Over Current Protection Alternatives

Motor Current Control With INA240

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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

- **Closed-loop Fluxgate sensors**
  - DRV401
  - DRV421

- **Open-loop**
  - DRV425

- **Current Sensing shunt solutions**
  - INAXXX
  - AMCXXX
  - ISO12X

- **Discrete OpAmp shunt solutions**
  - AMCXXX

**Measurement Accuracy**
- 0.1%
- 1%
- 10%
- 100A
- 1000A

**Primary Current**

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TI Information – Selective Disclosure
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

- **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

- **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

- **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

- **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

**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

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

TI Information – Selective Disclosure
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

• 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

- INA226
- INA231
- INA219
- INA220
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  

**Features/Benefits**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Current limit</td>
<td>up to 30A (scalable to &gt;100A)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>Response time</td>
<td>max 15µs (configurable)</td>
</tr>
<tr>
<td>Reverse polarity protection</td>
<td></td>
</tr>
<tr>
<td>Configurable delay time</td>
<td>to accommodate inrush current for 10µs, 50µs &amp; 100µs based on application</td>
</tr>
<tr>
<td>Power off resettable fuse</td>
<td></td>
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**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

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TI Information – Selective Disclosure
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

![Diagram of motor current sensing techniques](image-url)
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:


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**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


TI Information – Selective Disclosure
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

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

- $V_{OS} = 100\ \mu V$ & $V_{OS}\ \text{Drift} = 0.3\ \mu V/\degree C$
- 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

Target Applications

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

Tools & Resources

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

TI Information – Selective Disclosure
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
- AD8418
- LT1999
- MAX9918
- INA240
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 $\propto$ Motor Speed)

LOW SPEED
(Zoom in)
Performance As Inline Sensor –
How does INA240 compare with competition?

- PWM 40V/100nS
- Differential voltage developed across $R_{\text{sense}}$ 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 overshoot 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.

AD8207

AD8207: strange settling behavior

LT1999: large spikes

MAX9918: this is really bad!

• Compared with AD8207, **INA240 wins** by:
  ✓ Settling faster
  ✓ Higher Abs Max CM voltage 100V
    (AD8207 claims 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