Hardware Engineer Guide

For

Current Sensing

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Author	Date	Version	Changes
Shimi Cohen	10/4/2025	1.0	First Draft

1 Introduction

1.1 The Basics

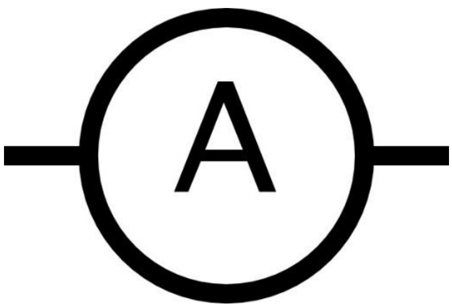
Current sensing is a fundamental technique in electronic systems for measuring the flow of electrical current. Precise current measurement enables critical functions, including:

- Power management and optimization
- Overcurrent protection and fault detection
- Battery charging and monitoring
- Motor control
- Load detection and analysis
- Energy metering and monitoring

This guide provides comprehensive coverage of current sensing techniques, implementation considerations, and practical circuit designs. The information presented will help engineers select the most suitable current sensing solutions for their specific applications and design requirements.

We will discuss important topics related to current measurement:

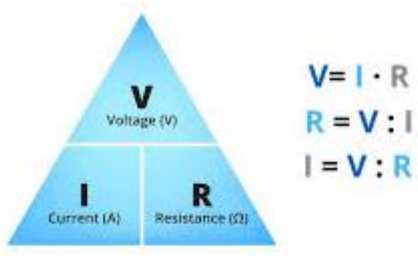
- Sensing Methods
- Shunt Resistors
- High-Side vs. Low-Side
- Analog-to-Digital Conversion
- Implementation Examples



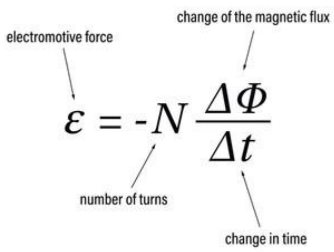
1.2 Sensing Principles

Current sensing relies on fundamental electromagnetic principles, primarily:

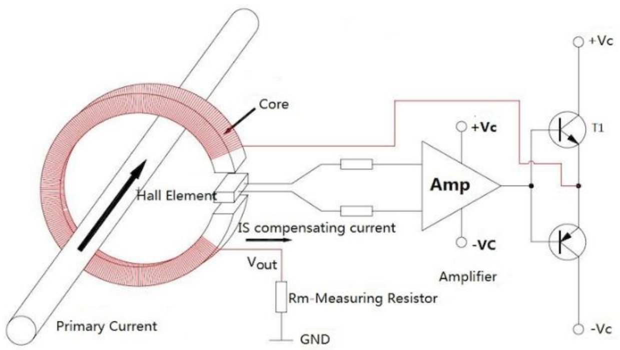
Ohm's Law: Measuring voltage drop across a known resistance



Faraday's Law: Detecting induced voltage in a coil by changing magnetic field



Hall Effect: Measuring voltage generated perpendicular to current flow in a conductor



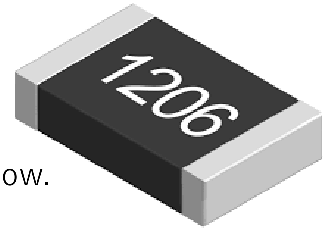
Each principle forms the basis for different sensing technologies:

Principle	Primary Advantage	Main Limitation
Ohm's Law	Simplicity, low cost	Power dissipation
Faraday's Law	Galvanic isolation	Limited frequency response
Hall Effect	Wide current range	Temperature sensitivity

2 Current Sensing Methods

2.1 Techniques

SHUNT RESISTOR



Operating Principle

Current flows via a precision resistor, which generates a voltage drop
This voltage is measured, amplified, and filtered to determine current flow.

Key Characteristics

- **Resistance Value**: Normally $0.1\,\Omega$ to $0.001\,\Omega$ for power applications
- **Power Rating**: Must handle I^2R power without excessive heating
- **Temperature Coefficient**: The Lower the Better ($< 20\,ppm/°C$ preferred)
- **Construction**: Four-terminal connections (2 for current and 2 for voltage)

Design Considerations

1. **Resistance Selection**
   - Lower resistance reduces power loss but decreases signal amplitude
   - Higher resistance improves signal-to-noise ratio but increases power dissipation
2. **Signal-to-Noise Ratio**
   - Minimum voltage drop typically 20-50mV for acceptable SNR
   - Maximum practical voltage drop usually 100-200mV to limit power loss
3. **Power Dissipation**
   - Adequate thermal management required to maintain accuracy
   - Check Power over Shunt Resistor - $P = I^2 \times R$

Package	Max Power (Typical)	Notes
2512	1W – 2W	Great for high current shunts
2010	0.75W – 1W	Good balance of size & power
1206	0.25W – 0.5W	Most used in mid-current
0805	0.125W – 0.25W	Standard for low-mid power
0603	0.1W	Best for sensing, not power

CURRENT TRANSFORMER SENSOR

Current transformers (CTs) offer galvanic isolation and are ideal for measuring AC currents.

Operating Principle

A CT works by electromagnetic induction. The primary conductor passes through a magnetic core, inducing a current in a secondary winding proportional to the primary current

Key Characteristics

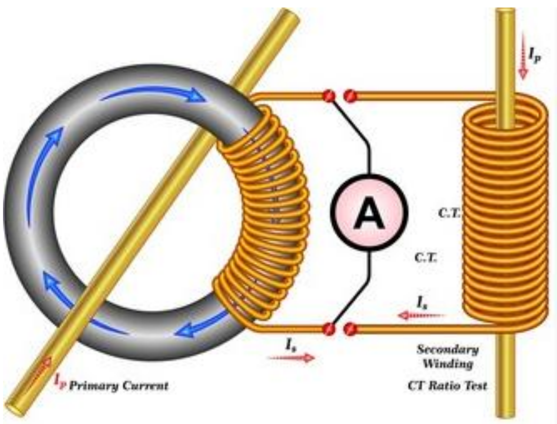
- **Turns Ratio**: Determines current reduction factor
- **Frequency Response**: Normally 20Hz to 100kHz
- **Burden Resistor**: Converts secondary current to measurable voltage
- **Linearity**: Core saturation limits maximum measurable current

Design Considerations

1. **Core Selection**
    - Ferrite: Higher frequency, lower cost
    - Silicon steel: Higher permeability, better low-frequency response
    - Nanocrystalline: Best overall performance, highest cost
2. **Burden Resistor Selection**
    - Higher resistance increases output voltage
    - Excessive resistance causes core saturation
    - Typical values: 10Ω to 100Ω
3. **Frequency Limitations**
    - Lower limit determined by core permeability
    - Upper limit determined by parasitic capacitance and core losses
4. **DC Current Components**
    - Standard CTs cannot measure DC
    - DC components cause core saturation
    - Solutions include air gaps or hall-effect

Applications

1. AC power monitoring
2. Variable frequency drives
3. Power quality analysis
4. Ground fault detection



HALL EFFECT SENSOR

Hall effect sensors measure current through its magnetic field without direct connection.

Operating Principle

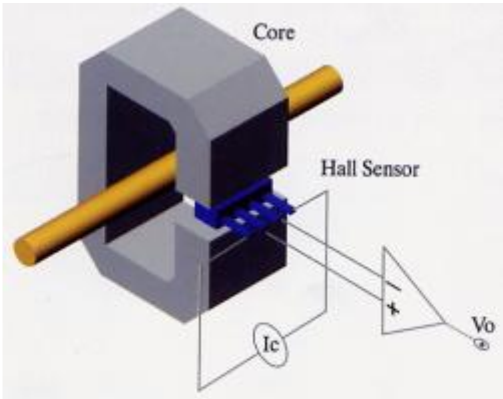
A Hall element generates a voltage perpendicular to the direction of current flow when exposed to a magnetic field.

Key Characteristics

- **Sensitivity**: 1-5 mV/G (gauss)
- **Frequency Response**: DC to 100kHz
- **Temperature Dependence**: Requires compensation
- **Output Type**: Linear voltage, digital switching, or current output

Hall Sensor Configurations

1. **Open-Loop**
    - Direct measurement of Hall voltage
    - Subject to temperature drift
    - Lower accuracy (1-3%)
2. **Closed-Loop**
    - Feedback coil nulls the magnetic field
    - Better linearity and temperature stability
    - Higher accuracy (0.5-1%)



Design Considerations

1. **Magnetic Circuit**
    - Concentrates magnetic field around Hall element
    - Reduces susceptibility to external fields
    - Improves linearity and sensitivity
2. **Temperature Compensation**
    - Critical for accuracy across temperature range
    - Modern ICs include integrated temperature compensation
    - Typical drift: 50-200 ppm/° C
3. **Zero Offset**
    - Values at zero current
    - Requires calibration

3 Low/High Side Sensing

3.1 Low-Side Sensing

Methode:

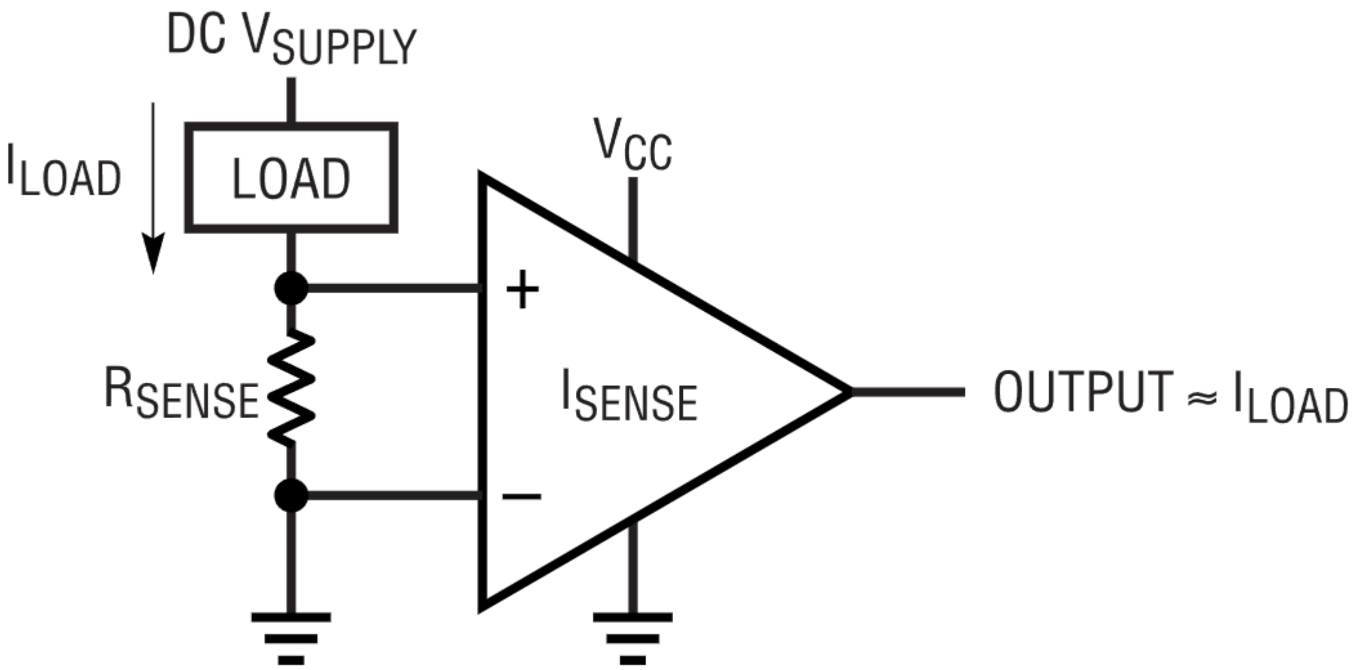
Current sensor between the load and ground:

Advantages:

- Simple implementation
- Common-mode voltage near ground
- Easy interface to ADCs and amplifiers

Disadvantages:

- Cannot detect ground faults
- Disrupts ground path
- Load no longer directly grounded



3.2 High-Side Sensing

METHOD:

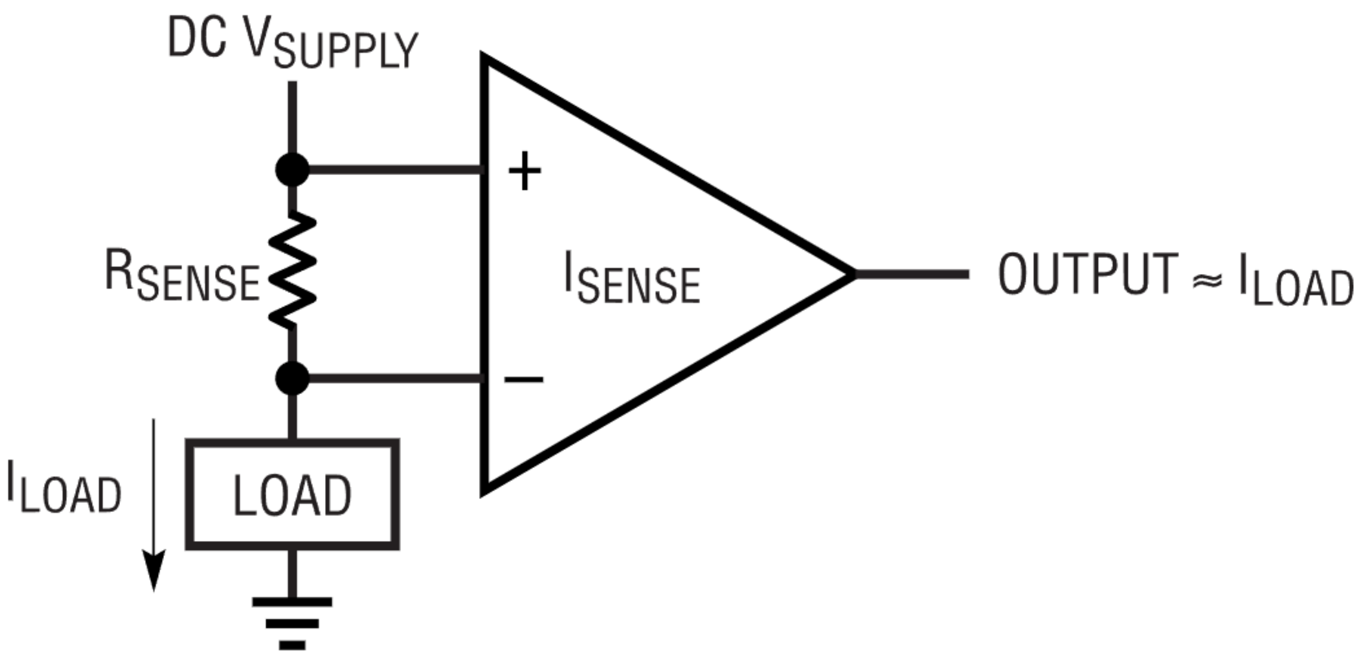
Current sensor between the power source and load.

ADVANTAGES:

- Detects all load faults, including ground faults
- Maintains direct ground connection to load
- Required for battery monitoring

DISADVANTAGES:

- Common-mode voltage equals supply voltage
- Requires specialized amplifiers or isolation
- More complex circuit design



4 Analog-to-Digital (ADC)

Analog To Digital Conversion converts the measured Voltage levels indicating the current into Values that can be read by a Controller or Processor (e.g., MCU, FPGA)

4.1 Key Specifications

Resolution

- Determines **smallest detectable** current change
- 12-bit common for general applications
- 16-24 bit for precision measurements
- Effective resolution is often limited by noise

Sampling Rate

- Determines highest measurable frequency component
- Practical systems use up to 10 times oversampling for accuracy

Input Range

- Must match conditioned signal output
- Programmable gain amplifiers (PGAs) extend effective range

Architecture

- **SAR** (Successive Approximation Register): Good general-purpose choice
- **Delta-Sigma**: Highest precision, lower speed (24 bit, <100kSPS)
- **Flash**: Highest speed, lower resolution (8-10 bit, >100MSPS)

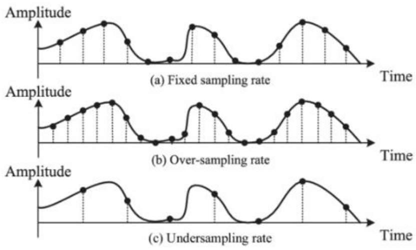
External VS. Internal

- MCUs often include built-in ADCs for basic current or voltage monitoring.
- Integrated ADCs offer moderate performance,
- External (stand-alone) ADCs deliver higher performance.
- MCUs communicate with external ADCs via interfaces like SPI or I^2C.

5 Digital Processing Techniques

Values read from ADC need to be processed properly to increase accuracy and reliability.

5.1 Common Methodes



Oversampling

- Improves effective resolution
- $\sqrt{N}$ improvement with $N\times$ oversampling
- Combined with digital filtering

Averaging

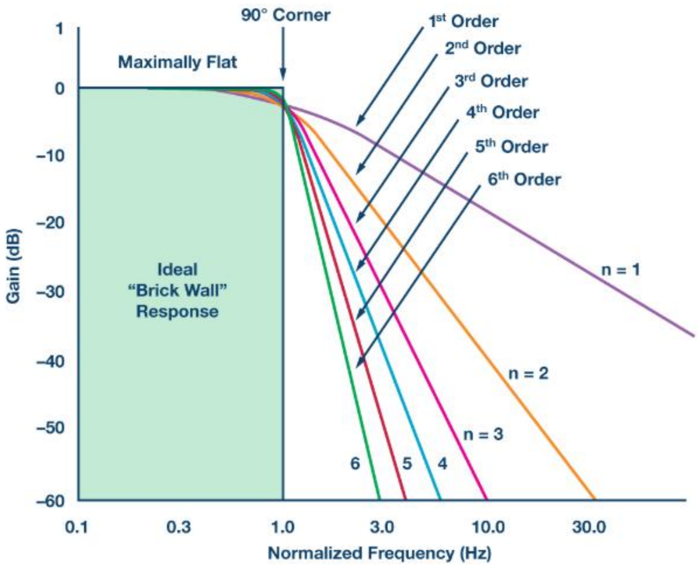
- Reduces random noise
- Simple moving average or weighted methods
- Trade-off between noise reduction and response time

Calibration

- Zero calibration (offset correction)
- Gain calibration (slope correction)

Digital Filtering

- FIR filters for linear phase response
- IIR filters for efficient implementation
- Adaptive filters for changing conditions



6 Implementation & Components

6.1 Common Requirements

Amplification

- Gain selection to match ADC input range
- Precision amplifiers with **low offset voltage**
- Low temperature drift characteristics

Filtering

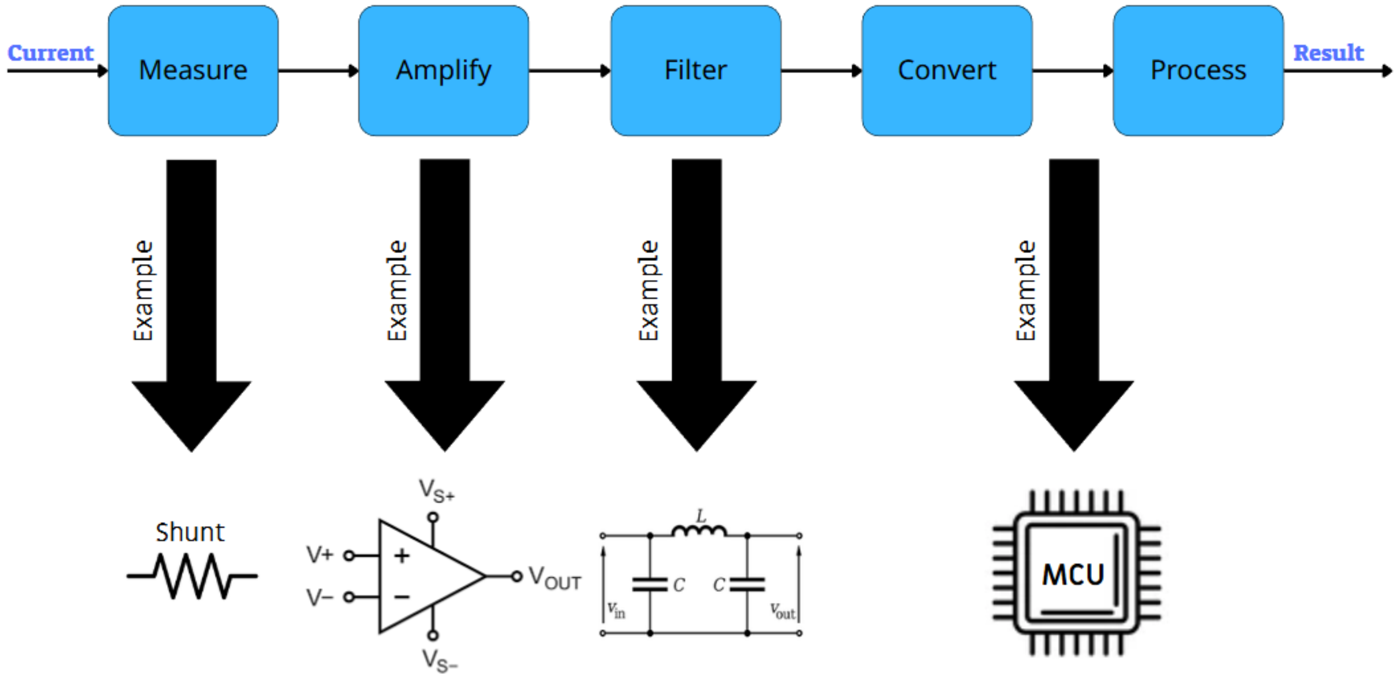
- LPF to remove noise
- Anti-aliasing filter before ADC sampling
- Notch filters for specific interference frequencies

Protection

- Overvoltage protection with clamp diodes
- Current limiting resistors
- Isolation for high voltage applications

6.2 Current Sensor Structure

Current sensing requires essential elements as followed:



6.3 Differential OPAMP Examples

Part Number	Manufacturer	Gain	CMRR	Bandwidth	Package
INA240	TI	20/50/100/200	140dB	400kHz	SOT-23, SOIC
AD8210	Analog	20	120dB	450kHz	SOIC
MAX40056	Maxim	25/50/100	135dB	1MHz	μMAX
ZXCT1107	Diodes	10/20	100dB	200kHz	SOT-23

6.4 Stand-Alone ADCs

Manufacturer	Component	Comm	Resolution	Sample Rate
Texas Instruments	ADS8881	SPI	18-bit	1 MSPS
Analog Devices	AD7980	SPI	16-bit	1 MSPS
Microchip	MCP3551	SPI	22-bit	3.75 MSPS
Maxim Integrated	MAX11166	SPI	16-bit	3 MSPS

6.5 Full Current Sensor Components

PN	Manufacturer	Shunt Type	Sample Rate	Resolution	Output / Comms
INA228	TI	External	20 Ksps (I^2C)	20-bit ΔΣ	I^2C / Alert Pin
MAX34407	Maxim	Internal (4x)	8 Ksps (x4 CH)	12-bit SAR	I^2C
PAC1954	Microchip	Internal (4x)	1 Ksps to 1024 ksps	16-bit ΔΣ	I^2C / SMBus
ADE7953	Analog Dev.	External	3.3 Ksps	16-bit	SPI / I^2C

Description

This list includes complete current sensing solutions with built-in ADCs. The output provides current data via standard communication interfaces. Some devices even integrate the shunt resistor, meaning you only need to add an MCU to read the values.

While these ICs are convenient, they come with performance trade-offs — particularly lower sample rates compared to discrete designs using an MCU with a high-speed internal ADC. However, for many applications, their accuracy and ease of integration make them a solid one-chip solution.

7 Design Challenges and Solutions

Various challenges arise in current sensing applications. This section presents common issues and proven solutions.

7.1 Noise Management

CHALLENGES:

- External electromagnetic interference
- Ground loop noise
- Power supply noise coupling
- Switching noise in PWM systems

SOLUTIONS:

1. **Physical Design**
    - Minimize loop area in current paths
    - Use twisted pairs for signal connections
    - Place guard rings around sensitive traces
    - Proper shielding of magnetic sensors
2. **Filtering Techniques**
    - RC filters at amplifier inputs
    - Common-mode filters for differential signals
    - Synchronous sampling for PWM applications
    - Digital filtering in post-processing
3. **Layout Considerations**
    - Star ground configuration
    - Component placement to minimize crosstalk
    - Isolation of analog and digital grounds
    - Proper bypass capacitor placement

7.2 High-Side Challenges

Challenges:

- Common-mode voltage outside amplifier range
- Level translation for microcontroller interface
- Maintaining CMRR over temperature
- Protecting low-voltage circuitry

Solutions:

1. **Specialized Components**
   - High common-mode voltage amplifiers
   - Chopper-stabilized amplifiers
2. **Circuit Techniques**
   - Resistive divider networks for very high voltages
   - Floating power supplies for amplifier circuits
3. **Protection Methods**
   - Transient voltage suppressors
   - Series resistance and clamping diodes

7.3 Dynamic Range

Challenges:

- Small signals overwhelmed by noise
- Large signals causing saturation
- ADC resolution limitations

Solutions:

1. **Multiple Range Approaches**
   - Switchable gain amplifiers
   - Auto-ranging circuits
2. **Advanced Techniques**
   - Logarithmic amplifiers
   - Programmable gain amplifiers
3. **Digital Methods**
   - Adaptive sampling rates
   - Multiple ADCs with different ranges

8 Calibration Techniques

Proper calibration significantly improves measurement accuracy.

8.1 Self-Calibration Methods

1. **Auto-Zero Techniques**
    - Periodically measures and subtracts offset
    - Effective for drift compensation
    - May require interruption of measurement
2. **Background Calibration**
    - Continuously monitors and adjusts parameters
    - No interruption to normal operation
    - More complex implementation
3. **Reference Measurement**
    - Uses internal reference current source
    - Compensates for multiple error sources
    - Higher component cost

8.2 Temperature Compensation

1. **Sensor-Based Compensation**
    - Temperature sensor near current sensor
    - Correction factors stored in lookup table
    - Polynomial approximation for continuous correction
2. **Algorithmic Compensation**
    - Mathematical models of temperature behavior
    - Real-time calculation of correction factors
    - Requires characterization of components

8.3 Calibration Implementation Example

1. Measure system at known zero current input
2. Store offset value in nonvolatile memory
3. Apply precise reference current (e.g., 90% of full scale)
4. Calculate the gain correction factor
5. Store gain factor in nonvolatile memory

9 PCB Layout

Proper PCB layout significantly impacts current sensing performance.

9.1 General Guidelines

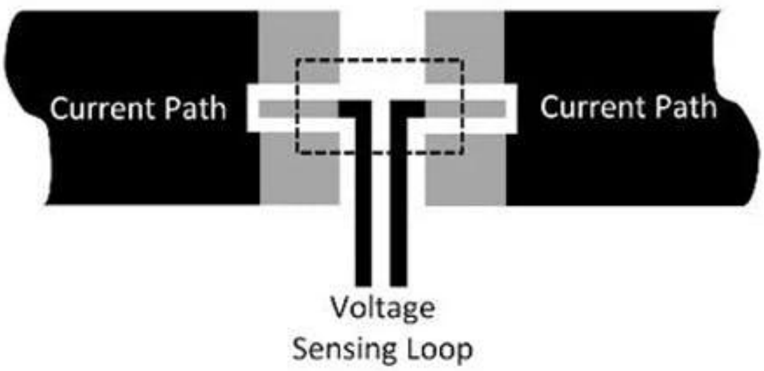
1. **Current Path Design**
    - Minimize resistance in high-current paths
    - Use shortest possible routes
    - Multiple vias for current sharing
2. **Signal Routing**
    - Keep analog signals away from switching noise
    - Use differential pairs for sensitive signals
    - Ground guard traces around high-impedance nodes
    - Avoid crossing analog signals with digital or power
3. **Grounding Strategy**
    - Separate analog and digital grounds
    - Single-point connection between ground systems
    - Avoid ground loops

9.2 Shunt Resistor Layout

Kelvin Connection Implementation

Key Points:

- Separate current path from sensing connections
- Minimize thermal gradient across shunt
- Keep sense lines short and equal length
- Place amplifier close to shunt



10 Software Considerations

Software plays a crucial role in modern current sensing systems.

10.1 Acquisition Algorithms

1. **Synchronous Sampling**
   - Coordinated with system events (e.g., PWM cycles)
   - Eliminates switching noise
   - Captures specific points of interest
2. **Oversampling and Decimation**
   - Sampling at multiple times the minimum rate
   - Applying digital filtering
   - Down-sampling to final rate with enhanced resolution
3. **Adaptive Sampling**
   - Variable rate based on signal dynamics
   - Higher rates during transients
   - Power saving during steady-state conditions

10.2 Digital Signal Processing

1. **Filtering Implementations**
   - Moving average filters for noise reduction
   - Notch filters for line frequency rejection
   - Kalman filters for optimal estimation
2. **Frequency Analysis**
   - Fast Fourier Transform for spectral content
   - Harmonic analysis for power quality
   - Wavelet analysis for transient detection
3. **Statistical Processing**
   - Standard deviation monitoring for noise estimation
   - Histogram analysis for distribution patterns
   - Outlier detection and rejection

10.3 Current Measurement Software Flow

1. INITIALIZE:

- *Configure ADC, gain settings*
- *Load calibration coefficients*
- *Set up filter parameters*

2. ACQUIRE:

- *Trigger ADC conversion*
- *Collect samples (oversampling)*
- *Store in buffer*

3. PROCESS:

- *Apply digital filtering*
- *Perform offset correction*
- *Apply gain calibration*
- *Calculate derived values (RMS, average, etc.)*

4. ANALYZE:

- *Check against thresholds*
- *Detect events of interest*
- *Update statistics*

5. COMMUNICATE:

- *Update displays/interfaces*
- *Log data if needed*
- *Send alerts if threshold exceeded*

6. CALIBRATE (periodic):

- *Check against reference if available*
- *Update calibration coefficients*
- *Compensate for environmental* factors

11 Troubleshooting Guide

Common issues and their solutions for current sensing applications.

11.1 Measurement Instability

Possible Causes

- Inadequate filtering
- Ground loops
- Power supply noise
- EMI interference
- Poor component selection

Diagnostic Steps

1. Check signal with oscilloscope at various points
2. Verify power supply ripple
3. Test with battery power to eliminate line noise
4. Check grounding configuration
5. Add temporary filtering to isolate cause

Solutions:

- Improve filtering (analog and/or digital)
- Modify grounding scheme
- Add shielding
- Relocate sensitive components
- Upgrade power supply regulation

11.2 Poor Accuracy

Possible Causes:

- Inadequate calibration
- Temperature effects
- Component tolerance
- Parasitic resistances
- Non-linearities in signal chain

Diagnostic Steps:

1. Verify with known reference source
2. Measure across temperature range
3. Check actual component values
4. Test at multiple points in measurement range
5. Verify PCB layout against design

Solutions:

- Implement multi-point calibration
- Add temperature compensation
- Use higher precision components
- Improve Kelvin connections
- Correct layout issues

11.3 Unexpected Offsets

Possible Causes:

- Thermoelectric effects
- Amplifier input bias current
- Ground potential differences
- Magnetic field interference
- Improper zeroing procedure

Diagnostic Steps:

1. Measure with zero current applied
2. Check offset across temperature range
3. Test with reversed connections
4. Shield from external fields
5. Verify power-up sequence

Solutions:

- Auto-zero function implementation
- Symmetrical design improvements
- Better shielding
- Chopper or auto-zero amplifiers
- Differential measurement technique

12 Step-By-Step Design

12.1 Current Sensor Design

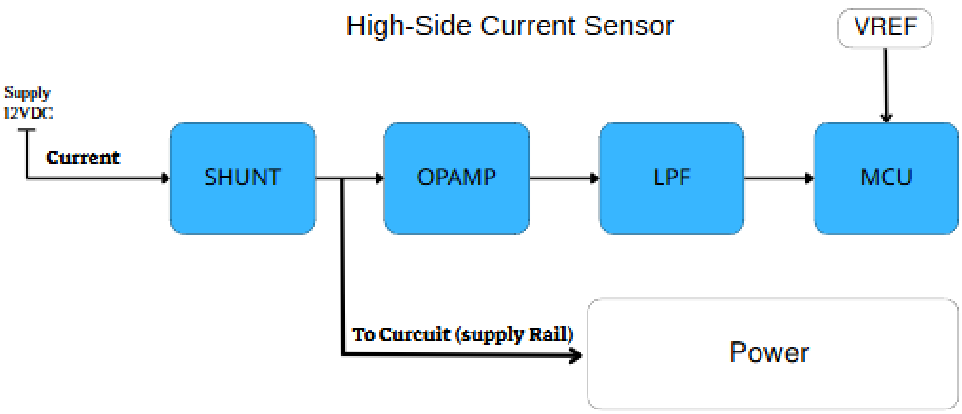
Example : Current Monitor for Video Board

Step 1: Parameters

Max Power	**10W**
Supply Voltage	**12VDC**
Max Current	**~0.83A**
Min Measurable Current	**100mA**
Accuracy Target	**±10mA**

Step 2: Architecture

- Shunt Resistor
- Differential OPAMP
- Low Pass Filter
- MCU (Integrated 14bit ADC)
- 3.3V VREF Supply



Step 3: Calculations

$VREF \ = \ \mathbf{3.3V} \ ; \ Accuracy \ = \ \mathbf{10mA} \ ; \ \ Min\ Current = \mathbf{100mA} \ ; \ Max\ Current \ = \ \mathbf{10A}$

$Max\_input(3V) \propto Max\_curr(10A) \ ; \ Min\_input(30mV) \propto Min\_curr(100mA)$

$$Required\ Resolution = \frac{\text{Max Current}}{Accuracy} \geq 1000$$

$$\frac{Max\_input}{Gain} \geq Vshunt \geq \frac{Min\_input}{Gain} \ \ \rightarrow \ \ 30mV \geq Vshunt \geq \mathbf{300\mu V} \ (check\ input\ offset\ volatge)$$

$$Rshunt = \frac{Min\_Vshunt}{Min\_curr} = \frac{300\mu V}{100mA} = \ \mathbf{3m\Omega}$$

$$Pshunt(max) = I(\max)^2 R = 100 \cdot 0.003 = \ \mathbf{0.3W}$$

$$Anti - Aliasing\ RC\ (Frequency) = \ 5Kzh = \frac{1}{2\pi RC} \rightarrow R = 100\Omega\,, C \ = 330nF$$

Step 4: Component Selection

Shunt Resistor

3mΩ / 1W (0.3W required) → 2512 Package

Operational Amplifier

Differential, Rail-to-Rail, 100 V/V Gain, Input offset Voltage <100uV

Filter

Two Stages of 5Khz Anti-Aliasing (LPF).

MCU

Integrated ADC 14bit is required]

Component	Part Number	Description
Shunt Resistor	WSLP2512R0030FEA	3mΩ , 2512 Package
2 x Resistors	ERA-3AEB101V	100Ω
2 x Capacitor	C0805C334K3RACTU	330nF
VREF	REF3333	3.3V
OPAMP	INA281A3	100V/V, 55uV Offset
MCU	STM32F358RC	ADC 14bit, 1Msps

Step 5: Schematics (simulation is Advised)