From tiny, battery-powered tire-pressure sensors to multimegawatt wind turbines, the nature of today’s electronics and the incessant drive to improve energy efficiency make energy measurement a hot topic for every designer. At the low end of the scale, portable electronics of every kind require ever-better battery management to increase runtimes and offer users an increasing number of features. At the national grid-power-generation level, fast, accurate, and rugged sensors are essential to providing the servo-loop feedback that balances generator output against constantly changing grid conditions. Between these two extremes are most applications, which span the gamut of automotive power conditioning through consumer electronics to industrial process control. In every case, the ability to measure current is a key requirement that semiconductor vendors and transducer manufacturers ease with a huge range of devices. In what has now become a separate market sector, domestic energy metering combines the ability to measure both current and voltage in a hostile environment at low cost (see sidebar “Electricity meters demand electronic measurements”).

Regardless of power level, measurements must almost invariably interface with supervisory logic, such as ADCs. Although designers frequently assume that voltage measurement is a breeze, today’s ICs and transducers often make it easier to measure current, especially in cases in which isolation from ac line supplies is an issue. But before delving into ac power measurements—and because the concepts translate with little if any modification—it’s worth reflecting on dc applications and the various approaches that can simplify a designer’s life. Of course, battery-powered applications have long used power measurements to report circuit status. Ironically perhaps, advances in mechanical and electrical components are making the classic ex-
The electromagnetic wattmeter that’s familiar to consumers everywhere is one of the few remaining electromechanical devices of the Victorian age. Its longevity owes much to unchanging electricity-demand patterns from traditional applications, such as heating and incandescent-bulb lighting. But today’s consumers present electricity suppliers with a massive burden of fluorescent lights, white goods, and other home electronics that draw substantial quantities of reactive power that traditional meters under-charge. As a result, many suppliers are considering alternative tariff structures for premises that exhibit poor power factors, demanding meters that report active and apparent power. Such measurements require ICs to compute measurement results, either interfacing with a low-cost electromechanical counter or to a microcontroller that typically provides LCD readouts that suit, for example, multiple time-of-day tariff structures. Recognizing the massive market potential, vendors including Analog Devices, atriamicosystems, Cirrus Logic, TDK Semiconductor, SCL India, STMicroelectronics, and Texas Instruments offer a range of chips that simplify power measurements in ac-line supplies.

Of these, the current market leader is Analog Devices with some 50 million meters deployed. Its latest product is the ADE7757A, a reduced-pin-count version of its popular ADE7755. The new chip minimizes cost by including an oscillator to drive the digital-signal-processing block and by providing a direct interface to a current shunt (Figure A). Its two 16-bit sigma-delta ADCs comprise the main analog circuitry, digitizing the voltage and current-channel signals at an oversampling rate of 450 kHz. The chip calculates real power by digitally processing the instantaneous power signal; that is, it derives real power from the real-time product of its voltage and current measurements. A highpass filter in the current channel removes any dc signal component that would otherwise contribute a constant error following multiplication.

The analog input bandwidth is about 7 kHz, allowing FFT algorithms to preserve accuracy when processing nonsinusoidal waveforms. The result is better-than-0.1% accuracy over a 500-to-1 dynamic range within the chip’s 45- to 65-Hz measurement bandwidth, which better the accuracy requirements of the IEC-61036 standard. Output signals comprise a pair of low-frequency pulse signals to suit electromechanical...
for recharging the energy source and in which correct device operation has safety implications, monitor circuitry measures discharges in nanoamperes per second as the device periodically switches between standby and active modes; an error signal indicates insufficient remaining charge (Reference 1).

Miniature applications such as TPMS demand ASICs, but coulomb counters are easy to implement as an ADC/timer task within a commodity microcontroller. More complex applications, such as smart battery packs, can take advantage of dedicated gas-gauge ICs that integrate peripheral power-management functions. Chips such as Atmel’s new ATmega406 surround the microcontroller’s core with voltage regulators and support circuitry—including FET drivers for battery charging and dual ADCs for current and voltage monitoring—to construct a self-contained controller for lithium-ion battery-pack chargers. With its 18-bit coulomb counter yielding 0.67-mA resolution using a 5-mΩ current shunt, the device’s ±30A range also suggests use in wider control applications that can take advantage of 40 kbytes of flash, 2 kbytes of RAM, and 512 bytes of EEPROM.

SAFEGUARD ACCURACY

Almost without exception, supervisory and control circuits require interfaces that refer measurement values to system ground, posing designers with the continual problem of how best to translate currents riding on arbitrary-level voltages to levels that suit off-the-shelf logic. Traditionally useful for high-sensitivity moving-coil dc ammeters, the classic low-side sensing technique inserts a current-

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**Figure B** The STPM01 energy-meter IC monitors live and neutral-line currents to help alleviate electricity theft.

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means of two sets of current inputs, IIP1/N1 and IIP2/N2 (Figure B). This feature bolsters the chip’s ability to detect some 20 forms of tampering and hence secure the meter from electricity theft—a common practice in some regions.

The analog front end suits current shunts, current transformers, or Rogowski coils, with device setup and calibration performed by programming its 48-bit OTP (one-time-programmable) memory using the chip’s SPI interface. This SPI link also communicates with a microcontroller. Calibration adjustments include voltage, current, phase correction, and temperature compensation. Dedicated outputs include LED drivers for instant visual status reporting, as well as an ac zero-crossing detector that can control external load switching to avoid arcing and interference generation. The STPM01 comes in a 20-pin TS-SOP; see the company’s Web site for pricing and availability. Both Analog Devices and STMicroelectronics offer reference designs and low-cost evaluation kits to simplify meter development.
sense resistor in the power-supply return path and measures the voltage that it develops. This arrangement also has the advantage of referring the measurement to neutral potential in high-voltage ac circuits, avoiding high common-mode voltages and simplifying transient protection—albeit without the ability to detect short-circuits between, say, a motor’s winding and its case. But to interface with logic, the necessity of tying the ADC’s signal ground to circuit ground and for all other circuitry to float at dynamic sense-resistor potential creates offset problems between multiple circuits.

It also makes it difficult to resolve the currents that individual circuits take—including the ADC—and introduces into the ground plane unwelcome impedances. Because an ADC’s input sensitivity is much less than an ammeter’s typical 75-mV full-scale value, an instrumentation amplifier that can handle common-mode voltages, including ground, must boost the sense voltage to a suitable level.

High-side measurements overcome these issues and are virtually mandatory in applications that share extensive common ground-return paths, such as cars. The problem now concerns ground-referencing a small sense voltage that’s riding on the positive supply line. A true-differential- or instrumentation-amplifier approach works well but calls for well-matched resistors to preserve CMRR (common-mode-rejection ratio) and maintain accurate gain performance (Figure 1a). For example, a 0.1% imbalance between any of the resistors degrades CMRR to 66 dB.

Available with fixed gains of 1 and 10, chips such as Maxim’s MAX4198/99 integrate these resistors and are capable of better than 0.01% gain accuracy with more than 110 dB of CMRR. Packaging options include the company’s miniature, eight-pin μMAX outline, whose prices start at approximately $1.25 (1000). The company also offers a range of parts for current-sensing applications. Analog Devices also offers a range of instrumentation amplifiers for high-common-mode sensing within its current-sense-amplifier range. For example, the AD8205’s 65V operating-voltage limit suits uses such as automotive 42V PowerNet monitoring. Flexible connections to the internal divider chain make it easy to bias and scale the output voltage to suit unipolar and bipolar measurements. The $1.35 (1000) chip comes in an eight-pin SOIC that’s specified for −40 to +125°C operation.

The difference-amplifier configuration also works well in high-voltage environments. For example, Linear Technology’s LT1990 accommodates common-mode voltages as high as ±250V when operating from ±15V supplies, with a gain of 1 or 10 set by external links. It also enjoys protection against common-mode transients of as much as ±350 or ±500V differentially, making it suitable for industrial use. With a minimum CMRR of 70 dB and maximum gain-accuracy error of 0.28%, the LT1990 comes in an SO8 outline; prices start at $1.35 (1000). A companion part, the LT1991, provides greater precision with input voltages as great as ±60V. It includes eight on-chip, precisely matched silicon-chromium resistors that allow gain settings of −13 to +14 with as little as 0.04% gain error and more than 75 dB of CMRR. The op amp’s input offset voltage is typically 15 μV with 3 nA of bias current. Operating from single 2.7 to ±18V supplies, the device has minimal power consumption at some 100 μA, yet the chip maintains a 560-kHz gain-bandwidth product that maintains its unity-gain −3 dB response at 110 kHz. The price for a 10-pin MSOP or leadless DFN starts at $1.39 (1000), and the part measures just 3 mm square.

Another take on the differential-amplifier approach uses a rail-to-rail input op amp to amplify the sense voltage directly at supply-rail voltages (Figure 1b). With P-channel MOSFET Q, acting as the current source, negative feedback impresses the differential across the sense resistor on R1. The current in R1 then flows to ground by means of R2, simplifying ground referencing and output-value scaling. In this case, CMRR depends solely on the op amp’s abilities, and the output voltage refers directly to ground. But choose rail-to-rail op amps with care, because they can be nonlinear within a few volts of the rail value when the transistors that work over the midrange cut off and another set for close-

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**Figure 1** IC difference amplifiers that integrate the gain-setting resistors work well in high-voltage applications (a). Rail-to-rail-input op amps offer very high common-mode and power-supply-rejection ratios (b).
to-rail operation take over (Reference 2). Alternatively, choose a device such as Linear Technology’s new LTC6101 for shunt-resistor measurements. This all-CMOS part integrates the op amp and FET to provide a minimum 110-dB PSRR (power-supply-rejection ratio). With a maximum input offset voltage of 450 µV and a 170-nA input bias current at room temperature, the device suits sense voltages as large as 500 mV in 4 to 60 V environments; response times lie within the 1-µsec region.

Erik Soule, general manager of Linear’s signal-conditioning division, notes that it’s possible to power the chip either from the battery side or from the load side, when it also measures its own consumption of some 250 µA at 14 V. “In practice, by using 0.1% gain-setting resistors, you can easily get better than 1% performance, because the resistors are the dominant error source,” he says. The guide price for the LTC6101 in a five-pin, 1-mm-profile SOT-23 package is $1.04 (1000). Soule advises that additional current-sense parts will follow, including a higher voltage version of the LTC6101 and a bipolar part with output buffering and four gain settings.

For high-precision work, Linear Technology offers its LT1787. This eight-pin device’s 40-µV input offset voltage allows 12-bit ADC precision with sense voltages of 250 mV. It operates from supplies of 2.5 to 36 V or as much as 60 V for the HV suffix, consuming some 60 µA, and presents around 120 dB of PSRR. Two terminals, FIL+ and FIL−, provide for additional differential- and common-mode signal filtering by adding a capacitor halfway across the chip’s input-divider chain (Figure 2). In operation, the op amp drives the potential between its inverting and noninverting inputs to zero, so the currents in the input resistors flow in Q1 and Q2. The current mirror sums and converts these currents to a single-ended output with a fixed gain of 8 from input to output. A bias pin provides a reference level for the voltage output and typically connects to an ADC’s reference voltage. This connection ensures that the IC’s current-to-voltage converter (ROUT) tracks ADC reference-voltage changes over time and temperature. Positive currents make the output voltage positive with respect to the bias level; negative currents do the opposite. The guide price for the SOIC version in both industrial- and automotive-temperature ranges is $2.05 (1000).

One option that suits many applications exploits a current mirror built from matched transistor pairs that reflects a tiny proportion of the load current to ground. In the first-generation ZDS1009 from Zetex Semiconductor, any voltage across sense resistor R1 impresses a balance current in R2 (Figure 3). If R2 equals R1, the transfer characteristic is (1×R1)×(R1/R2), making it easy to scale the ground-referenced output voltage to levels that suit ADCs. Today, the company’s ZXCT series uses a single external resistor to set circuit gain and comes in three- or five-pin SOT-23 outlines that typically offer 1% accuracy for 100-mV sense voltages within 2.5 to 20 V supply lines. Alan Buxton, marketing manager at Zetex, notes that the five-pin versions offer enhanced accuracy by including a ground pin for the IC’s quiescent current—which is typically 4 µA for versions such as the ZXCT1009 that are optimized for operation at the 100-mV sense-voltage level. Other versions suit sense voltages of 10 mV to 2.5 V.

“The three-pin versions offer greater design flexibility by floating their outputs. Designers can then accommodate arbitrary power-supply levels simply by adding a suitable zener between the chip’s output and the scaling resistor that connects to ground,” Buxton says. For automotive or industrial use, a zener diode between the input supply line and the IC’s current-output terminal protects the chip from transients that accompany relays and solenoids. During an over-voltage, the zener conducts to maintain a safe voltage across the device. The IC’s current-mirror design means that its transistors are forward-biased if subject to a sufficiently high reverse polarity, but the zener diode then provides a diode clamp to divert current away from the IC. Buxton says that it’s also possible to connect two devices back to back to create a bidirectional measurement circuit, and he adds that the company will soon release an IC with this capability. The three-pin SOT-23-packaged ZXCT1009 costs 45 cents (1000). Other vendors with dedicated ICs that simplify high-side DC-current measurements include Ixys,
National Semiconductor, and Texas Instruments. Ixys is a recent entrant into this sector. Its 40-cent (1000) IXI848 is an eight-pin SOIC device that operates with supplies of 2.7 to 40V. Characterized for sense voltages of 150 mV, the chip has a typical full-scale accuracy of 0.7%. Connections to internal precision resistors allow users to set gain at 10 or 50V/V to suit a range of external sense resistors. The voltage output typically requires buffering because it connects to a current source driving either 33 kV at a gain of 10 or 165 kV at a gain of 50. National Semiconductor’s LM3814 is unusual in that it integrates a delta-sigma modulator that outputs a PWM waveform with a center frequency of 160 Hz and 0.8% resolution, thereby suiting direct connection to a microcontroller. The chip also integrates sense resistors to accommodate 61 or 67A full-scale ranges, with 95.5 and 4.5% duty cycles, respectively, signaling positive and negative full-scale values. The LM3814 comes in an eight-pin SOP and costs around $1.50 (1000).

Reflecting its Burr-Brown heritage, Texas Instruments offers the five-pin SOT-23-packaged INA138 and INA168 unipolar monitors, which suit operation from 2.7V to either 36 or 60V. These current-output devices feature single-resistor scaling for ease of use and cost around 99 cents and $1.25 (1000), respectively. The company also offers a range of similar monitors with automotive AEC-Q100 qualification, such as the INA169, as well as a new range of voltage-output devices. This INA193/198 range tolerates input common-mode voltages of −16 to +80V and offers fixed transfer ratios of 20, 50, and 100V/V for use with external current shunts. Available now, these 80-cent (1000), five-pin SOT-23 parts operate from 2.7 to 13.5V supplies over the extended −40 to +125°C range.

**SENSE FETs SWITCH CURRENT**

A different approach to in-circuit current measurements uses a FET structure that has a small current-sense pad on the same die as the main power switch to build the so-called sense FET. Here, geometric matching between the power switch and the sense element again reflects a small proportion of load current to the sense pin, allowing a resistor to ground to generate a ground-referenced voltage. Typically suiting switching applications, International Rectifier’s N-channel HEXSense MOSFETs handle as much as 50A or as much as 500V with typical ±2.5% accuracy. Newly available in a lead-free version, the 60V-rated IRCZ44PBF has a maximum on-resistance of 0.028Ω that—given adequate heat-sinking—permits the device to handle 50A in a TO-220 package. It outputs a current with a sense ratio of 1-to-2460 to 1-to-2720. Connecting an op amp’s

![Figure 4 Infineon's high-side-switching sense FETs include a current mirror that reflects a small proportion of load current to ground.](image)
noninverting input to the device’s Kelvin-ground pin and the inverting input to its sense pin allows a single resistor in the op amp’s feedback loop to scale the output to arbitrary levels. The guide price is $1.45 (1000).

Infineon Technologies’ Sense-ProFET family of smart power switches includes similar current-sense abilities (Figure 4). Here, the load-carrying transistor has maybe 50,000 cells, and the sense transistor has around 10 cells. The op amp and the P-channel FET maintain the load transistor’s potential across the sense transistor and reflect a proportional current to ground; ideally, this current is equal to the load current divided by the ratio of the load-carrying and sense transistor’s cell counts. Built in a chip-on-chip technology, these N-channel high-side switches also include charge-pump drivers and a range of protection and diagnostic functions. Suiting automotive and industrial use, the family switches 17 to 165A in a variety of TO-252 surface-mount and TO-220/218 through-hole plastic packages. The highest current BTS555 has an on-resistance of just 2.5 mΩ and an internal short-circuit current limit of 520A. Uses for the current-sense function at this level include lowering the short-circuit limit with external circuitry to take advantage of the device’s extremely low switching losses (Reference 3). Guide pricing for the BTS555 is around $4.50 (1000).

ICs MEASURE AC AND DC

The traditional nonintrusive method of measuring ac current relies on current transformers that remain the technique of choice for precision measurements. In use, the current-carrying conductor passes through the current transformer’s core to form a single-turn primary winding; increasing the number of loops through the core increases the primary turns ratio to provide greater sensitivity. With careful design and balanced coaxial load resistors, the technique easily better 0.5% accuracy for everyday benchtop measurements, with special-purpose wideband devices—such as the CT6 oscilloscope current probe from Tektronix—working at...
frequencies as high as 2 GHz. Common benchtop uses include measuring main-terminal current in triacs during device turn-on, when the transformer's output can drive a scope's 50Ω termination resistor while another channel measures trigger voltage. This application presents negligible burden to the circuit under test and requires no power supply. But, because it is a transformer technique, frequency response tails off significantly below power-line frequencies, and it's impossible to measure waveforms that include a dc component.

Current transducers that use Hall-effect devices help overcome many application difficulties in the dc to 100-kHz bandwidth that most industrial-control applications require. Vendors such as Honeywell, LEM, and Sentron offer device ranges from a few amps to kилоamp levels that suit supervisory and control logic in applications such as wind turbines. Historically, such devices have been plagued with poor sensitivity and substantial temperature-related drift, due to the nature of Hall-effect semiconductors as well as the requirement for ±12 or ±15V power rails to supply the signal-conditioning circuitry. Today, ASICs that now often contain chopper-stabilized amplifiers condition the Hall-effect device's output within a feedback loop. The loop reduces temperature-related effects by an order of magnitude or more to provide a stable ratiometric output voltage that typically centers on \( V_{CC}/2 \), where \( V_{CC} \) can be a single 5V rail, simplifying the interface to ADCs. Sensitivity improvements typically employ magnetic-field concentrators that sandwich the Hall-effect device in the gap between the ends of a circular magnetic core.

Contemporary examples include LEM's LTS-series of single-pole, closed-loop current transducers, which operate from a 5V rail. Available with nominal primary current levels of ±6, ±15, and ±25A, these devices measure from dc to a response that's 0.5 dB down at 100 kHz or ~1 dB at 200 kHz. Weighing 10g and occupying a common through-hole mounting package that’s about 24 mm square and 10 mm wide, six pins on a 12.7-mm grid allow three serial/parallel connections to three internal sets of coils. In this way, each device offers pin-configurable gains of one, two, and three times greater than its respective nominal primary current level. In each case, the output voltage is \( 2.5V \pm 0.625V \) at this level, and the output voltage is linear to better than 0.1% to within 0.5V of the supply rails. This configuration allows, for example, the highest sensitivity LTS 6-NP version to measure 0 to ±19.2A. Another feature of these devices is a hole through the core's center that—given a single pass of the current-carrying conductor—provides an alternative unity-gain connection permitting differential measurements. The $10 (100) devices are widely available, including from catalog-distribution sources. Other series provide current outputs that suit, for example, 4- to 20-mA current loops within industrial instrumentation. Here, the ability to measure bidirectional dc currents suits isolated measurements in high-current battery arrays.

Other versatile devices that especially suit automotive and industrial applications include Allegro’s ACS current-sensor family. Recent additions to this growing range of Hall-effect devices that span ±5A to ±200A include the ACS754-050, a ±50A-rated sensor. Like other family members, this lead-free chip operates from a 5V supply and replaces a sense resistor—usually, with a two- to three-order-of-magnitude reduction in resistance, power dissipation, and voltage drop. This approach gives rise to some novel packaging for high-current use. In this case, the package resembles a conventional three-terminal power device.

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with the addition of two substantial “wings” that route power through the package with minimal insertion loss; the internal resistance is just 100 \( \mu \Omega \). The ratiometric voltage output comes from a chopper-stabilized Hall-effect IC built in BiCMOS that’s factory-trimmed to minimize gain and offset errors (Figure 5). The result is a total output-error figure of \( \pm 1\% \) at 25°C that’s held to \( \pm 5\% \) over –20 to +85°C; extended specifications show error of less than \( \pm 10\% \) at the –40 to +150°C automotive extremes. Its 35-kHz bandwidth and input-to-output isolation of 3 kV rms also suggest use in low-frequency ac applications, such as motor control. The ACS754 is available now for approximately \$3.23 (1000).

Bob Christie, Allegro’s European applications manager, points to the company’s new eight-pin SOIC-packaged ACS704, which is available in \( \pm 5\% \) and \( \pm 15\% \) versions: “The ACS704 brings the current into the SOIC package to get it as close to the Hall plate on the die as possible for greater accuracy and sensitivity, while still keeping its internal resistance down to 1.5 m\( \Omega \),” he says. He adds that, by bringing the current path into the package, the ACS704 also controls the creepage and clearance distances that make its 800V-rms isolation-voltage rating possible. Operating from a single 5V supply, output sensitivity is nominally 133 mV/A at 5A and 100 mV/A for the 15A device. The output voltage centers on \( V_{CC}/2 \) with a positive slope representing positive currents. Both versions have dc to 50-kHz bandwidth, which makes them useful in a range of low-current, space-constricted applications. Available now, the guide price is \$1.61 (1000).

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**REFERENCES**