Use of a Power Monitor with Multiple Inputs to Improve Opportunities for System Accuracy and Power Savings

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Agenda

- Monitoring power and energy – why?
- Monitoring power and energy – how?
  - Traditional methods
  - A more modern approach
- Current sensor market overview
- Use case to measure multiple voltage rails in a Kaby Lake Intel System
- Discussion
Industry Trends and Insights

- Cell Phones report on application power usage
- Laptops & some tablets report on application power usage

- Windows 10 systems are only 70% accurate without a power monitor IC

**E3 Software Estimation vs. Hardware Measurement**

<table>
<thead>
<tr>
<th>E3 Configuration</th>
<th>Approximate accuracy per power model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPU</td>
</tr>
<tr>
<td>Software Estimation</td>
<td>87%</td>
</tr>
<tr>
<td>Hardware Measurement</td>
<td>98%</td>
</tr>
</tbody>
</table>

Source: Microsoft Fall WINHEC 2017
Windows PC, Power Measurement and Error

- Software estimation
  - Relies on the CPU measurement
  - Relies on system modeling power in WIN10 OS

- Hardware estimation and requirements
  - Series resistors (1%) are used to measure power
    - Kelvin connectors
    - Sense resistor 2-20 mΩ (for the case of a PC)
      - Value based on the full scale load and current desired
      - Full scale voltage was based on 100mV (in this case)
  - Simultaneous sampling (ADC for V & I desired)
  - Known time stamp and always sampling
  - Synchronizing multi-rail measurement
  - High common mode range up to 20V rail to rail
Measurement Accuracy of Vsense and Vbus

<table>
<thead>
<tr>
<th><strong>VSENSE</strong> Measurement Accuracy</th>
<th></th>
<th>±0.2</th>
<th>±0.9</th>
<th>%</th>
<th>%</th>
<th>At +25°C typical, −40 to +85°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vsense Gain Accuracy</td>
<td>$V_{SENSE_GAIN_ERR}$</td>
<td>—</td>
<td>±1</td>
<td>±0.9</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Vsense Offset Accuracy, referenced to input</td>
<td>$V_{BUS_OFFSET_ERR}$</td>
<td>—</td>
<td>±0.02</td>
<td>±0.1</td>
<td>mV</td>
<td>mV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>VBUS</strong> Measurement Accuracy</th>
<th></th>
<th>±0.02</th>
<th>±0.5</th>
<th>%</th>
<th></th>
<th>At +25°C typical, −40 to +85°C</th>
</tr>
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<tr>
<td>Vbus Gain Accuracy</td>
<td>$V_{BUS_GAIN_ERR}$</td>
<td>—</td>
<td>±0.2</td>
<td>±0.5</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Vbus Offset Accuracy, referenced to input</td>
<td>$V_{BUS_OFFSET_ERR}$</td>
<td>—</td>
<td>±2</td>
<td>—</td>
<td>LSB</td>
<td>LSB</td>
</tr>
</tbody>
</table>

- Resistor error and device error should be added linearly for maximum error
- On the following slides we will review the device error
Vsense Error vs Input Voltage and Temperature

FIGURE 2-4: $V_{SENSE}$ Error vs. $V_{SENSE}$ Input Voltage and Temperature.

- Error converges after 0.5 mV Vsense input voltage
- Data sheet is for a 0 to 32 V common mode voltage
FIGURE 2-10: $V_{BUS}$ Error vs. $V_{BUS}$ Input Voltage vs. Temperature.

- Error converges after 0.5 V Vbus input voltage
Measurement Error Example

**Actual power** = $12V \times 1A = 12W$

Vbus = $12V$ at $I = 1A$

Vsense = $50mV$ (Rsense= 50 mohm)

**Measured power:**

Vbus = $12(1+\text{gain error}) + \text{offset} = 12(1.005) + 976uV = 12.06098V$

Vsense = $Vsense(1+\text{gain error}) + \text{offset} = 50mV(1.009)+0.1mV = 50.55mV$

Rsense = $.05 \text{ ohm} \times .99 = .0495 \text{ ohm}$  
[1% resistor]

Current = $50.55mV/(.0495) \text{ ohm} = 1.0212A$

**Measured Power** = $12.06098 \times 1.0212A = 12.31666W$

Error = $.317W = .317/12 = .0264 = 2.64\%$
Industry Trends and Insights

Data Center Management

- Cost of server ownership is in the utility cost
- Power Use Effectiveness (PUE)
  - Non-computing energy takes 45% - 60% of total energy
  - Top ranked concerns of executives in the industry
  - Thermal and energy management has become a key challenge in the design and operation of data centers.
- Office of Management and Budget (2016) set target PUE <1.5

Data Center Infrastructure Efficiency

\[
\text{IT Equipment Power} \times 100\% \div \text{Total Facility Power}
\]

<table>
<thead>
<tr>
<th>PUE</th>
<th>DCiE</th>
<th>Efficiency Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>33%</td>
<td>Very Inefficient</td>
</tr>
<tr>
<td>2.5</td>
<td>40%</td>
<td>Inefficient</td>
</tr>
<tr>
<td>2.0</td>
<td>50%</td>
<td>Average</td>
</tr>
<tr>
<td>1.5</td>
<td>67%</td>
<td>Efficient</td>
</tr>
<tr>
<td>1.2</td>
<td>83%</td>
<td>Very Efficient</td>
</tr>
</tbody>
</table>
Why DC Power/Energy Monitoring

- Why are companies using this feature
  - Actively managing total system power & limits
    - Inform end user and help alter their behavior
      - Running out of power and battery
      - Power providers are assessing out of range conditions
  - C-connectors enable adaptable power scenarios
  - Configuring for different run conditions saves power
  - Measurement and reporting
    - The laptop, tablet & cellular WIN10 battery utility
    - Monitor efficiency, aging, and faults
Measuring Power

● Traditional methods
  ● Use op amp circuits for high side current sensing and voltage monitoring
  ● Outputs of these circuits are fed to and ADC followed by a processor/controller
  ● Controller controls the ADC and multiplies current x voltage to get power
  ● Take many measurements over time
  ● Store results, and calculate energy usage
  ● Discrete resistors mean reduced accuracy or expensive calibration
Instantaneous Power

- **Instantaneous power** (in watts) : the power at any instant of time

\[ p(t) = v(t) \times i(t) \]

**Versus Accumulated Power (Energy)**
Measuring Power

- Discrete Current Sense Amplifier example

Discrete resistors add error
Requires ADC at output

ADC errors also contribute to final error via quantization

\[ V_{OUT} = (V_1 - V_2) \cdot \left( \frac{R_2}{R_1} \right) + V_{REF} \]
A More Modern Approach

- Use a Power Monitoring IC
  - Incorporates high side current monitor, bus voltage monitor, and ADC
  - Factory calibrated

PAC1720 example
Only sense resistors affect accuracy
Energy Measurements

- The easy way to do energy measurements: use a power monitoring chip
  - I2C/SMBus interface
  - Most report on current, voltage and power
  - Simplifies energy calculation when used with a known time stamp from the system host
    - Host can command the beginning and end of the integration period

- There are on the order of 40 I2C current sensor devices in the market
  - This does not include ASSPs (i.e. hot swap controllers)
High Level I2C Current Sensor Market Offerings

- Circle size is resolution 8 to 18 bits
- Full scale range is normally 10 mV to 100 mV
Tracking Power in Intel Reference Design

- 4x PAC1934 installed on an add-on board for Intel Kaby Lake validation system
- Sense resistors on the motherboard are wired to the add-on board
- Windows 10 driver used to facilitate data collection and interface to Windows E3 application via Energy Metering Interface
- These acronyms are explained shortly
Basic Applications Circuit

Note: V_{DD} and V_{DD I/O} may be connected together.
Kaby Lake Modification to Read 12 Current Sensors

The square hole fits over the heatsink on the processor. The two pin terminals around the outside are for the pairs of sense resistor wires.

- QFNs are 4 channel PAC1934 devices
4 x 4 channels = Only 12 Channels Used
PAC1934 EMI Utility
(Energy Metering Interface)

This Metering Reports tab lists all PAC devices in the system at upper left.

Detailed results are shown for all four channels of the selected devices.
Channel 1 Zoomed In

- Vbus
- Vsense
- Power
- Accumulated Power

- EMI Energy can be shown in a windows PC OS
- Soft Count is an ongoing count of samples after a refresh
PAC1934 Energy Metering Interface Utility

This Utility has versatile plotting capabilities.

You can see that power tracks Isense well, but Energy tells a different story.

- You can see this tracks Isense well
Energy Metering Utility

ZOOM Image

Tracks Isense with power
Microsoft Power View
Single Application Use Data

- Consolidated essential data on the next slide
- WIN10 allows for isolating the power consumed by key sources plus identified energy metering interface (EMI)
Microsoft Power View
Single Application Use Data

- Power view
  - Reports in millijoules
  - CPU, SOC, display, disk, network, MBB, other, EMI
- Selected rows show total
  - Listening to music on headphones, network being assessed, and having the web open

<table>
<thead>
<tr>
<th>Resource Application</th>
<th>CPU</th>
<th>SOC</th>
<th>Disp</th>
<th>Disk</th>
<th>Ntwk</th>
<th>MBB</th>
<th>Othr</th>
<th>EMI</th>
<th>Total millijoules</th>
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</thead>
<tbody>
<tr>
<td>System</td>
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<td>0</td>
<td>924564</td>
<td>824564</td>
<td>42609</td>
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<td>ZuneVideo</td>
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<td>0</td>
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</tr>
</tbody>
</table>
Microsoft Power View Apps Show EMI Utility Use

- We are now able to separate and read the individual voltage rails on the EMI (energy metering interface)
Microsoft Power View
Single Application Use Data

- Power view
- Selected rows now show measurements for the
  - Display Backlight
  - CPU Core 1

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<th>Disk</th>
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<th>MBB</th>
<th>Othr</th>
<th>EMI</th>
<th>Total millijoules</th>
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<tbody>
<tr>
<td>System</td>
<td>2443536</td>
<td>0</td>
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<td>ZuneVideo</td>
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<td>327520</td>
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</tbody>
</table>
Accurate Knowledge by Software Application Enabled

- The Kaby Lake modification uses sense resistors and a power monitoring IC to measure exact voltage rails

- A WIN10 driver and energy metering interface communicates specified rails to the OS

- These voltage rail can now be seen by Microsoft power view utility to report power by software application
Take Aways

- Adding a power monitoring IC enhances our ability to collect measurements and minimize measurement error.
- If you use a power monitor with an accumulator it enables you to see the energy use by rail over time.

The power monitoring system demonstrated by this case study greatly enhanced visibility and understanding of power/energy utilization in key loads/subsystems.
Discussion/Q&A

● Thank you! Questions?