Over Current Protection Alternatives

Motor Current Control With INA240

MHRS-Current Sensing Team

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Agenda

- 5 mins – Current & Power Measurement Introduction

- 20 mins – Over Current Protection: Circuits & Techniques
  - » Discrete vs. Integrated
  - » Dedicated / Analog Output / Multiple ALERTs
  - » Power Monitors

- 25 mins – Motor Current Control With INA240
  - » Introduction to Motor Current Sensing
  - » INA240 Performance Competitive Study

Current & Power Measurement use cases

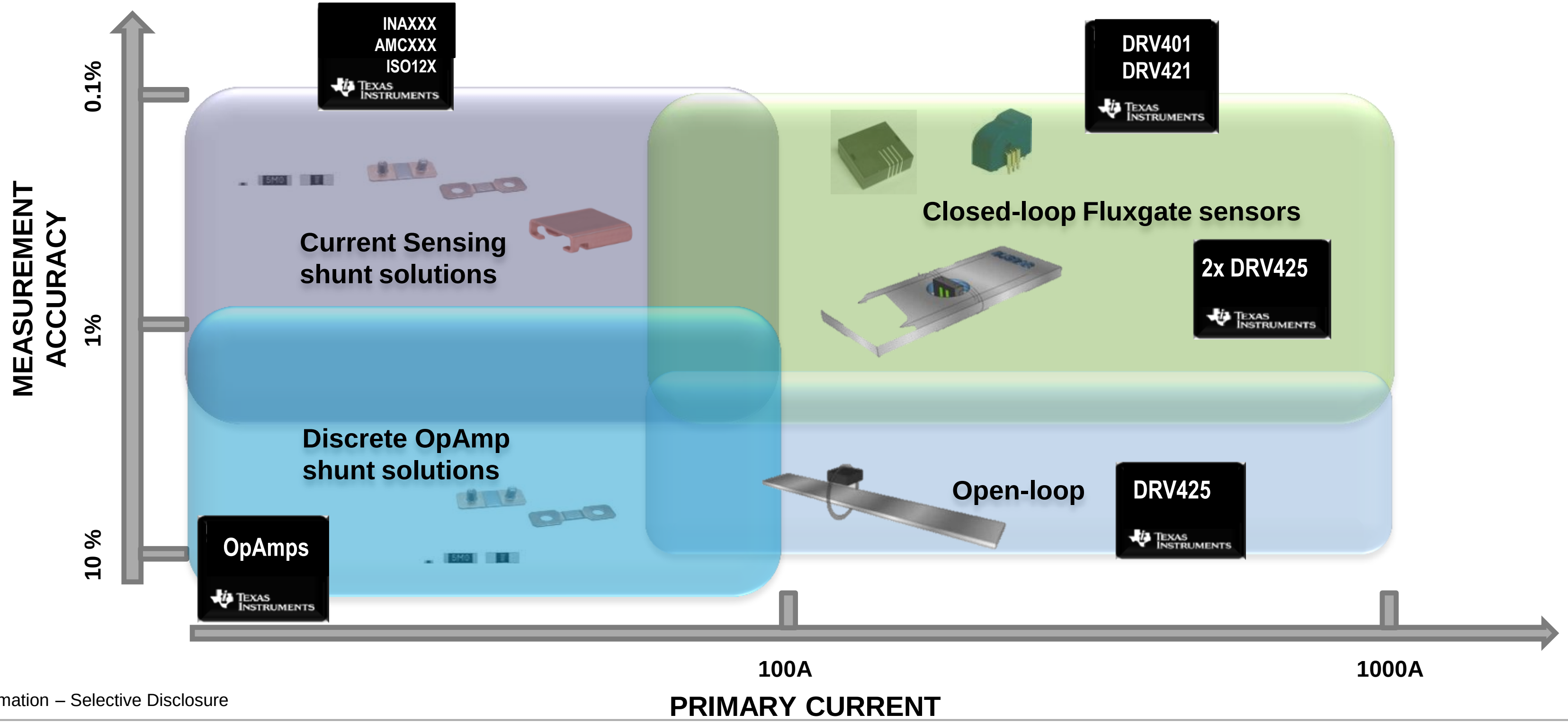
Solutions customers seek

Real-time overcurrent protection (OCP)

Current and power monitoring for system optimization

Current measurement for closed loop circuits

TI's wide range of Current Sensing solutions



Overcurrent Protection Alternatives

The strengths and challenges of the various overcurrent protection alternatives

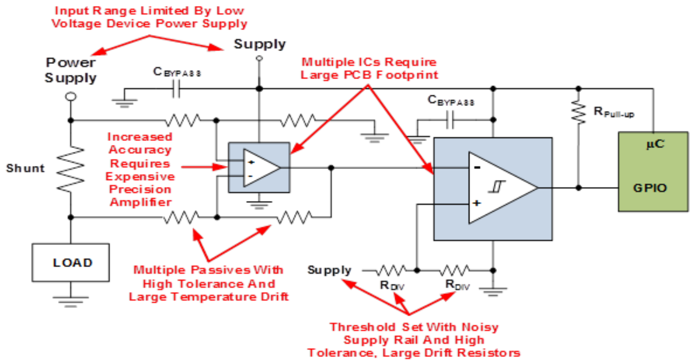
Why is overcurrent protection important?

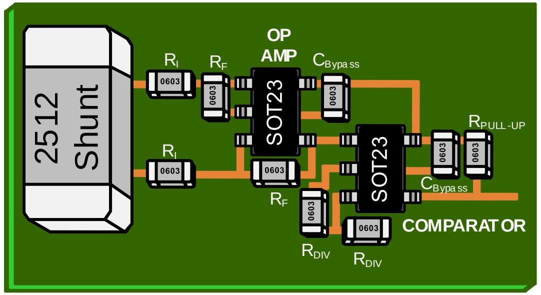
- Overcurrent protection is the most basic form of current monitoring
- Historically, OCP has been managed by measuring the system's **temperature**.
  - Temperature typically is a lagging indicator.
  - The increase in system temperature normally is a result of increased current flow.
  - Measuring the current allows the system integrator to manage the thermals in their systems more efficiently and anticipate problems instead of reacting to potential issues.
- System thermal management has become more critical as two trends work against each other in modern electronic systems: driving **higher performance** in **smaller form factors**.

Fuses for overcurrent protection

- Using a fuse is the most common overcurrent implementation, "after the fact".
- The sole purpose is to open in the event of an extended over-current condition
  - Very simple
  - Effective in protecting the system from gross, over-current events
- Challenges to overcome:
  - Offers protection for a single event
    - The fuse is destroyed by the over-current event while protecting the remainder of the system
    - For the system to become functional again, the fuse must be replaced
      - This could involve rework at the board level to remove and replace the blown fuse
  - Typically requires that the current significantly exceed (4 times or more) the rating of the fuse in order for a quick open to occur
    - Difficult to predict the precise over-current level at which the fuse will open; requires more margin to be built into the protection scheme.
  - Does not provide information on the system's actual operating conditions.
- It is better to protect "before the fact", what are the alternatives?
  - The next serval slides will try to picture the very condensed history of the evolution of current protection with active circuits.

Classic Op-amp & Comparator Implementation

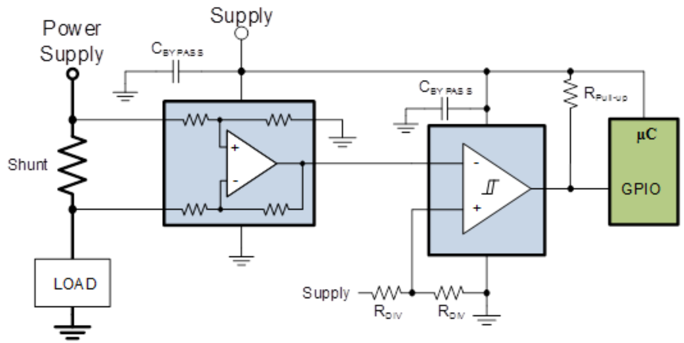


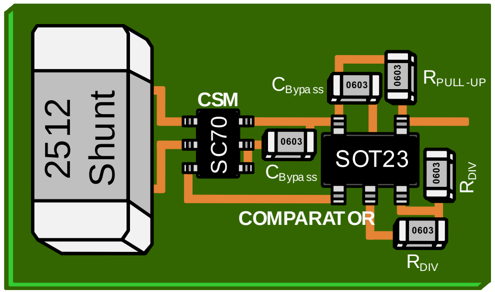


Op Amp + Comparator OCP

- Strengths:
  - Possibly the lowest cost to implement
  - Fastest response time with high-speed amp and fast comparator
  - Offers both overcurrent detection and current monitoring
  - Second source alternatives
- Challenges:
  - ACCURACY & SPEED cost money!
    - Temperature drift
  - Typically Low-side only
    - High-side limited to op-amp supply rail
  - Board Space / Component Count

Current Sense Amplifier & Comparator Implementation



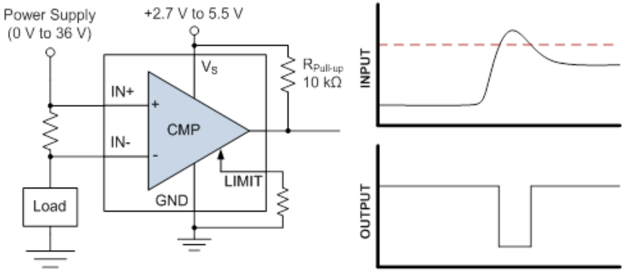


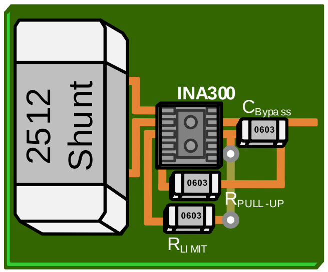
CSM + Comparator OCP

- Strengths:
  - More accurate current measurement than typical op-amp implementation
    - Smaller shunt enabled by lower V_{OFFSET} lowers power consumption
  - Fast response time with fast comparator
  - Offers both overcurrent detection and current monitoring
  - Comparator second source alternatives
- Challenges:
  - For comparator function:
    - ACCURACY costs money!
      - Temperature drift on comparator
    - SPEED costs money!
  - Board Space / Component Count

Overcurrent Alert Only Implementation

- INA300 Current-Sense Comparator



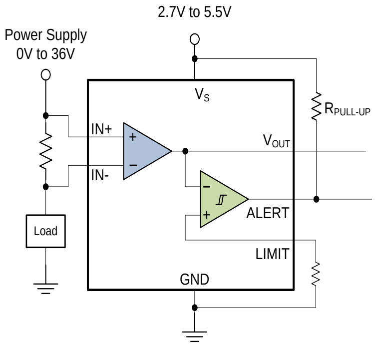


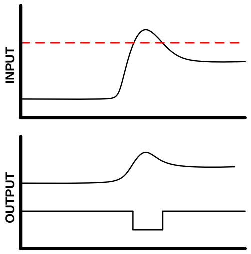
INA300

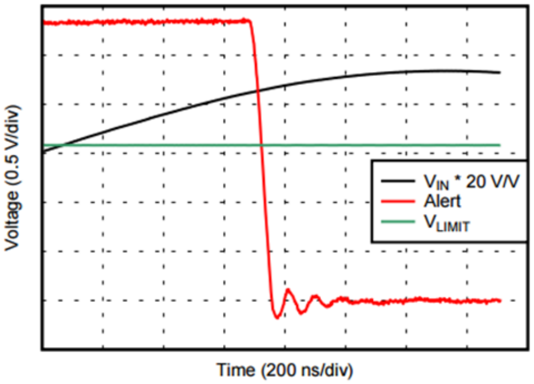
- Strengths:
  - Simplest implementation with only a single external threshold setting resistor required and no additional design considerations
  - High-side or low-side capable
  - 70% smaller footprint versus op-amp and comparator implementation
  - Miniaturization of Over–Current Detection enables rethinking system level management via subsystem monitoring
    - Utilization & efficiency: Only use those portions of the system that are needed & are enabled
    - Localized Fault Identification
    - Offload event detection: Operates independently and only wakes system controller when needed
- Challenges:
  - ALERT only – no actual current information supplied to system

Overcurrent Alert w/ Analog Output Implementation

- INA301 high-speed, precision current sense amplifier with integrated comparator



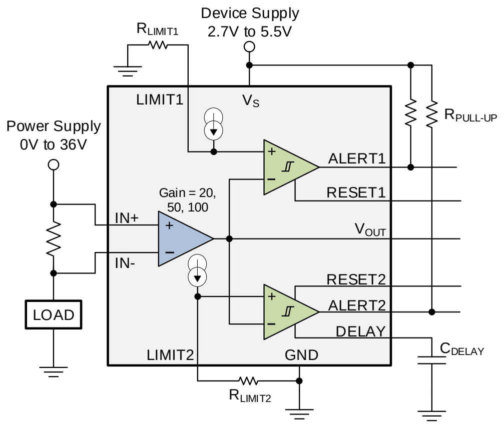


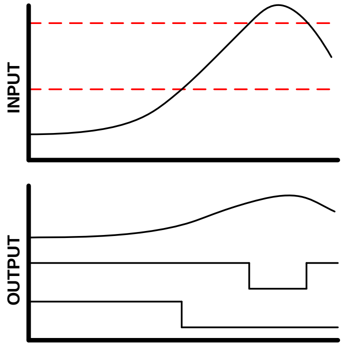


Total Propagation Delay

- Strengths:
  - Offers both overcurrent detection and current monitoring
  - High-side or low-side capable
  - Simple implementation with only a single external component required
  - Fast response time
    - INA301 @ 1µs (0.6us Typ)
- Challenges:
  - Design needs to comprehend current range, over-current limit, and following stage input range.

Multi-Level Overcurrent Alert w/ Analog Output Implementation

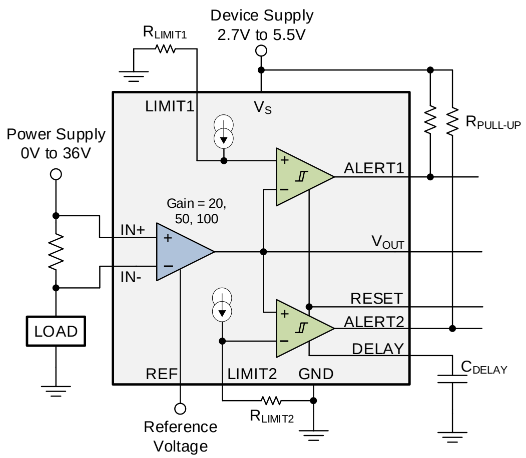


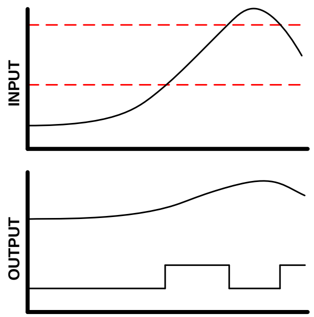


- **INA302**
  - High/Low-Side, Bi-Directional, Zero-Drift Current Sense Amplifier with Multi-Alert High-Speed Comparators
  - In development, sample in 3Q2016

- Strengths:
  - Offers both overcurrent detection and current monitoring
  - Dual ALERTS - enables system implementation flexibility such as WARNING and SHUTDOWN
  - High-side or low-side capable
  - Simple implementation with only a single external component required per comparator
  - Fast response time
    - INA302 @ 1µs
- Challenges:
  - Design needs to comprehend current range, over-current limit, and following stage input range

Windowed Multi-Level Overcurrent Alert w/ Analog Output Implementation



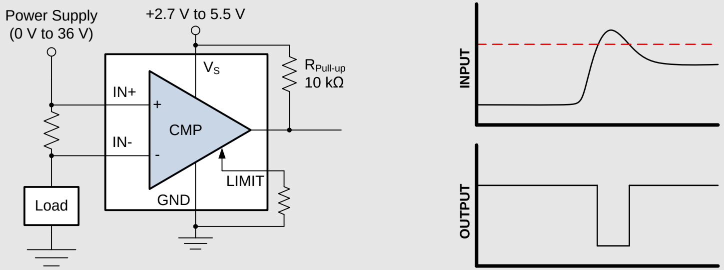


- **INA303**
  - High/Low-Side, Bi-Directional, Zero-Drift Current Sense Amplifier with High-Speed Window Comparator
  - In development, sample in 3Q2016

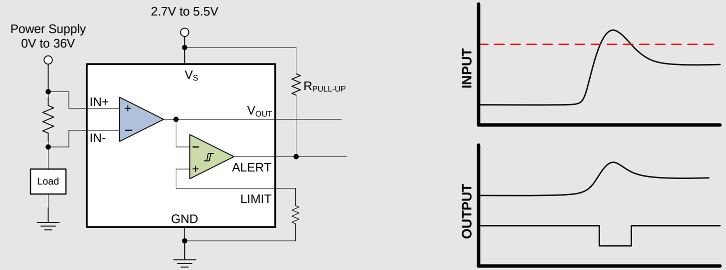
- Strengths:
  - Offers both overcurrent detection and current monitoring
  - Window ALERTS enables bi-drectional current measurement or both OVER and UNDER current detection
  - Simple implementation with only a single external component required per comparator
  - Fast response time
    - INA303 @ 1µs
- Challenges:
  - Design needs to comprehend current range, over-current limit, and following stage input range

Over-Current Detection Topologies – A summary

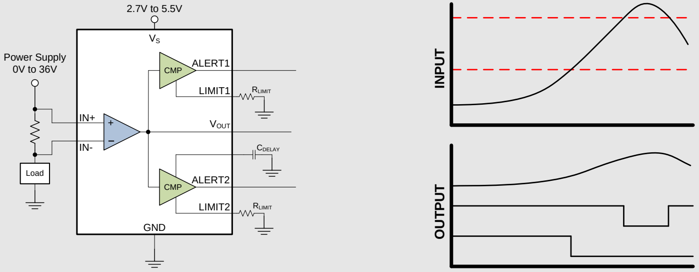
INA300: Overcurrent Alert Only



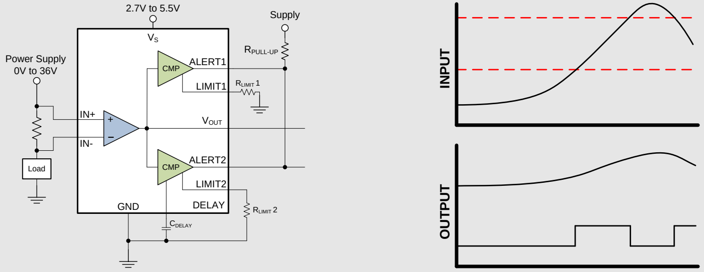
INA301: Overcurrent Alert w/ Analog Output



INA302: Multi-Level Overcurrent Alert w/ Analog Output



INA303: Windowed Multi-Level Overcurrent Alert w/ Analog Output



Production | New | Roadmap

Over-current Protection Roadmap

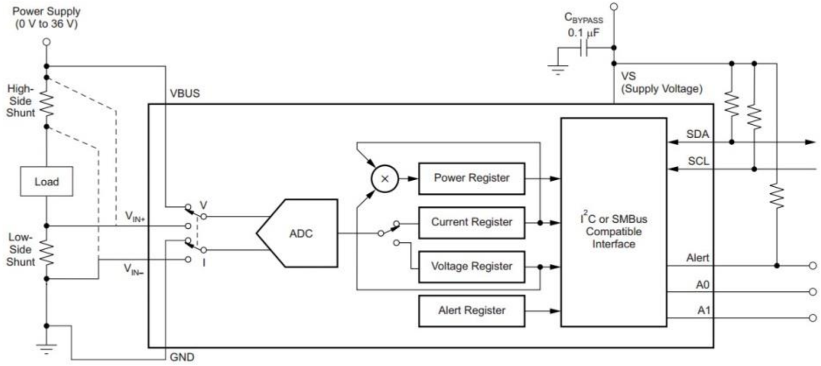
Production or Past PPR

- **INA300 QFN/MSOP - Now**
- **INA301 MSOP – Now**
- **INA301-Q1 – Now**
- INA300-Q1- MSOP – 8/16
- INA302 – sample 9/16
- INA303 – sample 9/16

Planned for 2017

- INA302-Q1/INA303-Q1
- INA380/INA2380/INA4380
  - INAx180 + comparator/ch – 1,2,4 ch
- INA380/INA2380/INA4380-Q1
- INA311/INA312/INA313
  - INA240 + INA302/3 Comparator – 3 SKUs
- INA311/INA312/INA313-Q1

Digital Power Monitor Implementation



- INA226
- INA231
- INA219
- INA220

- Strengths:
  - Offers both overcurrent detection and current monitoring
    - Additionally, offers bus voltage and power monitoring
  - Flexible, Programmable ALERT settings:
    - Over/Under Current
    - Over/Under Bus Voltage
    - Over Power
  - Low-side or High-side Capable
  - Programmable conversion time
- Challenges:
  - Response time can be slower due to digitization

Over-current Protection via Power Monitor Roadmap

Production or Past PPR

- **INA219 MSOP - Now**
- **INA220 MSOP - Now**
- **INA220-Q1 MSOP - Now**
- **INA226 MSOP - Now**
- **INA226-Q1 MSOP - Now**
- **INA230 QFN - Now**
- **INA231 WCSP – Now**
- **LMP92064 xxx - Now**
- **INA3221 QFN - Now**

Planned for 2017

- INA226 WCSP
- INA230 MSOP
- INA230-Q1 MSOP
- 1.8v INA3221
- INAxxx – HV INA226

OCP TI Design - Automotive Precision eFuse *TI Design #: TIDA-00795*

Features/Benefits

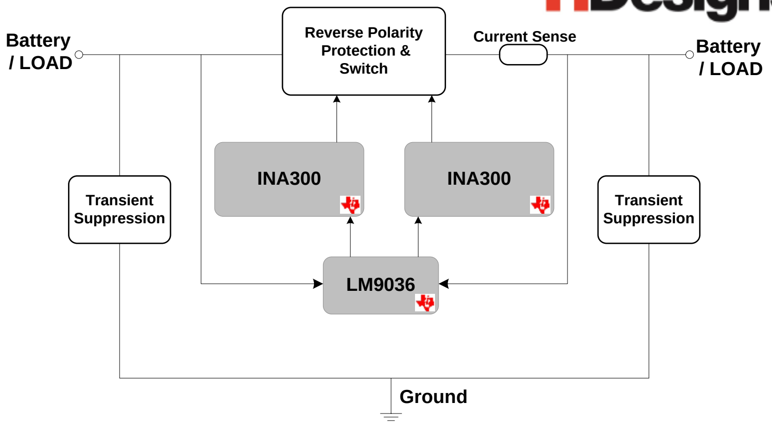
Current limit: up to 30A (scalable to >100A)	Accuracy <3%
Response time: max 15µs (configurable)	Reverse polarity protection
Configurable delay time to accommodate inrush current for 10µs, 50µs &100µs based on application	Power off resettable fuse

Target Applications

- Automotive eFuse Box
- Body Control Module
- High-side smart switch

Tools & Resources

- **TIDA-00795**
- **Design Guide**
- **Design Files:** Schematics, BOM, Gerbers, and more
- **Devices:**
  - INA300-Q1
  - LM9036

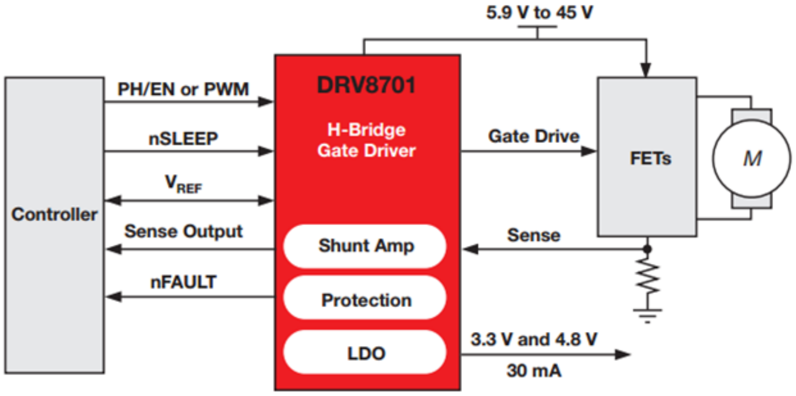


Motor Control / Solenoid / Induction loads Current Monitoring

Why, where, and the strengths and challenges of each of the options.

Motor Current Sensing - Discrete vs. Integrated:
- Why do I need separate Current sensor(s) anyway?

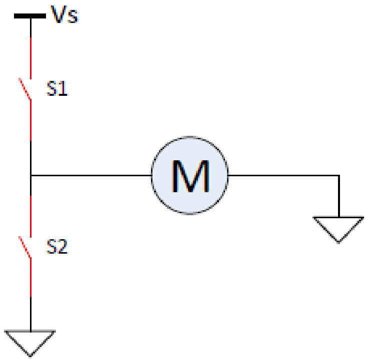
- Many motor drivers, such as DRV series have built-in current sensors.
- Trade off between cost and performance:
  - Driver integrated current sensor
    - Limited performance
    - No additional cost, great if adequate for the job!
  - Discrete Current Sensor
    - Can be optimized considering topology, performance and cost
    - TI offers a broad portfolio of dedicated Current Sensors, including Current Shunt Monitors (CSM) to address whichever sensing topology you choose!

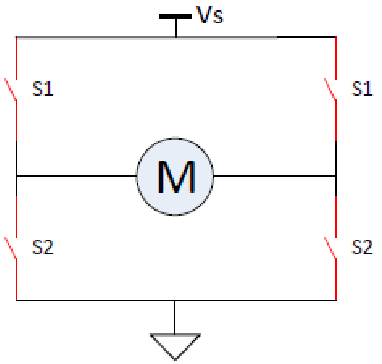


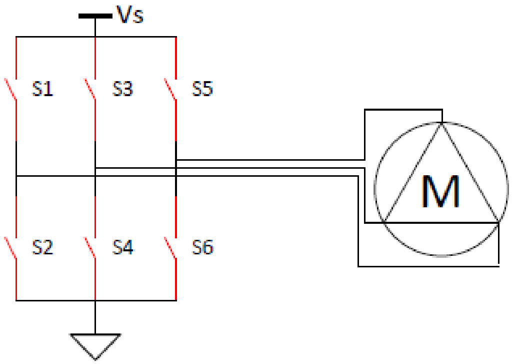
TI motor drivers, such as DRV8701 has built-in current sensing amplifier

DC Motor Driver Topologies(with variations)

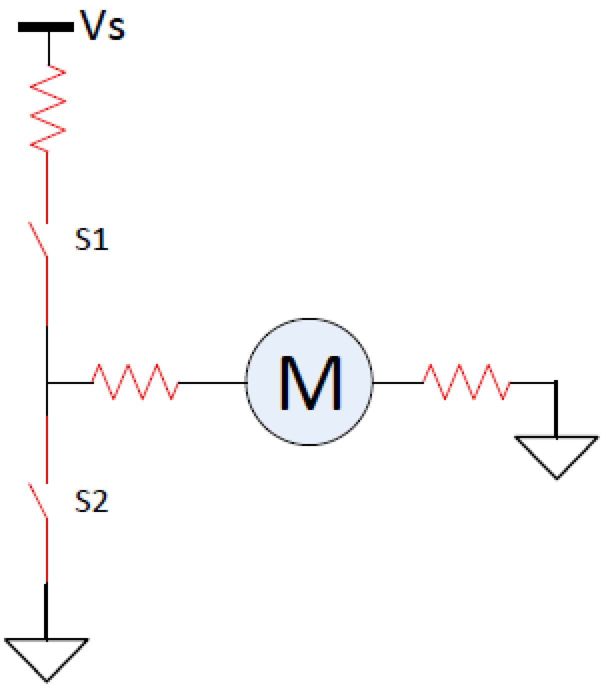
- Half bridge
  - Brushed DC motor;
  - Three modes: Run, Coasting and Breaking
- H bridge
  - Brushed DC motor
  - Four modes: Run, Reverse, Coasting and Breaking
- 3 Phase
  - BLDC motor – electrically commutated.
  - Four modes: Run, Reverse, Coasting and Breaking







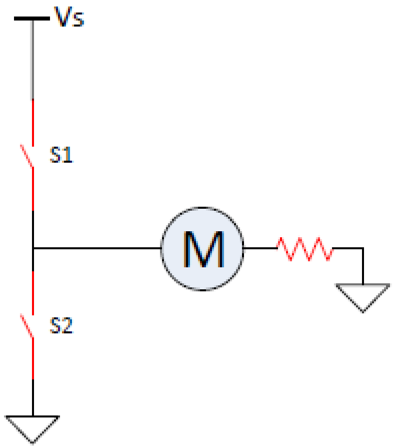
Half bridge & H-Bridge Motor Control Current Monitoring Options



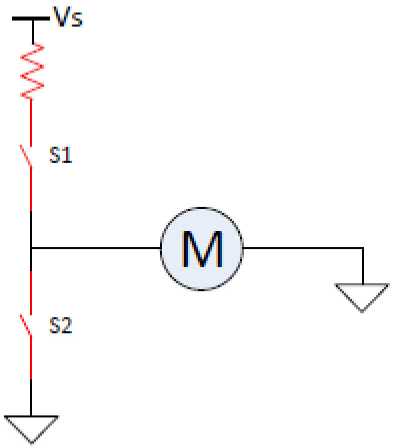
- Current information is used in:
  - Current is directly related(proportional) to torque
  - Speed/Torque control
  - Safety - guard against short circuit, stalled motor and used to monitor the general health of the motor
- Current sensing techniques in motor control
  - Noninvasive
    - Current transformer: $\frac{I_1}{I_2} = \frac{N_2}{N_1}$
    - Hall sensor
  - Resistor based current sensing
    - High side
    - Low side
    - In-line

Resistor based motor current sensing techniques – pros and cons

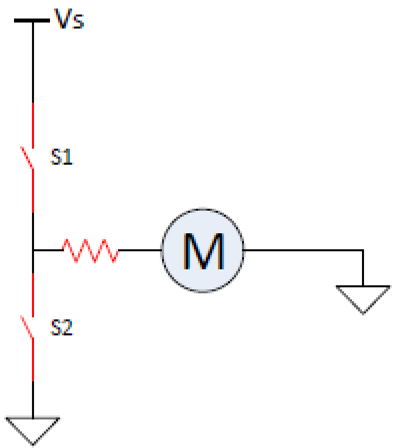
- Low side
  - Advantages
    - Low common mode voltage
    - Low voltage Amp possible
  - Disadvantages
    - Ground variation
    - Unable to detect fault
    - Driver current does not necessarily equal to motor phase current



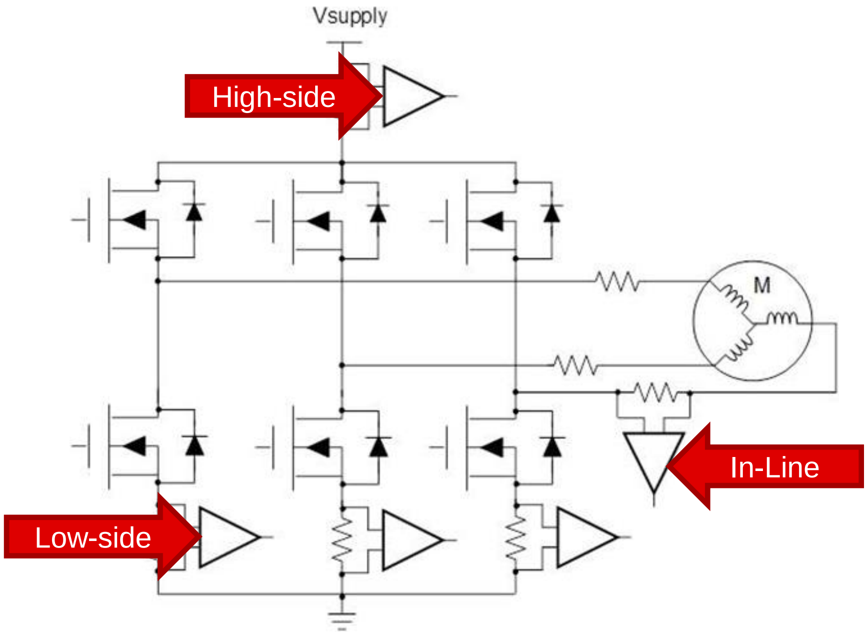
- High side
  - Advantages
    - Stable Common mode voltage
    - Fault detection
  - Disadvantages
    - Stable but high Vcm
    - Driver current does not necessarily equal to motor phase current



- In-line
  - Advantages
    - True motor phase current
  - Disadvantages
    - PWM common mode voltage
    - Sensing amp must have good DC and AC CMRR



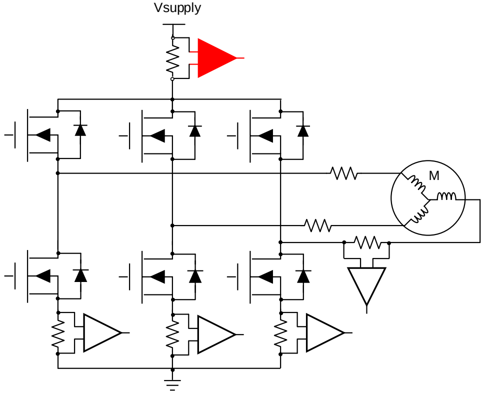
3Phase Motor Control Current Monitoring Options



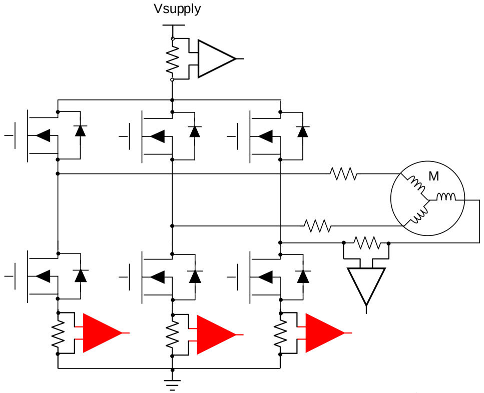
- Three choices
  - Low side (DC link or separate driver leg measurement)
  - High side(including DC link, or separate driver leg measurement)
  - In line
- Why do we measure current in motor control?
  - Torque and speed control (two-loop)
  - Safety
  - Could be used for rotor position sensing in sensorless BLDC, replacing Hall sensors or BEMF sensing

High-side & Low-side Motor Current Monitoring

- High-side (DC link or bridge)
  - Stable Vcm ☺
  - High voltage I_sense Amp ☹
  - Driver current does not always equal to phase current ☹



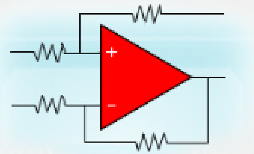
- Low-side (DC link or bridge)
  - Low Vcm ☺
  - Low voltage I_sense Amp ☺
  - Driver current does not always equal to phase current ☹
  - Ground variation ☹



Conventional High-side or Low-side sensing: – What Does TI have to offer?

- TI’s broad CSM portfolio for sure can offer you one device for either High or Low side current sensing:
- http://www.ti.com/lsds/ti/amplifiers-linear/current-sense-amplifiers-overview.page

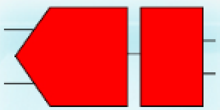
Analog Output



Integrate the full analog signal processing and provide a voltage or current output

Explore products ›

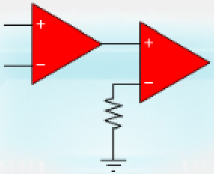
Digital Output



Integrate the full signal conditioning path and utilize a standard 2-wire digital interface

Explore products ›

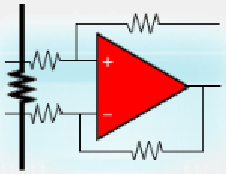
Comparator Output



Provides a simple ALERT signal when the load current exceeds a threshold.

Explore products ›

Integrated Shunt

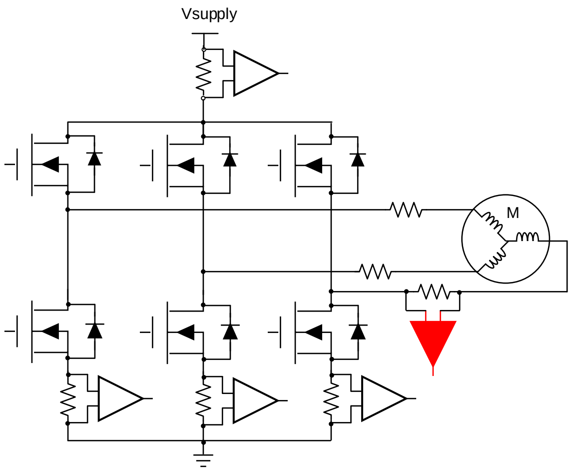


Offers a low-drift, precision integrated sense element.

Explore products ›

In-line 3phase Motor Current Monitoring

- True phase current at all times, NO guess work ☺
- PWM Common Mode voltage seen by I_sense Amp ☹
- High voltage combined with high dV/dT poses steep challenge to I-sense Amp ☹
- Availability of suitable Current Sensors limits the adoption of this topology.



Signal's Frequency Contents:

- The differential signal (useful information) is relatively narrow-band, and small;
- The CM PWM signal (not useful) is wide-band and BIG.

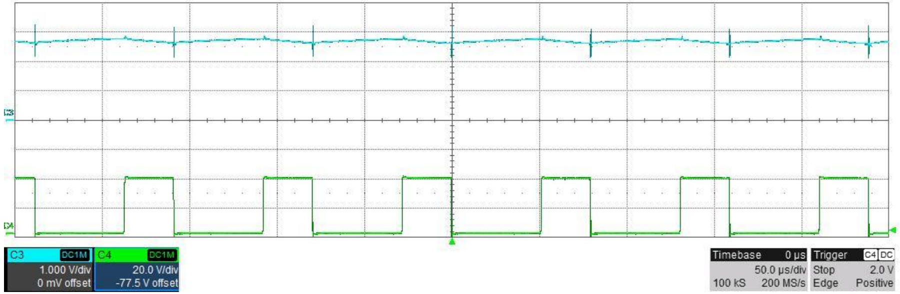
An ideal inline sensor:

- Amplifies only differential signal; "blind" to Common Mode signal.

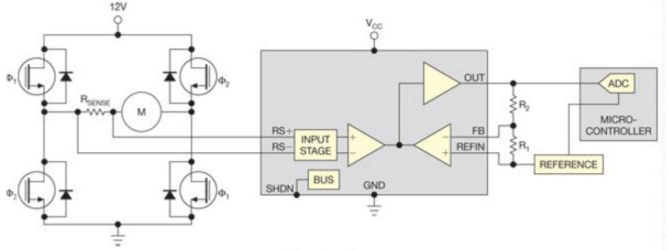
Why Is Inline Current Measurement Challenging?

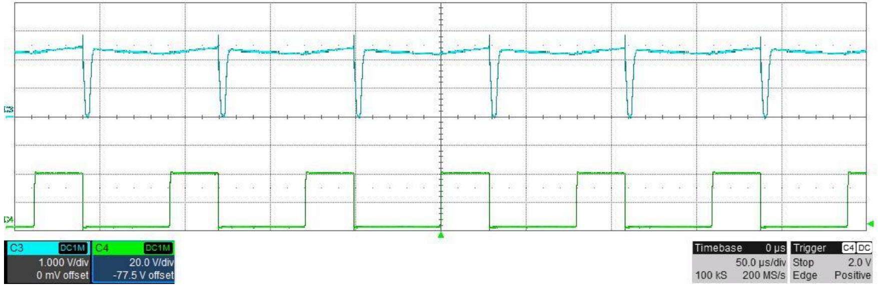
– The tale of a competitor… it is not a trivial task!

This is how the phase current should look like



This is how this competitor looks like





Competitor Paper: http://www.edn.com/design/analog/4369564/Monitor-PWM-load-current-with-a-high-side-current-sense-amplifier

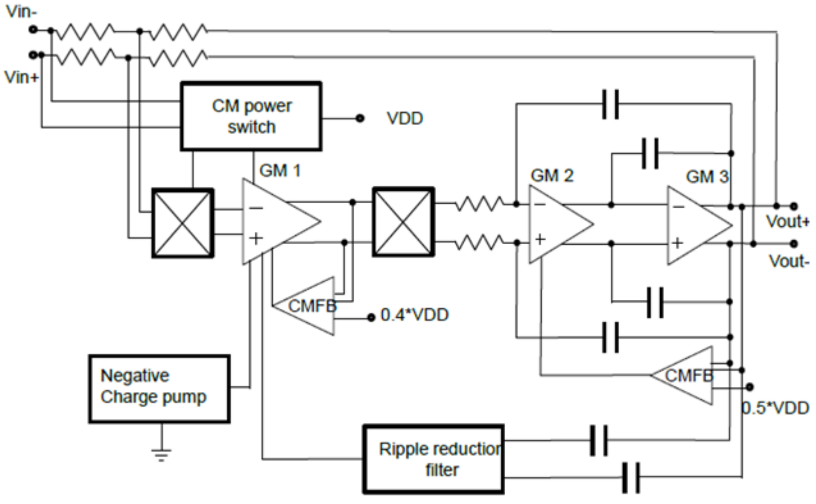
How Does INA240 Solve the Problem?

Novel Architecture:

- Chopper amplifier achieves exceptionally accurate Gain; zero Vos; zero Drift over temperature.
- In-package E-trim achieves superior resistor matching, resulting in excellent DC CMRR of better than 120dB.
- Minimizing coupling - Chopper amplifier without conventional feedforward path for improved AC CMRR performance, better than 90dB @50KHz
- Fully differential signal path further suppresses CM signal

Small signal bandwidth 150KHz@G100

- Exceptional settling, capable of PMW of 100KHz.
- Most motor drivers work in 20-40KHz range.



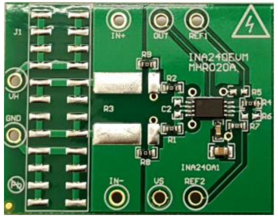
INA240 Input Stage

INA240

Features/Benefits

• Fast-transient common-mode voltage input filtering • High AC CMRR: 90 dB @ 50 kHz	Allows for in-line motor and solenoid/actuator current sensing
High Accuracy, High-speed performance • V_{OS} = 100 µV & V_{OS} Drift = 0.3 µV/°C • Gain Error = 0.25% & Gain Error Drift = 10 ppm/°C • 100 kHz Bandwidth (Gain = 100)	Enables precise current measurement under harsh motor environments
Wide common-mode input voltage range: -4 V to 80 V	Allows for motor supply voltages as high 48 V and inductive kick-back

Tools & Resources



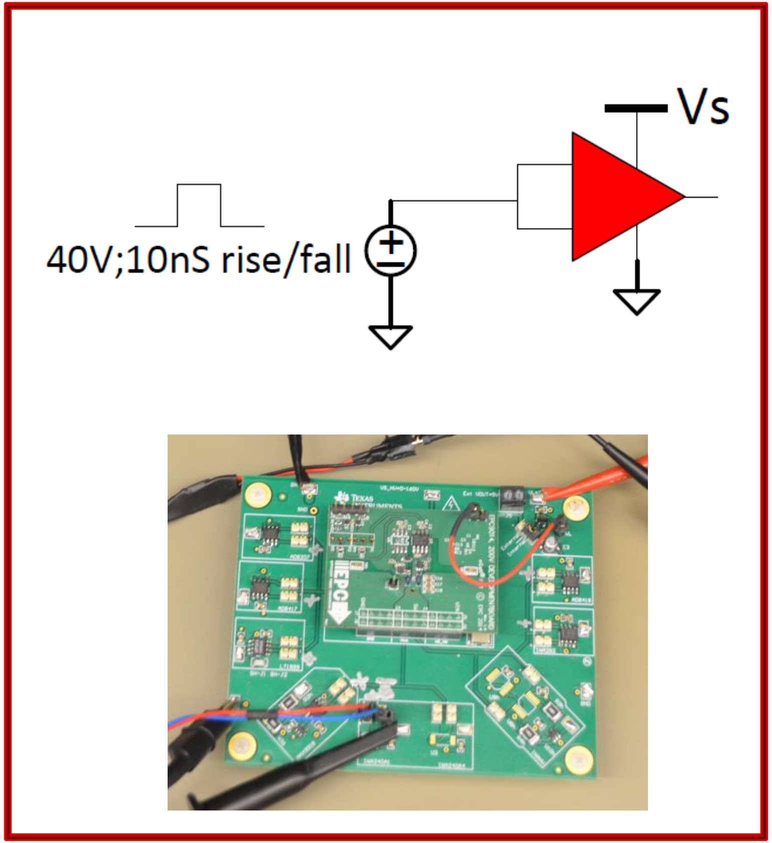
- INA240EVM
- User's Guide
- TINA-SPICE Model
- INA240 Datasheet

Target Applications

- Motor control
- Solenoid / Valve Control
- Power Delivery Systems
- Telecomm Equipment
- Pressure Regulator

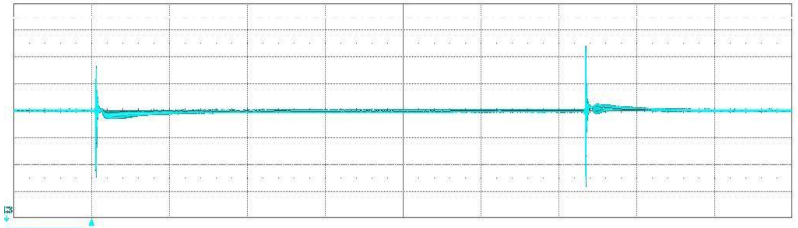
Performance With Fast Edge, CM Step Input –
How does INA240 compare with competition?

- Common Mode input voltage
  - INA240 can survive 100V/10nS
  - Some competitors claim ABS MAX of 65V
  - In our test a step of 50V/10nS often blows the competitor parts up
  - That is why we settled on 40V/10nS step for this study
- INA240 and other competitor devices are tested
- The inputs of the DUT are shorted together
- The same CM input voltage is fed to one device at a time.
- An ideal inline sensor:
  - Should reject CM input completely.
  - The sensor output should show no disturbances at all.

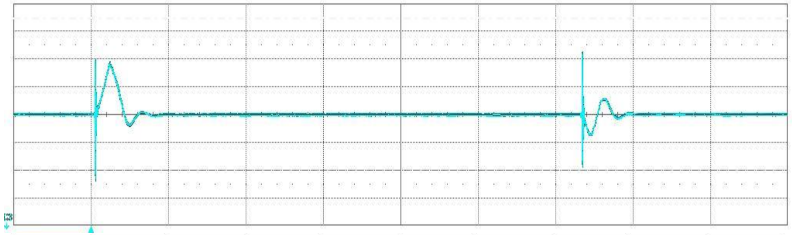


Common Mode Step Rejection Performance Comparison

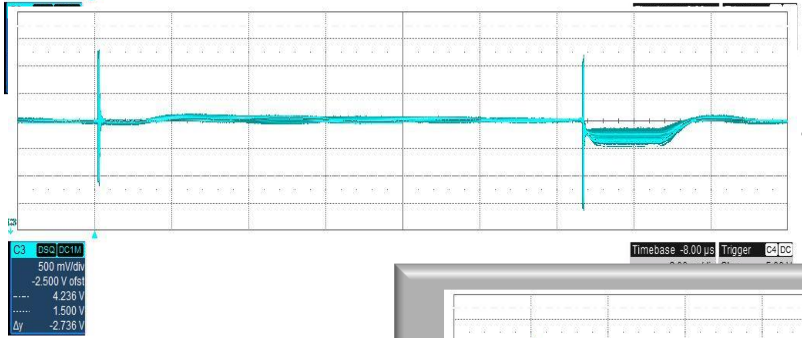
- Common Mode Input of 40V; rise time 10nS.



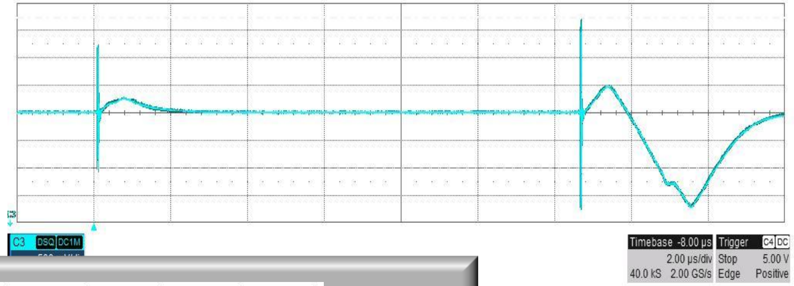
AD8207



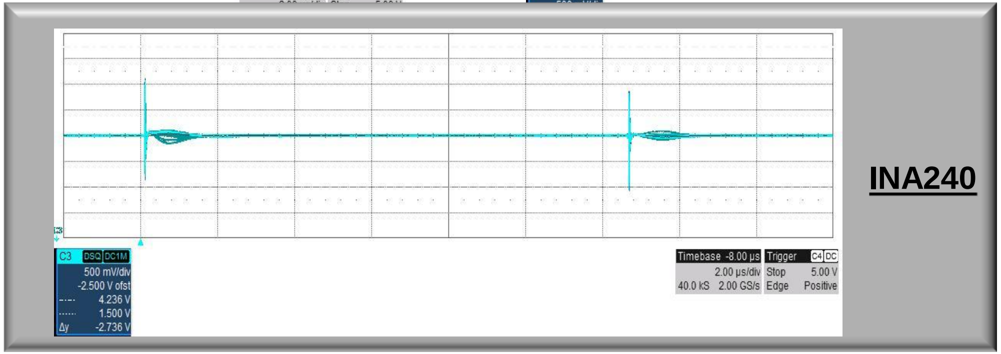
LT1999



AD8418



MAX9918

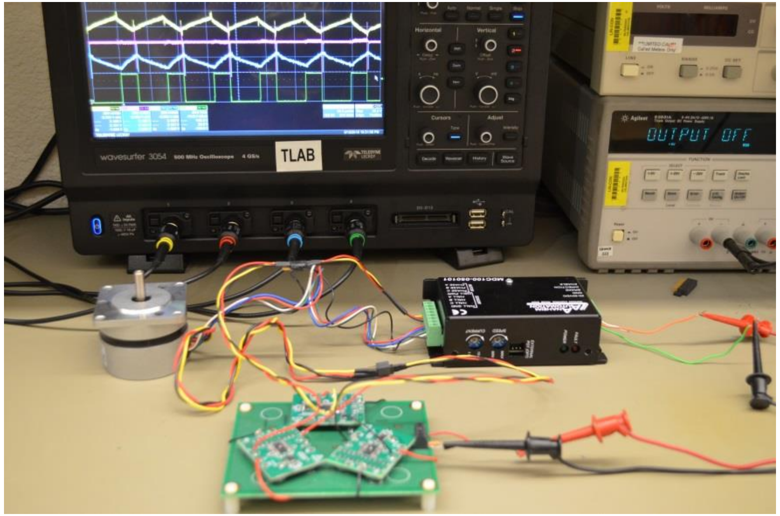


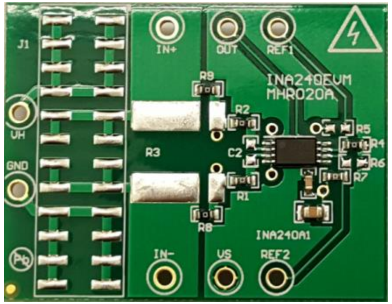
INA240

Texas Instruments

Performance As Inline Sensor –
How does INA240 perform?

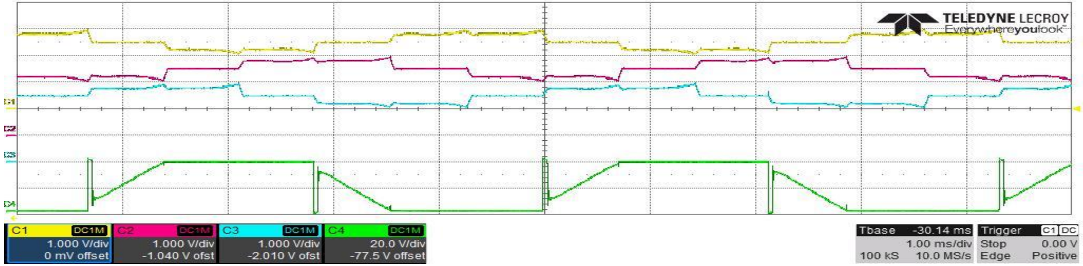
- Three (3) INA240, each in one of the 3 phases
- **INA240EVM** is perfect for this task with its versatility
  - sense resistor footprint provided;
  - configurable output reference for bi-directional output;
  - configurable input source and filtering.
- The INA240's are inserted between the motor and controller





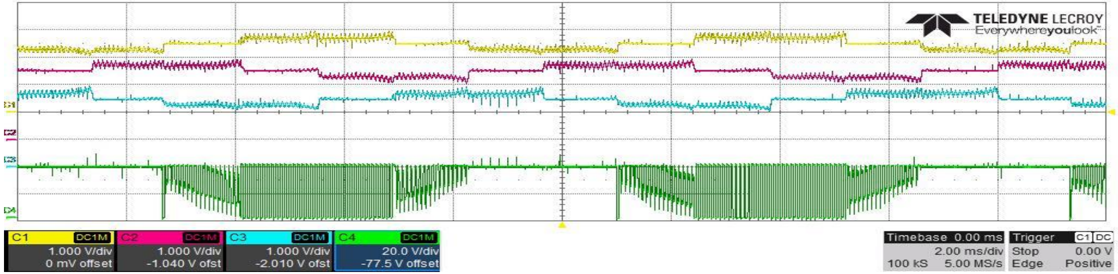
Test Results – INA240 as inline sensor

FULL SPEED

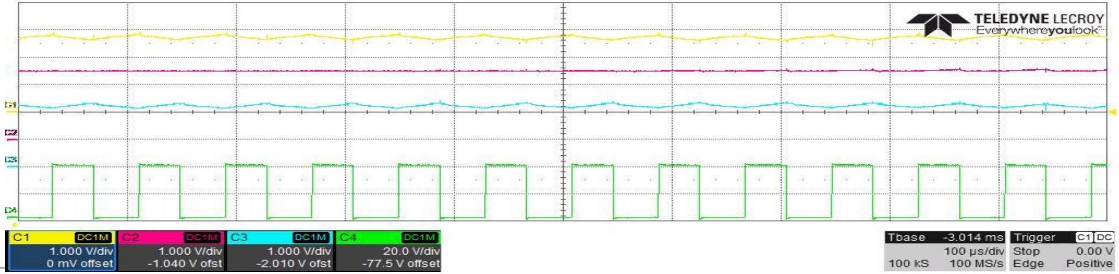


LOW SPEED

(BEMF ∝ Motor Speed)

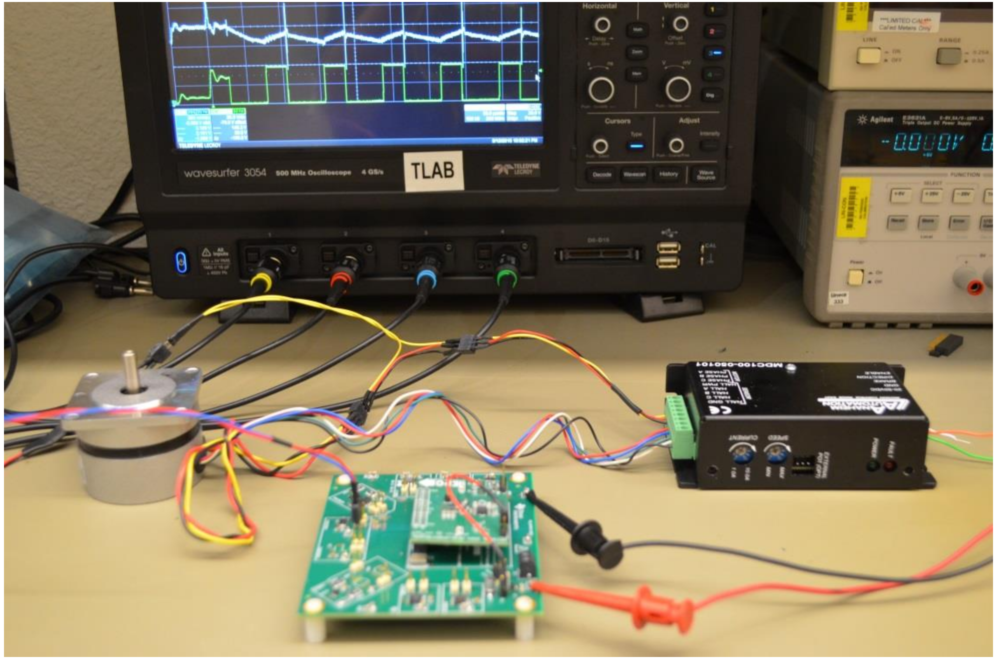


LOW SPEED (Zoom in)

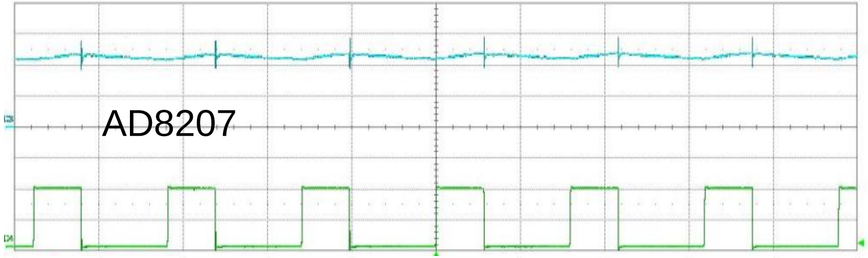


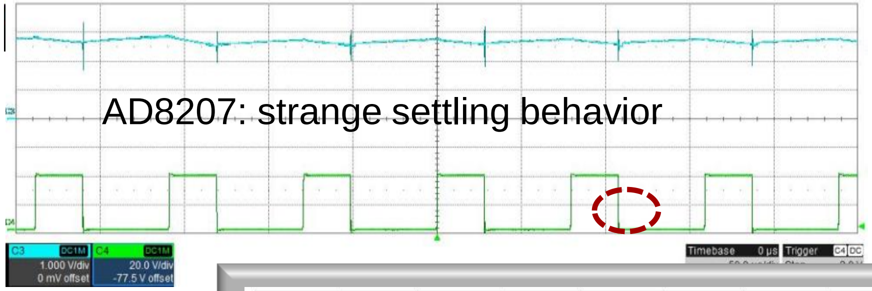
Performance As Inline Sensor –
How does INA240 compare with competition?

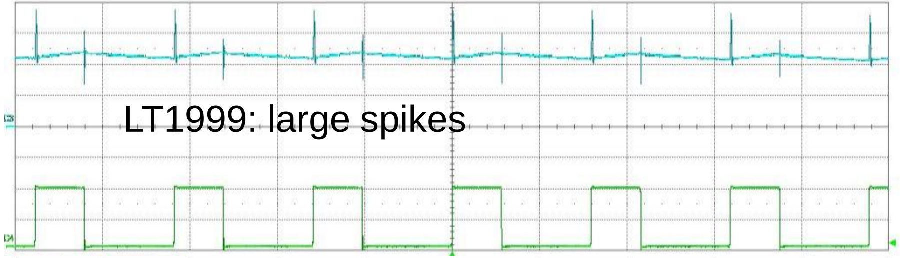
- PWM 40V/100nS
- Differential voltage developed across R_sense due to current flow
- The total input voltage is composed of a small differential voltage and a PWM CM voltage
- The same input voltage is fed to INA240 and other competitor parts
- A good inline sensor should:
  - Have excellent AC CMRR - small over shoot at transitions
  - Settles quickly after step transition
  - Other subtle criteria such as DC CMRR, accuracy that are not easy to tell visually

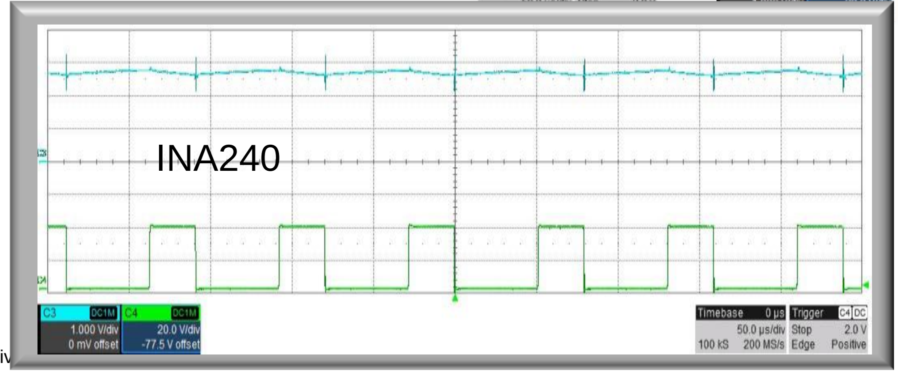


Test Results –inline sensor comparative study: Left Column top to bottom: AD8207 AD8417(G=60) AD8418 MAX9918; Right Column top to bottom: LT1999 INA282(G=50) INA240. Scale 1V/Div for all.









- **Compared with AD8207, INA240 wins by:**
  - ✓ **Settling faster**
  - ✓ **Higher Abs Max CM voltage 100V (AD8207 claimes 65V)**
  - ✓ **Survivability at high dV/dT – 100V/10nS (AD8207 often blows up with 50V/10nS CM step)**

Summary

INA240 offers best in class performance for motor inline current sensing:

- Exceptional accuracy
- -4V to 80V specified CM operation
- Unparalleled High dV/dT survivability
- Superior DC and AC common mode rejection
- Fast settling