Current and voltage sensing in EVSE and solar

Bart Basile
SEM – Grid Infrastructure – Renewable Energy
Asia FAE Summit - 2018
Additional resources

- AC charging station system resources
- DC charging station system resources
- Solar inverter system resources
- TI.com training portal
- TI reference designs library
Overview

• **System overview**
  • Overview current sensing
    – Shunt based measurement
    – Isolated current sensing
    – Magnetic measurement
  • Overview voltage sensing
    – Non-isolated measurement
    – Isolated voltage sensing

• Additional information / Q&A
Levels in EV charging stations

<table>
<thead>
<tr>
<th>EVSE Type</th>
<th>Power Supply</th>
<th>Charger Power</th>
<th>Charging time* (Approx.) for a 24kWH Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Charging Station: L1 Residential</td>
<td>120/230VAC &amp; 12 A to 16A (Single Phase)</td>
<td>~1.44kW to ~1.92kW</td>
<td>~17 Hours</td>
</tr>
<tr>
<td>AC Charging Station: L2 Commercial</td>
<td>208 ~ 240VAC &amp; 15 A ~ 80A (Single/ Split Phase)</td>
<td>~3.1kW to ~19.2kW</td>
<td>~8 Hours</td>
</tr>
<tr>
<td>DC Charging Station: L3 Fast Chargers</td>
<td>300 to 600VDC &amp; (Max 400A) (Poly Phase)</td>
<td>From 120kW up to 240kW</td>
<td>~30 Minutes</td>
</tr>
</tbody>
</table>

* Charging time does NOT scale linearly with EVSE charge capacity

AC charging station: Level 1 & 2

DC charging station: Level 3

**AC Charging System Power Flow**

- Grid
- EVSE
- OBC
- AC/DC Converter
- Battery Pack

**DC Charging System Power Flow**

- Grid
- EVSE + AC/DC Converter
- xN stack
- OBC
- AC/DC Converter
- Battery Pack
Charging station topology

AC Charger

DC Fast Charger

DC Fast Charger - PFC

DC Fast Charger – DC/DC
Solar system overview
Solar inverter topology

Solar Inverter

Solar MPPT

Solar DC/AC
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What are the key parameters when selecting a current sense amplifier?

- Configuration
- Common mode
- Bandwidth
- Directionality
- Offset
- Gain
- Output
Current sensor key parameters

- **Low-side sensing**: shunt resistor placed between the system load & ground

- **Bandwidth** depends on the application

- **Directionality**: Can the sensor measure current in both directions?

- Amplifier’s OFFSET ($V_{OS}$) is important because $V_{OS}$ cannot be bigger than the sense voltage, $V_{SENSE}$

- The GAIN amplifies the small signal $V_{SENSE}$

$V_{CM} \approx 0V$
How to size the shunt resistor

- We need the following to size the shunt resistor
  - Load current range
  - Available supply voltage
- Obtain output voltage range from CSM datasheet
  - INA282 Input and Output Range:
    - For this example, Vs = 5V, therefore:
  - INA282 Gain = 50 V/V
- Refer it back to the input by dividing by the device’s gain
  - Using 5A < I_{load} < 10A for this example
- Note: R_{shunt} value is directly related to both power and accuracy
- Resistor power dissipation results in self heating (drift) and system power losses
- So, use the largest R_{shunt} that your system can tolerate

P = Input Range x Current
P = 92mV x 10A = 0.92W
Accuracy is the key

- Worst case accuracy vs.
- Probable accuracy (Root–mean–square)

- Error sources:

<table>
<thead>
<tr>
<th>Description</th>
<th>Referred to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input offset voltage ($V_{\text{OS}}$)</td>
<td>Input</td>
</tr>
<tr>
<td>Offset voltage drift ($\frac{\Delta V_{\text{OS}}}{\Delta T}$)</td>
<td>Input</td>
</tr>
<tr>
<td>Offset voltage shift ($\frac{\Delta V_{\text{OS}}}{\Delta t}$)</td>
<td>Input</td>
</tr>
<tr>
<td>Gain error (%)</td>
<td>Output</td>
</tr>
<tr>
<td>Common-mode rejection (dB)</td>
<td>Input</td>
</tr>
<tr>
<td>Power supply rejection (dB)</td>
<td>Input</td>
</tr>
<tr>
<td>Input offset current ($I_{\text{OS}}$)</td>
<td>Input</td>
</tr>
<tr>
<td>Shunt resistor tolerance (%)</td>
<td>Input</td>
</tr>
</tbody>
</table>

Offset dominates error at small signal inputs

Gain error dominates error at large signal inputs
## General purpose op-amp vs. current sense amplifier

<table>
<thead>
<tr>
<th>General purpose op-amp</th>
<th>Current sense amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Bandwidth is usually specified with unity</td>
<td>• Usually specified at a fixed gain</td>
</tr>
<tr>
<td>• $V_{\text{offset}}$ is measured at the input of the op-amp as shown in the graphic with blue circles</td>
<td>• $V_{\text{offset}}$ is measured at the input resistors as shown in the graphic with gray circles</td>
</tr>
<tr>
<td>• Needs a larger PCB footprint as at least two gain resistors and an op-amp are needed</td>
<td>• Smaller PCB footprint as the amplifier, gain resistors and compensation capacitors are all integrated in the same package</td>
</tr>
<tr>
<td>• Offset voltage temperature drift is given for the op-amp alone</td>
<td>• Offset voltage temperature drift takes into account the amplifier and gain resistors’ variations</td>
</tr>
<tr>
<td>• CMRR specification is only for the op-amp</td>
<td>• CMRR specification takes into account the amplifier and gain resistors’ variations</td>
</tr>
<tr>
<td>• Gain error and its temperature drift are determined by the tolerance of the external resistor network</td>
<td>• Gain error and its temperature drift are specified as the resistors are integrated</td>
</tr>
<tr>
<td>• Common mode voltage is limited by the supply rail</td>
<td>• Common mode voltage is independent of the supply rail and can go up to 80V</td>
</tr>
<tr>
<td>• System error typically ~10%, even with precision passives</td>
<td>• System error &lt;1% possible</td>
</tr>
</tbody>
</table>

**Typical current measurement circuit**

- General purpose op-amp (red)
- Current sense amplifier (gray)
Integrated current sensing benefits vs. discrete solutions

Discrete current sensing circuits approach

Typical considerations
- Op-amp
  - Low cost
- Gain resistors
  - Low cost

Integrated current sensing approach

Result: Accurate measurements with low temperature variations

Average measurements accuracy with large temperature variations

- Integrates the op-amp and all the gain resistances
- Stable over the entire temperature range
  - Integrated gain resistors
  - $V_{OS}$ (1µV/°C Drift)
- Low-side & high-side capable
Shunt-Based, <1% Accurate, ±100A, High-Side, Bi-directional Current Measurement Reference Design

Features
- Shunt-based ±100A continuous bi-directional current measurement solution
- **Maximum shunt voltage limited to ±25 mV** to reduce power dissipation
- High-side current sense circuit with common-mode voltage of 80V, supporting batteries ranging from 6V to 60V
- Calibrated **DC accuracy of <1% across temperatures -25°C to 85°C**
- Can interface directly with differential or single-ended ADC
- Fast over-current **fault alert in either direction** for system safety
- **Adaptable for current sensing even close to fast switching nodes** without any external common-mode filtering

Benefits
- High current measurement using shunts in a small form-factor, addresses space sensitive and high power density needs.
- High accuracy with low shunt resistance value, reduces power loss and hence shunt sizing
- Scalable solution to measure low and high currents
- Common design for DC and low frequency pulse current sensing
- Ideal fit for 12V/24V/36V/48V battery current sensing applications

Target applications
- Battery chargers
- Uninterruptable Power Supplies (UPS)
- Energy storage systems
- Battery management systems
- AC-DC power supplies

Tools & resources
- **TIDA-01141 and tools folder**
- **Design guide**
- **Design files**: Schematics, BOM, gerbers, and more
- **Device datasheets**: INA240, LM2903/393, LM4041

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Additional shunt resources

- Tech notes
- Online training series
- Error estimation tool
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Current sensor key parameters

- **High-Side Sensing**: shunt resistor placed between the supply and load.
  - larger $V_{CM}$

- **Isolated Output**: provides a very high common mode capability to high side sensing

- **Voltage Output**
  - $V_{OUT}$

- **Current Output**

- **Digital Output**

- **Bit-stream Output**
Isolated amplifier vs. $\Delta\Sigma$-modulator

- **Isolated amplifier**

- **Isolated $\Delta\Sigma$ modulator**

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**Decimation (averaging) filter**
- e.g. C2000
- Sitara
- AMC1210
- FPGA

**3 conversion stages...**

...each stage adds errors

<10 bit accuracy on system level

**single conversion stage**

All processing in digital domain

>14 bit accuracy on system level
Isolated modulator design considerations

- 80% lower power dissipation vs. ±250mV
- ±50 mV drop
- Isolation enables common mode voltages above 1kV
- Fully integrated converter and amp reduces offset and temperature drift
- Isolated bias power supply required for high side
- LVDS option for improved EMI & better signal integrity with long transmission lines
- External clock input simplifies system level synchronization
- AMC13xx
- Controller
- Bias Supply
- MCU or FPGA (with decimation filter)
Shunt-Based High Current Measurement (200-A) Reference Design with Reinforced Isolation Amplifier

Features

- Shunt-based 200 A peak current measurement solution with reinforced isolation
- Maximum shunt voltage limited to 25 mV to reduce power dissipation
- High-side current sense circuit with high common-mode voltage of 1500-Vpeak, supporting up to 690-V AC mains powered drives
- Calibrated AC accuracy of <1% across temperatures -25°C to 85°C
- Can interface directly with differential or single-ended ADC
- On-board 1.65-VREF to level shift output
- Small form factor push pull-based isolated power supply to power high-side circuit

Benefits

- High current measurement capability using shunts in a small form factor.
- Lower power dissipation reduces shunt sizing
- Common design for line current and motor current sensing

Target applications

- Variable speed drives
- UPS
- Active front-end converters

Tools & resources

- TIDA-00912 and tools folder
- Design guide
- Design files: Schematics, BOM, gerbers, and more
- Device datasheets:
  - AMC1301
  - OPA2376
  - OPA376
  - REF2033
  - SN6501
  - LM4040

Board Image

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Sensor implementations

Closed-loop current sensors

- Magnetic core picks up field around conductor
- **Sensor IC inside the core**
- Compensation coil drives magnetic field to zero

**Fluxgate**
- DRV401
- DRV421

**Hall**
- DRV411

Open-loop current sensor

- Magnetic field generated as current flows through conductor
- **Sensor IC (DRV425)** inserted into the bus bar opening
- Second DRV425 used to reject external disturbances
Closed-loop measurement principle

- **Primary (measured) current**
- **Magnetic core** concentrates the magnetic field induced by the current through the primary conductor
- **Sensor** measures the current, which is proportional to magnetic field, through the primary coil

**Diagram:**
- Compensation coil induces exact magnetic field back into the core to effectively cancel out any magnetic field
- Analog frontend amplifies / filters input signal and drives compensation current to coil
- Current sensing amplifier reads voltage across shunt resistor set by compensation current

**Components:**
- DRV421
- DRV401 or DRV411
- DRV425

**Texas Instruments**
Fluxgate Magnetic Current Sensing Reference Design with High Linearity for 3–Phase Inverters

**Features**
- Designed to accurately measure three phase inverter currents up to 50ARMS (nominal) and 150A (maximum)
- 200 kHz bandwidth, closed-loop current sensing using magnetic module and fluxgate sensor (DRV421)
- Calibrated current measurement accuracy of ±1% (typical) across temperature range from -25°C to 85°C
- Hardware based overload and ground fault detection enables fast response for protection of power switches

**Target applications**
- Variable speed drives
- UPS
- Solar inverters

**Tools & resources**
- **TIDA-00905 and tools folder**
- **Design guide**
- **Design files:** Schematics, BOM, gerbers, and more
- **Device datasheets:**
  - DRV421
  - TLV1117-33
  - TLC372

**Benefits**
- Simplifies over-current protection for power switches
- Interface with 3.3V or 5V ADCs of microcontrollers
- Validated reference design for fluxgate current sensor
- Common reference design for line current and motor current measurement

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Sensor implementations

Closed-loop current sensors

- Magnetic core picks up field around conductor
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- Compensation coil drives magnetic field to zero

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<tr>
<td>DRV401</td>
<td>DRV411</td>
</tr>
<tr>
<td>DRV421</td>
<td></td>
</tr>
</tbody>
</table>

Open-loop current sensor

- Magnetic field generated as current flows through conductor
- **Sensor IC (DRV425) integrated core and compensation coil**
- Compensation coil drives magnetic field to zero
DRV425 - value for high-current measurements

Benefits
- Sensor integrated into the bus bar for isolated measurement up to 1000s of amps
- Differential measurement inside the bus bar further increases immunity to stray fields and to frequency effects and to overcurrent conditions
- Lower power than shunt based solutions
- Compact module design and ease of installation
- High SNR by replacing discrete hall sensors
- Lower complexity and single temperature calibration
- <1% error over wide dynamic range
Bus bar theory of operation

ABSTRACT

Traditional bus bar current measurement techniques use closed loop current modules to accurately measure and control current. These modules usually require a large magnetic core that encloses the entire bus bar. Because the compensation current generated inside the module is proportional to the bus bar current, the power dissipation can be as high as several watts. An alternative approach is to use two DRV425 devices connected in a differential configuration and mounted on opposite sides of a printed circuit board (PCB). This board is then placed into a cutout (hole or slot) located in the center of a bus bar.

Figure 1 shows the alternate approach using two DRV425 devices. When a cutout (hole or slot) is placed in the center of the bus bar, the current is split in two equal parts. Each side of the cutout will generate magnetic field gradients that oppose one another inside the cutout. The high sensitivity and linearity of the two DRV425 devices allow small opposing magnetic fields to be sensed and the current to be measured with high-accuracy levels. The DRV425 devices are placed equidistant from the center of the cutout and oriented in opposite directions to provide a differential measurement. This differential measurement also helps to reject stray magnetic fields.

Application report

Magnetic field calculator
Bus bar design simulation

- FEMM scripts to estimate magnetic field strength at each DRV425 device
  - 2D simulator
- Script definition and instruction presentation
Isolated High-Current Magnetic Bus Bar Sensing Circuit

**Features/Benefits**

<table>
<thead>
<tr>
<th>Feature/Feature</th>
<th>Benefit/Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated precision current measurement w/ fluxgate sensor</td>
<td>Greatly reduced system design complexity</td>
</tr>
<tr>
<td>Dual sensor design to eliminate external interferences</td>
<td>Measures up to 110A of AC, DC, or pulsed current</td>
</tr>
<tr>
<td>Small form factor</td>
<td>Greatly reduced cost vs current transformer approach</td>
</tr>
</tbody>
</table>

**Target applications**

- Distribution automation – terminal unit
- Bus-bar power monitoring

**Tools & Resources**

- **TIPD205**
- Design guide
- **Orderable #:** DRV425-BUSBAR-EVM
- **Design files:** Schematics, BOM, gerbers, software, and more
- **Device datasheets:**
  - TI DRV425

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*Texas Instruments*
Design considerations for dual DRV425 bus bar applications

Problem statement

“What configuration is best for my design?”

Understanding the system level influences for any magnetic field measurement is critical to achieving the best performing system. Stray magnetic fields cannot be eliminated but can be minimized. Selecting the configuration that is best suited for a given design is critical for optimal performance.

- Lead solution: DRV425
- TI tech note: SBOA185

Applicable end equipments

- DC-DC converters
- 3-phase motor
- 3-phase AC current measurement
- General purpose drives

Magnetic fields based current sensing is a common approach for measuring high currents (>100A) and/or high voltages (>100V).

Utilizing 2 DRV425 devices with the axis of sensitivity in opposite directions allows for cancelation of stray magnetic fields.
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• Additional information / Q&A
Voltage sensor key parameters

- What are the key parameters when selecting a voltage sensor?
System architecture

Option 1: System ground – Earth

Option 2: System ground – DC-
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• Additional Information / Q&A
AC voltage sensing

- Need to measure both positive and negative polarity of AC signal
- Resistor dropper chain of 10Mohm used to attenuate voltage signal
- Neutral reference works for multiple phases
- Center in ADC input range using VCC/2 reference voltage input
DC voltage sensing

- HV resistor dropper chain
- Floating reference to system ground
- Potentially unsafe depending on grounding and isolation topology
TIDA-01606 - 10kW 3-Phase 3-Level Grid Tie inverter reference design for solar string inverter

**Features**

- Rated nominal/Max input voltage at 800V/1000V DC
- Max 10kW/10KVA output power at 400VAC 50/60Hz Grid-tie connection
- Operating power factor range from 0.7lag to 0.7lead
- High Voltage (1200V) SiC MosFET based full bridge inverter for Peak efficiency of 98.5%
- Compact output filter by switching inverter at 50KHz
- <2% output current THD at full load.
- Isolated driver ISO5852S with reinforced isolation for driving High voltage SiC FET and UCC5320S for driving middle Si FET.
- Isolated current sensing using AMC1301 for load current monitoring
- TMS320F28379D Control card for digital control.

**Benefits**

- 3-Level T-type inverter topology for reduced ground current in transformer less grid tie inverter applications.
- Reduced size at higher efficiency using low Rdson SiC Mosfet for same output power.
- Platform for testing both 2-level and 3-level inverter by enabling or disabling middle devices through digital control.

**Target Applications**

- String Inverter
- Central Inverter

**Tools & Resources**

- **TIDA-01606 and Tools Folder**
- **Design Guide**
- **Device Datasheets:**
  - TMS320F28379D
  - ISO5852
  - UCC5320S
  - AMC1301
  - OPA4350
  - LMT87
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When to use isolated voltage sensing

- The ADC (or MCU with on-chip ADC) is not referenced to the same point as the resistive divider (i.e. DC- or Neutral)
- Safety regulations require actual isolation barrier to be in place (while not relying on the resistors only)
Isolated DC voltage sensing

- Fully isolated voltage sensing solution
- Requires external bias supply
- Digital or analog output, like the current sensing amplifiers
- A high impedance input reduces impact on the voltage divider circuit
Isolated DC voltage sensing

- Implementable with AMC1311 reinforced isolation amplifier
- AMC1311 has a gain of 1V/V, so input should be scaled to match ADC
- DC-Link of 1000V is scaled down to 2V input using 6Mohm resistor chain
- 0-2V input range ensures linearity across signal chain
- Additional amp/filter can be used on the output if required
High-Bandwidth Phase Current and DC-Link Voltage Sensing Reference Design for 3-Phase Inverters TIDA-01541

Features

- Reinforced isolated 3-phase inverter suited for 100-690V AC drives rated up to 10kW, 50A
- Phase current range of +/-50A (nominal) using a 5-mOhm shunt and a reinforced isolated amplifier with +/-250mA input range and 200kHz bandwidth
- Power management: External power supply 5V ISO and 15V (bootstrap) and DC-link voltage
- Protection against DC bus under-voltage, over-voltage, over-current, ground fault and over-temperature
- Bootstrap based power supply for high side gate driver reduces overall cost for power supply requirement
- Interface to host MCU: 3.3V interface to C2000 LaunchPad (PWM signals 1-6, three phase currents, DC-link voltage, STO, Trip)

Benefits

- Reinforced isolated amplifiers with high bandwidth enable low latency current sensing and fast over-current detection to protect the power stage. Enables use of MCU with integrated or external SAR ADC.
- Calibrated current measurement error of ±0.5% across temperature range from -25°C to 85°C (measured w/ inverter running)
- Reinforced isolated amplifier with low power consumption allows powering from the gate drivers bootstrap capacitor w/ simple LDO.
- Reinforced isolated amplifier with high-impedance input optimized for precision sensing of high-impedance nodes like DC-link voltage, ±1% error for DC-Link voltage sensing accuracy.

Target Applications

- Servo Drives, Robotics & CNC
- AC Inverter & VFD

Tools & Resources

- TIDA-01541 and Tools Folder
- Design Guide
- Design Files: Schematics, BOM, Gerbers, etc.
  Device Datasheets:  
  - AMC1301
  - AMC1311
  - UCC21520

Board Image

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TI Designs – current sensing

**Shunts**
- **Non-Isolated**
  - **TIDA-00528 (OPA333/INA226)**
    - 40 to 400 V Uni-Directional Current/Voltage/Power Monitoring Reference Design
    - Max Voltage: 400 V
    - Max Current: 8 A
- **Isolated**
  - **TIDA-00555 (AMC1100)**
    - Isolated Current/Voltage Measurement Using Fully Differential Isolation Amplifier
    - Max Voltage: 300 V
    - Max Current: 40 A
  - **TIDA-00080 (AMC1304)**
    - Isolated Current/Voltage Measurement Using Fully Differential Isolation Amplifier
    - Max Voltage: 1 kVAC
    - Max Current: 200 A
  - **TIDA-00601 (AMC1304)**
    - Isolated Current/Voltage Measurement Using Fully Differential Isolation Amplifier
    - Max Voltage: 1 kVAC
    - Max Current: 90 A
  - **TIDA-00738 (AMC1304)**
    - Wide Input Current Using Shunts and Voltage Measurement for Protection Relays
    - Max Voltage: 300 VAC
    - Max Current: 60 A

**Hall**
- **TIDA-00218 (hall)**
  - AC Current Measurement with Hall Effect Sensor
  - Max Current: 12 A
- **TIPD180**
  - ±50A Current Sensor using Closed-Loop Compensated Hall Element Reference Design
  - Max Current: 50 A

**Fluxgate**
- **TIPD196**
  - ±15 A Current Sensor Using Closed-Loop Compensated Fluxgate Sensor Reference Design
  - Max Current: 15 A
TI Designs – voltage sensing

Isolated

- TIDA-00555 (AMC1100)
  40 to 400 V Uni-Directional Current/Voltage/Power Monitoring Reference Design
  - Max Voltage: 400 V
  - Max Current: 8 A

- TIDA-01541 (AMC1311)
  High-Bandwidth Phase Current and DC-Link Voltage Sensing Reference Design for Three-Phase Inverters
  - Max Voltage: 1000 V
  - Max Current: 15 A

Non-Isolated

- TIDM-HV-1PH-DCAC (OPA4350)
  Single-Phase Inverter Reference
  - Max Voltage: 380 V
  - Max Current: 6 A

- TIDA-01606 (OPA4350)
  Three-Phase Grid Tie Inverter Reference Design for Solar String Inverters
  - Max Voltage: 1000 V
  - Max Current: 18 A
Additional information on EV charging

- AC charging station
- DC charging station
- TI reference designs library
- TI.com training portal
Additional information on solar inverter

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- TI.com training portal
Q&A