High-Performance Power ICs and Hall-Effect Sensors

Hall Effect Technology for Server, Backplane and Power Supply Applications
Hall effect technology offers a current sensing technique to the power system designer that can improve system efficiency compared to shunt resistors for DC current sensing and allow for integration of system level monitoring and control in low cost offerings while reducing PCB and external component requirements and space compared to shunt resistors for DC and Current transformers for AC current sensing.

A review of the Hall effect, how this physical property can be used to sense current, the advantages and disadvantages of the technology in current sensing and how those disadvantages have been mitigated through technological advances will be discussed. Modern semiconductor manufacturing and packaging techniques to advance low cost, high performance, and high volume production will be also discussed.

With the advent of the development of a basic Hall Effect current sensor technology, how this technology was and can be adapted for monitoring and measuring current, voltage and voltage-current parameters will be reviewed.
How Hall Effect Devices Work

The Hall Effect was discovered by E. F. Hall in 1879.

- Magnetic field generated by current flowing in lead-frame is concentrated at hall plate
- A bias voltage across the hall plate sets up a fixed current
- The moving charges in the hall plate are acted upon by the Lorentz force \( F = q(v \times B) \)
  - In the presence of a magnetic field, this force pushes charges to opposite sides of the Hall plate
- The resulting Hall voltage \( V_{\text{Hall}} = B \perp I / \text{nte} \)
  - This signal is cleaned up and amplified to provide a sensitivity in mV/A

Basic Hall Element  Basic Hall Device Circuit  Magnetic Flux Applied

The voltage output is directly proportional to the strength of the magnetic field.
Transfer Function of Analog Hall Sensor

- Large magnetic field drives the Hall element output into saturation
- Sensitivity = change in output (voltage) resulting from change in input (gauss)
  - Ranges typically from 0.7 mV/G to 16mV/G
- Null offset = Quiescent Voltage = Output for zero Gauss
  - Ratiometric (0.5 x Vcc) to supply voltage (Vcc) – Bi-Directional ~ 2.5V @ 5.0V
  - Ratiometric (0.1 x Vcc) to supply voltage (Vcc) – Uni-Directional ~ 0.5V @ 5.0V
- Span = Vout (positive B field) – Vout (negative B field) ~ 4V @ 5.0V
Analog or Linear Hall Effect IC’s with programmability of output parameters

- Offset / Quiescent Voltage
- Sensitivity / Gain
- Sensitivity / Gain Temperature Coefficient
- Polarity
- Output Clamp
# Table 1: Commonplace, Inexpensive Current-Sensing Techniques

<table>
<thead>
<tr>
<th>Widely Used Sensors</th>
<th>Insertion Loss</th>
<th>Circuit Isolation</th>
<th>External Power</th>
<th>Frequency Range</th>
<th>Offset (Zero I)</th>
<th>Accuracy (Est.*)</th>
<th>Rel. Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive dc</td>
<td>Yes</td>
<td>None</td>
<td>None</td>
<td>&lt;100 kHz</td>
<td>None</td>
<td>&gt;99%</td>
<td>Lowest</td>
</tr>
<tr>
<td>ac</td>
<td>Yes</td>
<td>None</td>
<td>None</td>
<td>&gt;500 kHz</td>
<td>None</td>
<td>&gt;99%</td>
<td>Low</td>
</tr>
<tr>
<td>Hall-Effect Open-Loop</td>
<td>None</td>
<td>Yes</td>
<td>Yes</td>
<td>≥20 kHz†</td>
<td>Yes</td>
<td>90-95%</td>
<td>Med</td>
</tr>
<tr>
<td>Closed-Loop</td>
<td>None</td>
<td>Yes</td>
<td>Yes</td>
<td>≥150 kHz</td>
<td>None</td>
<td>&gt;95%</td>
<td>High</td>
</tr>
</tbody>
</table>

| Current Transformers  | Yes (ac)       | Yes               | None           | Constant‡       | None            | >95%§             | Highest    |

* (Estimated): accuracy and precision very dependent upon design implementation.
† 20 kHz to 25 kHz represents (typical) usable frequency limit.
‡ Current transformers (usually) designed for limited frequency range.
§ Accuracy very contingent upon component and cost factors.
**Sense Resistor Current Sensor**

Ohms Law Applied

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**Advantages**
- Low Cost
- Proven
- Reliable
- Simple
- Accuracy

**Disadvantages**
- Power dissipate (I^2R) - Efficiency and Heat
- Drop voltage (IR) - Supply rail voltage regulation
- No isolation
- Requires trading off sense resistance, maximum current levels to be sensed, resolution, power/efficiency, signal-noise ratio, current resolution
- Potentially adds inductance to circuit
Hall Effect Current Sensor
Biot–Savart Law, Right Hand Grip Rule and Hall effect Applied

Advantages
- Low Voltage Drop
- Low Power Dissipation
- Inherent Isolation

Disadvantages
- Supply current requirement to support Hall element
- External Magnetic field interference
- Bulky / Space Requirements
- Limited frequency range (Bandwidth, Response Time)
- Output Noise
- Output Stability - Stress, Temperature and Mechanical
- Limited sensitivity
- Programmability
- Dv/dt susceptibility
- Cost
Early Single-Element Hall Device

Significant Susceptibility to Thermal and Mechanical Stress

Four-Element Hall Device (arrows indicate current)

Some Susceptibility to Thermal and Mechanical Stress

Graphs showing the relationship between ambient temperature and switch/release points for both devices.
Dynamic Offset Adjust
Chopper-Stabilized Hall Circuit

Minimal Susceptibility to
Thermal and Mechanical Stress
Allegro’s next generation fab process allows for faster amplifiers

- Innovative new circuits (patents pending)
- Faster chopping frequencies
  - 150KHz → 210KHz → 420KHz
- Higher bandwidth (-3dB)
  - 30KHz → 80KHz → 120KHz
- Lower noise (p-p)
  - 100mV → 38mV → 10mV
- Faster rise times
  - 9 uS → 6 uS → 4 uS
Through Hole Packaging Innovation
Enabling Technology (50 - 200 Amps)

Internal Current Carrying Conductor Resistance - 130 μΩ

- Standardizing to High Volume Traditional Semiconductor Packaging Techniques Critical
  - Lower Cost
  - Reduce Size
  - Increase Quality
  - Increase Through Put
Surface Mount Packaging Innovation
Enabling Technology (5 – 40 Amps)

- Flip-Chip with Ball Bond Attach to Lead Frame
- Standardizing to High Volume Traditional Semiconductor Packaging Techniques Critical
  - Lower Cost
  - Reduce Size
  - Increase Quality
  - Increase Through Put
Through Surface Mount Packaging Innovation
Enabling Technology

- High Current path is strictly kept in the lead-frame of the device
  - Tightly Control Sensor – Magnetic Coupling Mechanical Dimensions
  - Robust inrush/Transient tolerance

- Silicon and circuitry is isolated from high current path
  - Can be used in high side sensing applications
  - Can be on switching nodes or primary side in power supplies

<table>
<thead>
<tr>
<th>SOIC - 8</th>
<th>SOIC - 16</th>
<th>SOIC - 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Current Carrying Conductor Resistance – 1.0 to 1.25 mΩ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Inside an Allegro Current Sensor

The close proximity of the current carrying conductor and the silicon forms a parasitic capacitor

\[ C_p = \varepsilon_0 \varepsilon_{il} A_{eff}/D \]

This capacitor directly couples noise on the current carrying lead frame to the circuitry.

In high dV/dt environments, this noise is extremely difficult to filter out.
Current Sensor Shield Solution

- It is not possible to eliminate or reduce the parasitic capacitor
  - Reducing effective cross sectional area of the lead frame would adversely increase the resistance
  - Increasing the distance between the lead frame and the Hall Plate reduces the magnetic coupling and overall sensitivity of the device

- Adding an electrostatic shield between the silicon and the current carrying lead-frame allow the noise to bypass the silicon
  - Shield layer connected to device ground in package.
Allegro Current Sensor Shield Performance

- Output voltage of both an unshielded and shielded current sensor measured during a high dV/dt transient voltage event.

- Transient voltage: 275 V in ~100 ns or 2,750V/µS

- No current flows through the device leadframes, common mode voltage applied to leadframes.

- 5 V supply to both devices is clean.

- Shielded output disturbance is orders of magnitude smaller than unshielded output disturbance.
Typical 240VA Protection Circuit
Resistor Current Limit Sense

- Typical discreet solution has ~17 components in circuit
- Power dissipation in FET and Shunt is ~ 2.4W at 20A
- 12V at load is assumed
  - Protection strictly a function of current exceeding 20A
  - Does not provide actual current value
    - Requires Higher Sense resistor values increasing voltage drop and power loss
Voltage Drop
Shunt Resistors Versus ACS760

- Shunt Resistor - 5 mOhms
- Shunt Resistor - 3 mOhms
- ACS760

AMPS (A)
VOLTS (V)
Power Dissipation
Shunt Resistors Versus ACS760

- Shunt Resistor - 5 mOhms
- Shunt Resistor - 3 mOhms
- ACS760

AMPS (A)

WATTS (W)
Hall Effect Hot Swap/Protection Circuit

- 240VA solution reduced to ~ 9 components
- Power Loss reduced by ~ 600mW per protection channel
  - 6-12 240VA channels per system (peak savings of ~ 7.2W)

Added Functionality:
- True 240VA protection
  - Voltage monitored at load
  - Internal power calculator detects 240VA threshold
- Load Switch Short detection and alert
- Output of actual current (65mV/A)
- 2nd over-current protection threshold set by user
- Hard short circuit protection with ~2μs response
- Latched Fault
Block Diagram
Hall Effect Based Sensor in Server Backplane
240V*A Fault

C1=Fault, C2=Load Current 10mV/A, C3=Gate, C4=Over Power Fault Delay
Hall Effect Based Sensor in Server Backplane
Over Current Fault

C1=Fault, C2=Load Current 10mV/A, C3=Gate, C4=Over Current Fault Delay
Hall Effect Based Sensor in Server Backplane
Hot Swap with Inrush Current Limit

C1=Enable, C2= Voltage Output of Load Current, C3=Gate, C4= Load Current
Hall Effect Based Hot-Swap Device
Features & Benefits

- Reduces power dissipation
  - Eliminates need for external shunt resistor
- Internal charge pump gate drive for external N-Channel MOSFET
- Four independent faults are monitored:
  - 240VA Power Fault
    - Remote sensed load voltage times monitored leadframe current
    - Can convert to over-current protection device
    - Fault delay set by user with external capacitor
  - Over Current fault
    - User adjustable over current threshold External switch short fault detection
    - Fault delay set by user with external capacitor
  - Hard short protection circuitry
    - Gate disabled in less than 2μs of detection
  - MOSFET failure detection
    - When device is disabled or after a fault, if current is monitored flowing through leadframe, S1Short is pulled low
- Fully integrated Hot-Swap IC
Hall Effect Based Hot-Swap Device in Development
Hall Effect Current Sensor in UPS or Inverter Applications
Hall Effect Current Sensors in Development
Hall Effect Current Sensors in Development
ACS Family Features & Benefits

<table>
<thead>
<tr>
<th>Feature</th>
<th>710</th>
<th>711</th>
<th>712</th>
<th>756</th>
<th>760</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vcc range</td>
<td>3.3/5V</td>
<td>3.3/5V</td>
<td>5V</td>
<td>3.3/5V</td>
<td>12V</td>
<td>Improves noise immunity resulting in more accurate measurements</td>
</tr>
<tr>
<td>Integrated Shield</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Improves noise immunity resulting in more accurate measurements</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>12KHz</td>
<td>&gt;100KHz</td>
<td>80 KHz</td>
<td>&gt;100KHz</td>
<td>50KHz</td>
<td>Higher BW enables precise control for motor applications</td>
</tr>
<tr>
<td>Fast fault pin</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Protection for IGBT modules</td>
</tr>
<tr>
<td>Filter pin</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Reduce output noise for improved accuracy and resolution</td>
</tr>
<tr>
<td>Ultra low output noise</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Improves measurement accuracy</td>
</tr>
<tr>
<td>Zero current reference</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Provides A/D reference current</td>
</tr>
<tr>
<td>Isolation voltage</td>
<td>3KV</td>
<td>&lt;100V</td>
<td>2.1KV</td>
<td>3KV</td>
<td>-</td>
<td>Higher isolation voltages allows direct</td>
</tr>
<tr>
<td>Hotswap controller</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Used in server backplane protection circuits</td>
</tr>
<tr>
<td>Short circuit protection</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Safely shutdown systems before short circuit condition</td>
</tr>
<tr>
<td>Overpower protection</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>240VA meets UL requirements</td>
</tr>
<tr>
<td>Overcurrent protection</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Safely shutdown systems before overcurrent condition</td>
</tr>
<tr>
<td>Load switch failure</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Early detection of load condition prevents damage to system</td>
</tr>
</tbody>
</table>

The ACS Family of current sensors offer a unique solution versus shunt designs

- Lower noise to improve low current accuracy
- Fast response time for use in protection circuitry
- Inherent isolation and level shifted output – suitable for directly monitoring inductive loads and high side currents
- Integrated Shield makes device suitable for use in switching applications (i.e. switching power supplies)
- Low insertion loss – 1.0 to 1.2mΩ (710/711/712), 130μΩ (756) leadframe resistance
- Small package capable of measuring up to 200A - ACS756
The ACS Family of current sensors will continue to improve in performance, features, and value based on innovation in new semiconductor and packaging technologies.

User community / application requirements and “wish lists” will advance these innovations.

Merging of Processes

Merging of Function

Merging of Resources
Question, comments and suggestions can be referred to:

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