basics of Design

ACCURATELY MEASURE NANOAMPERE AND PICOAMPERE CURRENTS

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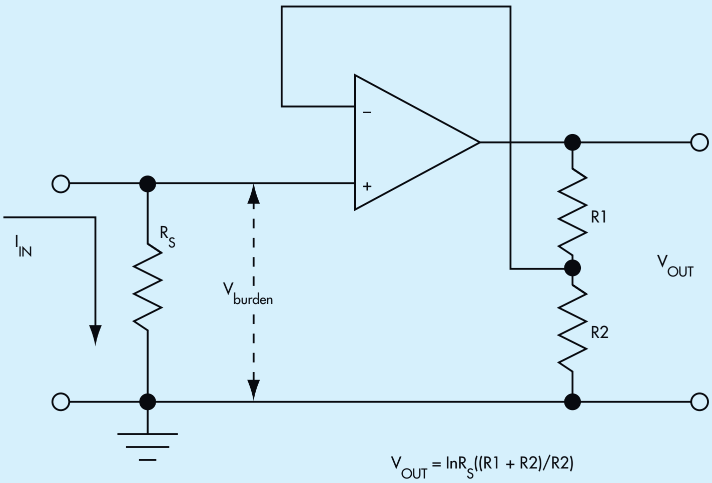
Measuring current is always a nuisance because you have to break the circuit to put the measuring device in series with the circuit. That problem never goes away. Still, any high-end digital multimeter can accurately measure currents down into the microampere and high-nanoampere range. But the process gets tricky as the current levels fall into the low-nanoampere and picoampere ranges.

At these levels, noise becomes a real problem. Also, the internal impedances of the measuring instrument or circuit become extremely critical to ensure an accurate measurement. By following a few key guidelines, though, designers can achieve accurate low-current measurements with moderately priced test equipment.

The Shunt Ammeter Approach

Typical digital multimeters (DMMs) make low-current measurements by passing the current to be measured (I_{IN}) through a precision resistor (R_S) known as a shunt and then measuring the voltage across it *(Fig. 1)*. The voltage produced across it by the current to be measured is called the burden voltage (V_{burden}). The burden voltage is an error source since it subtracts from the applied voltage. This causes the current flow to be less than the actual value, thereby producing an error.

As an example, assume that you want to measure the input leakage current to an IC with an input impedance of 1 M| ±2%. Further



1. This standard shunt ammeter circuit passes the current to be measured through the shunt resistor to produce a voltage. The amplifier provides gain and an output to be sent to a DMM.

A Dozen Applications Requiring Low-Current Measurement

1. Dark current in photodiodes
2. Fiber-optical alignments
3. Insulation resistance measurements
4. Leakage current measurements.
5. Materials and discrete components characterization
6. Biochemistry measurements (e.g., ion currents through membranes)
7. Scanning electron microscope (SEM) beam current measurements
8. Photomultiplier current measurements
9. Sensor characterization
10. Semiconductor device I-V characterization
11. Spectrometer/fluorometer measurements
12. Particle and beam monitoring

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assume that the test voltage must be very small due to the IC internal circuit restrictions. A test voltage of 0.1 V is used. The test voltage may come from a calibrated external precision source or from within the ammeter itself in some equipment. With a test voltage of 0.1 V and a 1-M| input impedance, the current should be $0.1/1 \times 10^6 = 100 \times 10^{-9}$ or 100 nA.

The current flowing through the shunt produces a burden voltage that changes the measurement outcome. A typical burden voltage in a quality DMM may be as high as 50 mV on very low-current ranges. This subtracts from the applied test voltage, so the indicated current is really $(0.1 - 0.05)/1 \times 10^6 =$ 50 nA. The result provides an unacceptable 50% error.

If you think in terms of the total equivalent circuit, it is the voltage source, the impedance of the IC, and the shunt resistor in series. The voltage source and the circuit impedance should form a good current source with a high internal impedance 10 to 100 times the shunt impedance. The lower the shunt impedance compared to the impedance of the device under test (DUT), the more accurate the measurement.

Using a lower shunt resistance can reduce the error. But that must be traded off depending upon test voltage range and any voltage restrictions on the DUT. Most DMMs have selectable current ranges where several shunt values are available.

A More Accurate Method

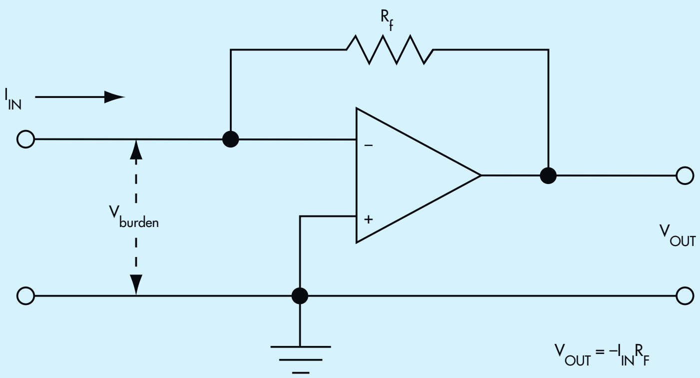
Designers can improve accuracy significantly by using a feedback ammeter with an operational amplifier or transimpedance amplifier to convert the input current into a voltage *(Fig. 2)*. The output voltage is the product of the input current to be measured and the feedback resistor value.

This arrangement produces much lower burden voltages as low as 20 µV because the "shunt" is in the feedback path and can be made bigger than it could be otherwise. It now appears divided by the gain of the op amp as the input "shunt."

Using such an arrangement to make the previously described leakage measurement provides $I = (0.1 - 0.0002)/1 \times 10^6 = 99.8$ nA. Based on the desired or expected current measurement, this is an error of about 2%, which is a major improvement over the previously described measurement.

The feedback ammeter method is the basic architecture for dedicated picoampere meters. Having a dedicated picoammeter in addition to a more general-purpose DMM may be excessive, though. Just remember that with a feedback ammeter, the maximum current is usually no more than 20 mA. For higher currents, it's back to the basic shunt ammeter found in a basic DMM.

2. This feedback ammeter circuit injects the current to be measured directly into the summing junction of the op amp. The output is a voltage proportional to the current that is measured on a DMM.



Cabling Issues

There are two primary cabling issues: cable capacitance effects and shielding from noise. When using a standard shunt ammeter arrangement, the cable capacitance and any amplifier input capacitance will slow down the measurement, as that capacitance has to be charged through the high impedance of the DUT. Charge and settling times are long, meaning the measurement isn't instantaneously valid. Using the feedback ammeter method greatly mitigates this problem.

As for noise, it can significantly affect the accuracy of the low current measurement. The ac line noise is especially significant, and it can easily overwhelm any sensitive amplifier in the input. Therefore, coax cable or shielded twisted-pair cables are essential for reliable measurements. Always use the cables recommended by the equipment manufacturer to ensure best results. And remember, no amount of filtering can eliminate the effect of ac line induced noise.

Current Amplifier Specs

Here are some critical specifications and features to look for when buying a current amplifier for low current measurements.

- Gain setting (V/A): Gain setting determines the current range. Selectable gain/range, usually from a low of 10^4 (1 mA) to as high as 10^{10} (1 nA) in high-end instruments, is desirable.
- Burden voltage: The lower the burden voltage, the better (<200 µV), with higher figures in the higher current ranges. The typical range is 20 µV to 200 mV.
- Accuracy: It should commonly be in the 0.1% to 0.7 % range, depending on your needs. Also, it's very sensitive to temperature.
- Settling time: Also known as rise time, settling time is measured at the 10% to 90% levels, depending on the range selected. Its common range is 500 µs to 100 ms.

Other important specifications include output voltage range to drive DMM and rms noise.

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Key Error Sources in Low Current Measurement

Most of these effects aren't great enough to be issues on their own in most noncritical day to day current measurements. But with nanoampere and picoampere measurements, these effects can invalidate any measurement. Conditions vary widely, so be aware. Caution advised!

- Electrostatic coupling: Any charged body brought close to the measuring device can stimulate electrostatic interference. The pickup is capacitively coupled and can produce nanoampere-level or even microampere-level currents, invalidating any measurement. The solution is good cable shielding, and in some cases, shielding the DUT.
- Triboelectric effects: These effects result from the movement of a conductor against an insulator, as in a cable. The resulting friction-induced noise will introduce measurement errors. Special cables can reduce this effect and eliminate cable movement and vibration in the test setup.
- Piezoelectric effects: The flexing or deflection of certain insulators such as plastics or ceramics creates these noise voltages. Again, proper cabling and the restriction of cable movement usually solve the problem.
- Leakage currents: These can occur on cables, connectors, the measuring instrument, or the DUT. Contaminants like dirt, grease, fingerprints, or solder flux can create alternate current paths that introduce error. Designers should clean all surfaces with alcohol before the measurement.
- Offset current: Offset current in the measuring amplifiers while already low can change with temperature. This drift over time will change the measurement. The solution is to ensure that the measuring instrument and the DUT have warmed up over time so their temperatures are stable.
- Light effects: Some DUTs may be sensitive to light. Light sources can induce noise currents, further invalidating any measurements. Shielding from the light sources solves the problem.
- Electrochemical effects: These effects occur on pc boards where two metals (copper, flux, etch material, etc.) produce tiny, weak battery effects that can produce significant current errors. Thoroughly cleaning the boards solves the problem.
- Dielectric absorption: This type of error is produced when a voltage across an insulator polarizes or charges that insulator, which can later discharge and produce a leakage current. Using reduced voltages and waiting a sufficient period for the charge to dissipate will correct the problem.
- Acoustic noise: Ambient noise from any source can produce vibrations that also can produce some of the other effects described above.
- Thermal noise: Noise voltage and current from the random motion of electrons produced by heat in the shunt or DUT are proportional to the square of the resistance value. Using lower values of shunt and feedback resistors as well as lower noise resistors (e.g., metal film) will minimize the problem.