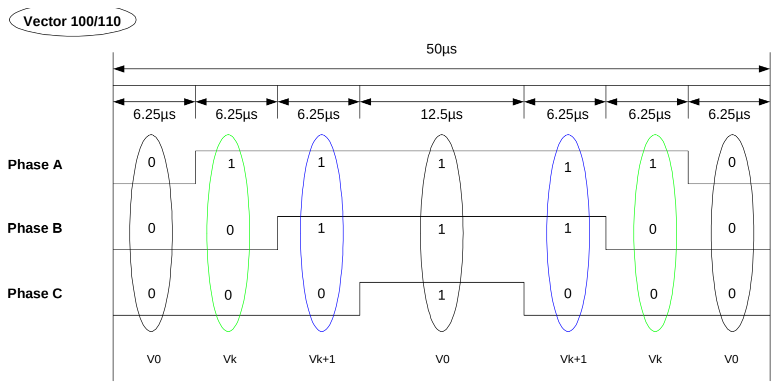
- Motor sees the same vector!

Application requirements Power Steering

- **Current measurement**
  - Only one shunt for cost reasons
  - very short time to measure current
  - increasing accuracy requirements
  - high current in application lead to negative spikes at shunt



- OpAmp requirements
  - input range +/-5V spikes 4
  - high bandwidth typ. 20 MHz UGBW
  - low input offset down to +/- 1.5mV
  - high CMRR > 60db minimum



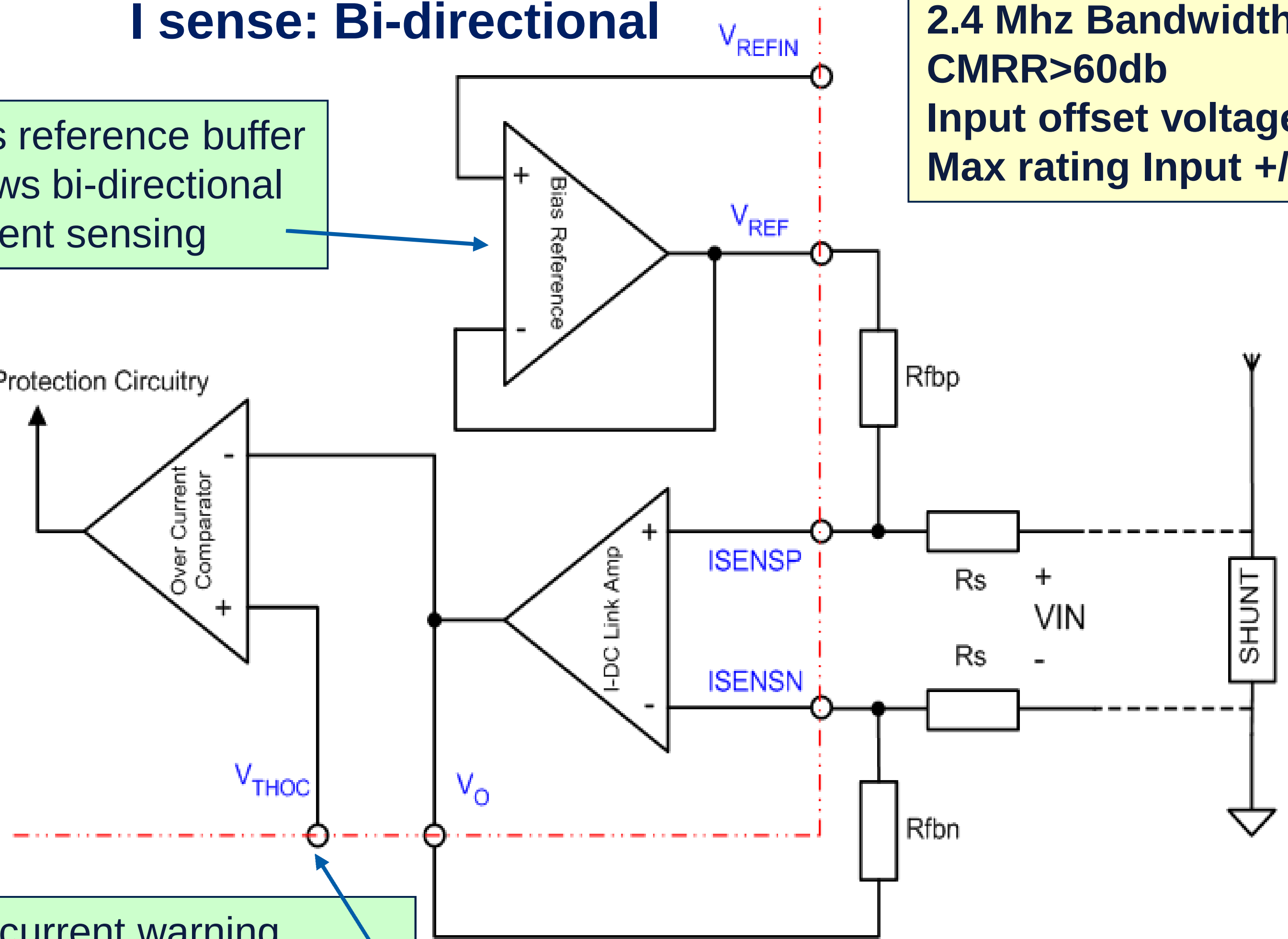
TLE7183 / 89 / 84 /86

TLE7189F 3-Phase Driver IC for 12V

I sense: Bi-directional

Bias reference buffer allows bi-directional current sensing

2.4 Mhz Bandwidth @ gain 15
CMRR>60db
Input offset voltage <+/-1.5mV
Max rating Input +/-5V



Over current warning with adjust. Current level

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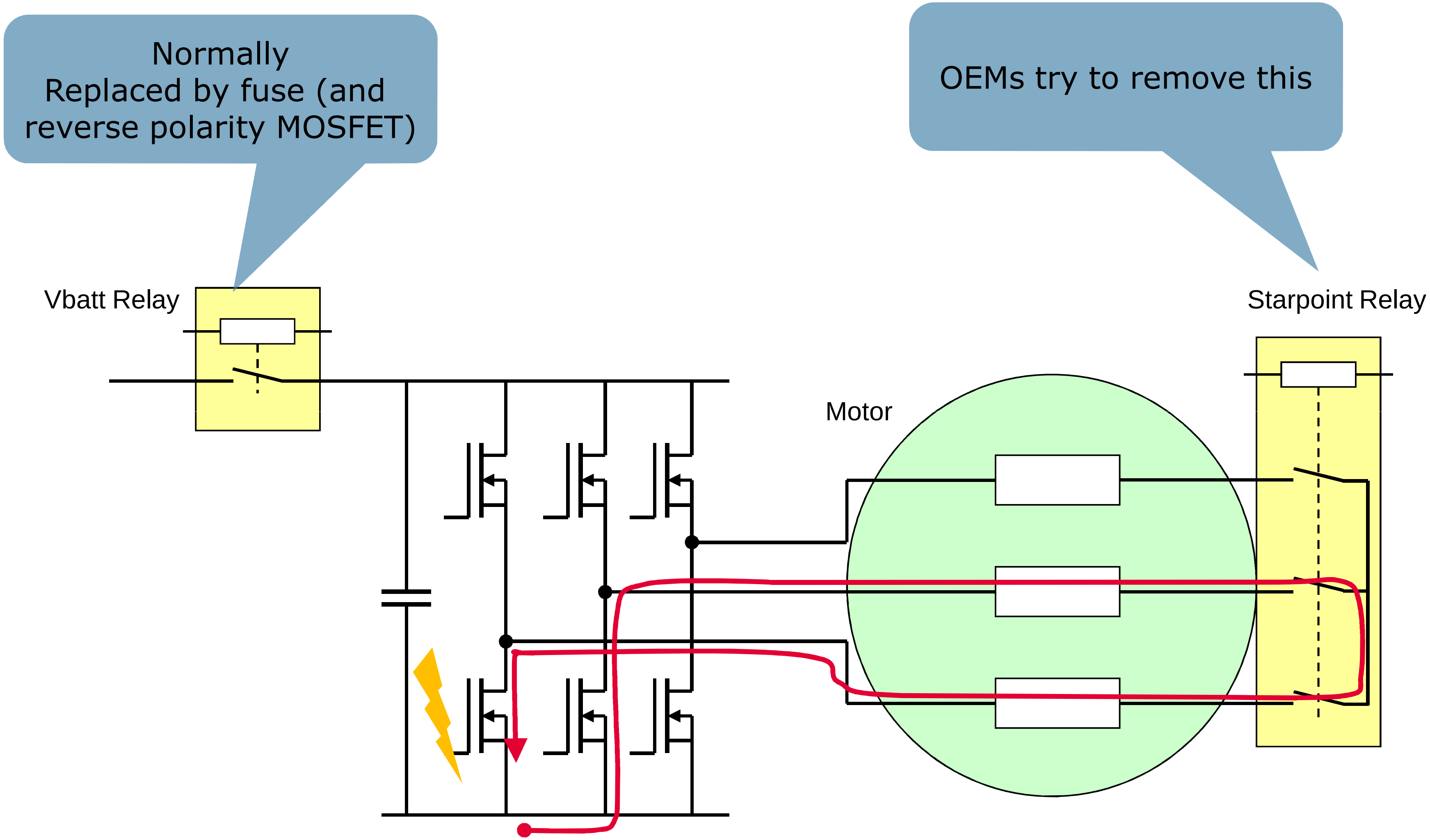
    - Star-Point relay vs. MOSFETs

EPS relay removal



Task of starpoint relay @ PMSM : Avoid currents like shown to avoid breaking

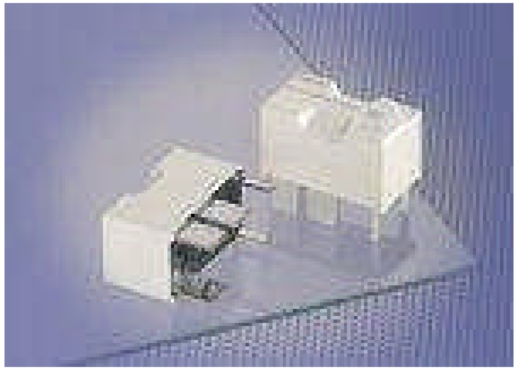
EPS relay removal

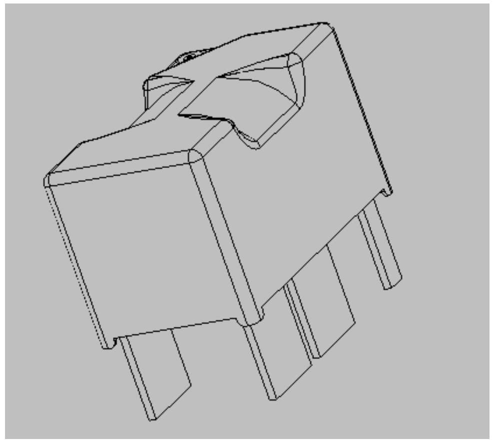
Product Features (Please use the Product Drawing for all design activit

Product Type Features:
- Product Designation = High Current Solutions
- Series = V23135

Electrical Characteristics:
- Nominal Voltage (VDC) = 12
- Rated Current @ 85° C (A) = 90
- Coil Resistance (Ω) = 150
- High Power Relays >75A = Yes
- Contact - Switching Current Min. (mA) = 1000
- Contact - Switching Voltage Max. (VDC) = See Load Limit Curve
- Coil - Rated Power (W) = 0.96

Body Features:
- Mounting Bracket(s) = Without
- Length (mm [in]) = 32.30 [1.272]
- Width (mm [in]) = 18.30 [0.720]
- Height (mm [in]) = 18.70 [0.736]
- Weight (g [oz]) = 30.00 [1.058]

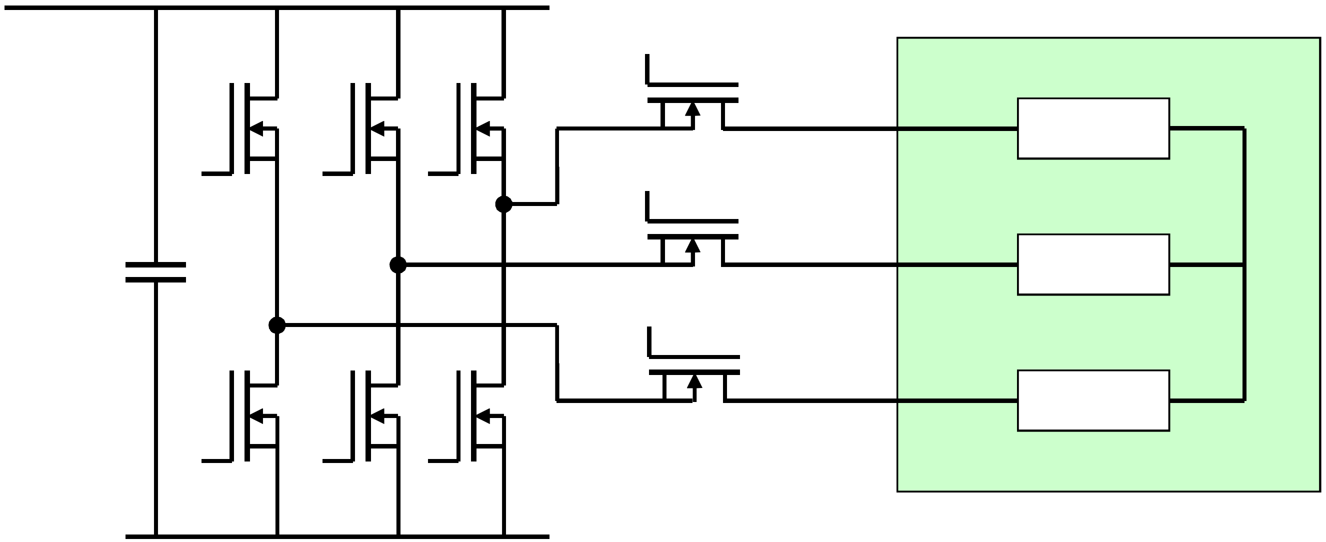




- Remove why?
  - Too big
  - Too expensive
  - Not robust enough (produces fails over lifetimes)

EPS relay removal

- **Alternative**
  - Use MOSFETs to disconnect phases
  - But: In emergency case no freewheeling path
  - High avalanche robustness of MOSFET required
  - Or: Intelligent MOSFET switch off strategy
  - Charge pump of driver can be used for supply



EPS relay removal

- But be careful
- Many patents around
- E.g.:

(10) International Publication Number
WO 2010/116182 A1

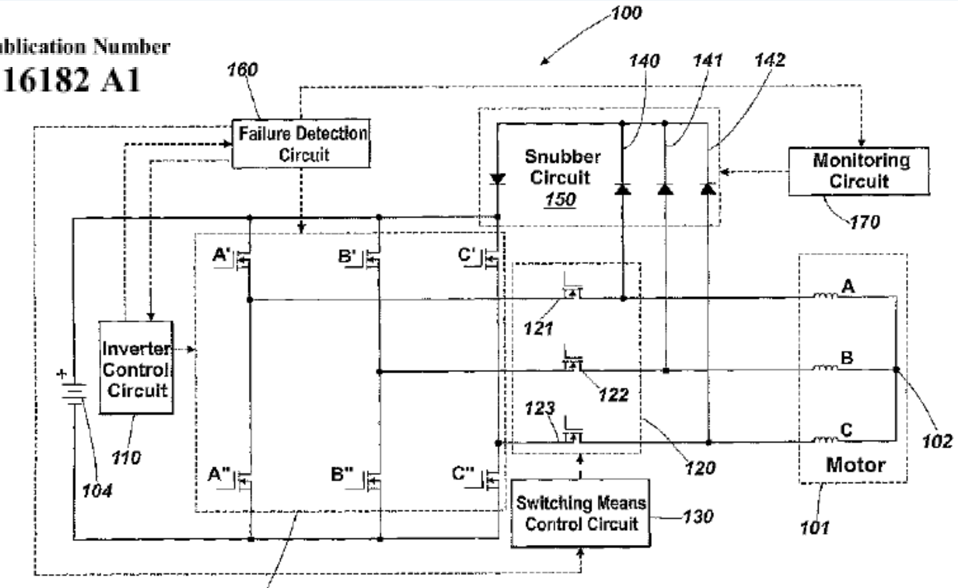


Fig. 2

(10) **Patent No.: US 7,019,479 B2**

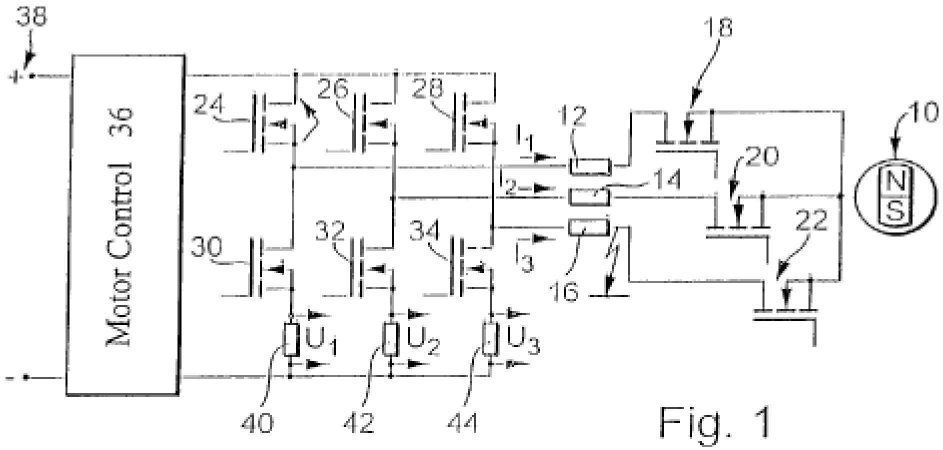
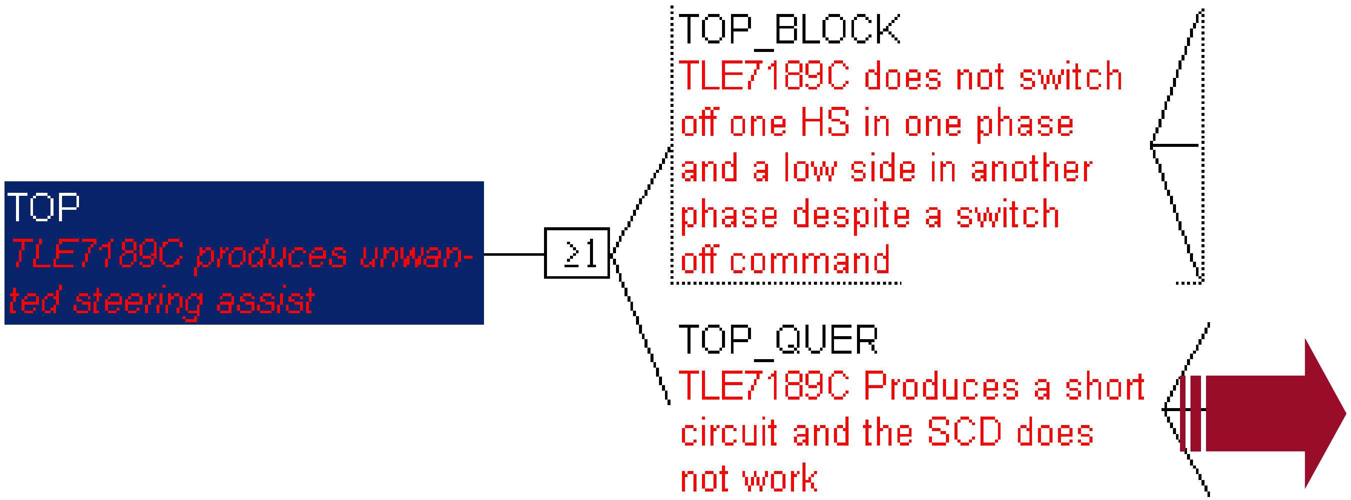


Fig. 1

TLE 7189
SIL 3 supporting features

"Single failure does not cause short in bridge or motor operation"

FTA for TLE7189 proves:



SCD was decided to be important

TLE7189 " Driver"

Philosophy

Use TLE718X and add SIL3 related supervision:

"sleeping bug is excluded by repeated testing"

- ⇨ **VCC check (monitors the uC supply)**
- ⇨ **Test function for VCC check**

- ⇨ **SC-Detection (monitors short circuit of MOSFET)**
- ⇨ **Test function for SC-Detection at 0A**

- ⇨ **High voltage inputs (18V)**

- ⇨ **"Common mode failure analysis" (FTA) available, tailored to the FMEA and the FTA of the target system**

Electric Power Steering Requirements vs Products

Requirement	TLE7189	TLE7183	TLE7185	TLE7184/6
160A B6-Bridge				
powerful output stage	4	4	4	4
Robust to spikes	4	4	4	4
Separate Source connections	4	4	4	4
Floating output stages	4	4	4	4
Highest efficiency (0-100%dc)	4	4	low cost	low cost
OpAmp requirements				
input range +/-5V spikes	4	4		4
high bandwidth	4	4		4
low input offset	4	~		4
high CMRR	4	4		4
Functional Safety Features	4			4
Integrated 5 or 3.3V Vreg				<70mA


We commit.
We innovate.
We partner.
We create value.