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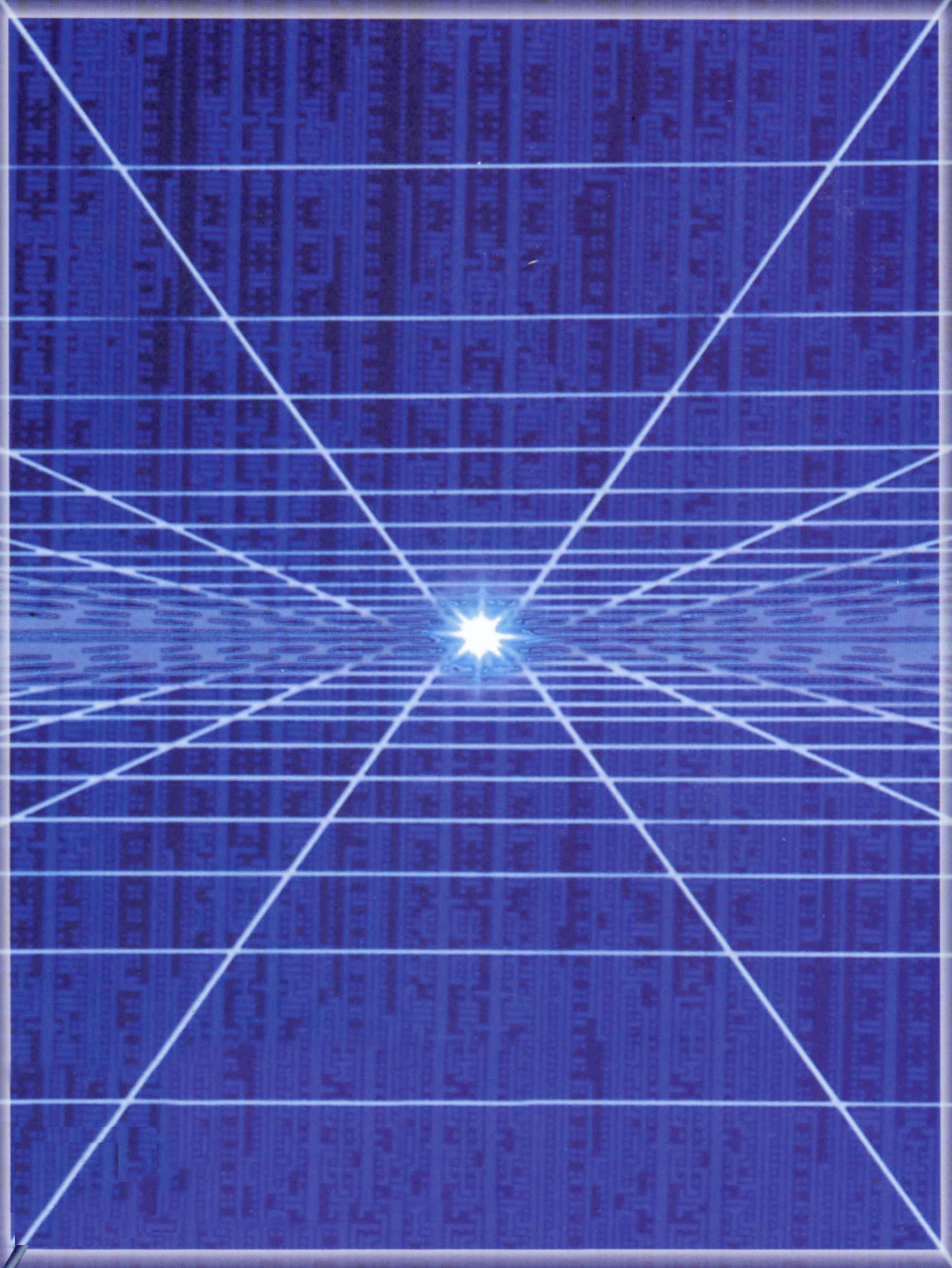
## MEASUREMENTS & CONTROL



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# Advanced Measurements:
## A Postgraduate Tutorial
## Part 2 – Instrument Designs

*Product brochures highlight equipment strong points, but how do you know which features and specifications are relevant to your measurement needs? Measurement equipment specifications can be separated into two categories: (1) those that are strictly internal to the instrument, which you have to be aware of but cannot change, and (2) those that are related to external factors, such as the test circuit and environment, which you can control to some extent. Part 1 of this series focused on the relationship between external factors and specifications affecting instrument accuracy, test throughput and noise immunity. Part 2 covers internal specifications and the instrument designs that determine them, and examines specifications from the input terminals to the bus connector and emphasizes internal error sources that affect low-level measurements.*

*MARK CEJER and DALE CIGOY*

### FRONT-END SPECIFICATIONS

*Input impedance* is defined as the shunt resistance and capacitance (or inductance) measured between the instrument's input terminals. It is a function of front-end design and is a limiting factor in measurement accuracy. Typical values for benchtop digital multimeters (DMMs) range from 10 MΩ on the higher voltage ranges to 1 GΩ or more on lower ranges. (See Table 1 for a list of engineering units and prefixes.)

To minimize loading errors, an instrument's input impedance must be much higher than the output impedance of the signal source and its test circuit. When making measurements on high impedance circuits and devices, input impedance becomes a critical specification. An electrometer, which is a highly refined DC multimeter, can have an input impedance of 200 TΩ in parallel with 20pF. By comparison, a data acquisition card might have an input impedance of 100 MΩ in parallel with 200 pF.

*Voltage burden* is important when you make low current measurements. This is expressed as a voltage drop across the instrument's input terminals, which is a function of the series resistance of the current source and the internal series resistance of the instrument. As illustrated in Figure 1, voltage burden error is the difference between an instrument's measured current value and one that would be attained with an ideal ammeter. Table 2 lists typical voltage burden specifications for different types of instrument.

*Input bias current* is the current flow into an instrument's input terminals when making voltage measurements. It is a function of the instrument's preamplifier circuit and bias voltage. For low-level voltage measurements, input bias current should be as low as possible to avoid errors due to voltage drop across the signal


**Keithley Model 2425 SourceMeter. (Courtesy of Keithley Instruments)**

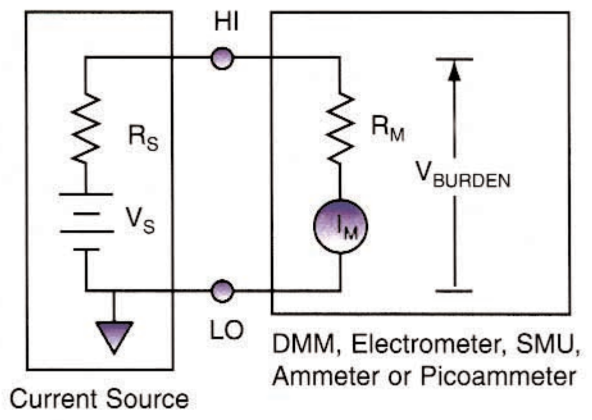
| Table 1 - Engineering units, prefixes and exponents | | |
|---|---|---|
| Symbol | Prefix | Exponent |
| y | yocto- | $10^{-24}$ |
| z | zepto- | $10^{-21}$ |
| a | atto- | $10^{-18}$ |
| f | femto- | $10^{-15}$ |
| p | pico- | $10^{-12}$ |
| n | nano- | $10^{-9}$ |
| μ | micro- | $10^{-6}$ |
| m | milli- | $10^{-3}$ |
| (none) | (none) | $10^{0}$ |
| k | kilo- | $10^{3}$ |
| M | mega- | $10^{6}$ |
| G | giga- | $10^{9}$ |
| T | tera- | $10^{12}$ |
| P | peta- | $10^{15}$ |
| E | exa- | $10^{18}$ |
| Z | zetta- | $10^{21}$ |
| Y | yotta- | $10^{24}$ |

| QUANTITIES | | |
|---|---|---|
| Symbol | Unit | Quantity |
| V | volts | emf |
| A | amperes | current |
| Ω | ohms | resistance |
| C | coulombs | charge |
| s | seconds | time |
| W | watts | power |
| F | farads | capacitance |
| Hz | cycles/s | frequency |
| K | degrees | temperature |

(Source: *Keithley Low Level Measurements Handbook*, 5th Edition.)

source's internal resistance. Typical bias current values are 50pA for a nanovoltmeter and 5fA for an electrometer.

*Zero offset* is another characteristic of measurement instruments that can cause errors. It shows up as a non-zero reading when the instrument is connected to a low impedance source with no voltage present, which results from such things as the voltage preamp circuitry, thermoelectric EMFs and rectification of radio frequency interference (RFI). As discussed in Part 1 of this series, autozeroing circuitry is used maintain accuracy, but can slow down measurements. An instrument designed with a servo front-end amplifier employs a self-regulating feedback circuit (Figure 2) that virtually eliminates zero drift. This also eliminates wasted measurement time usually required for autozeroing, thereby increasing measurement throughput. There are other techniques for dealing with thermal EMFs and RFI that will be discussed later.




$$I_M = \frac{V_S - V_{Burden}}{R_S} \quad \text{or} \quad I_M = \frac{V_S}{R_S}\left(1 - \frac{V_{Burden}}{V_S}\right)$$

**Figure 1 – Effects of voltage burden on current measurement accuracy.**

| Table 2<br>Typical instrument specifications for voltage burden | | |
|---|---|---|
| Instrument | Voltage Burden on Lower Ranges | Voltage Burden on Higher Ranges |
| DMM | 150 mV | 1.5 V |
| Source-Meter | 1 mV | 1 mV |
| Picoammeter | 200 μV | 2 mV |
| Electrometer | 20 μV | 4 mV |

## NOISE SPECIFICATIONS

Part 1 of this series discussed externally-generated AC line noise and random noise. Inside an instrument, front-end circuitry has features that can minimize the effects of these noise sources, but this varies by instrument (see Figure 3). Still, this circuitry is an internal noise source itself, particularly the A/D converter and preamp. Specifications for internally generated noise are expressed in different ways that reflect different types of measurements. Lower values of noise allow more accurate measurements. The most common specification methods are outlined below.

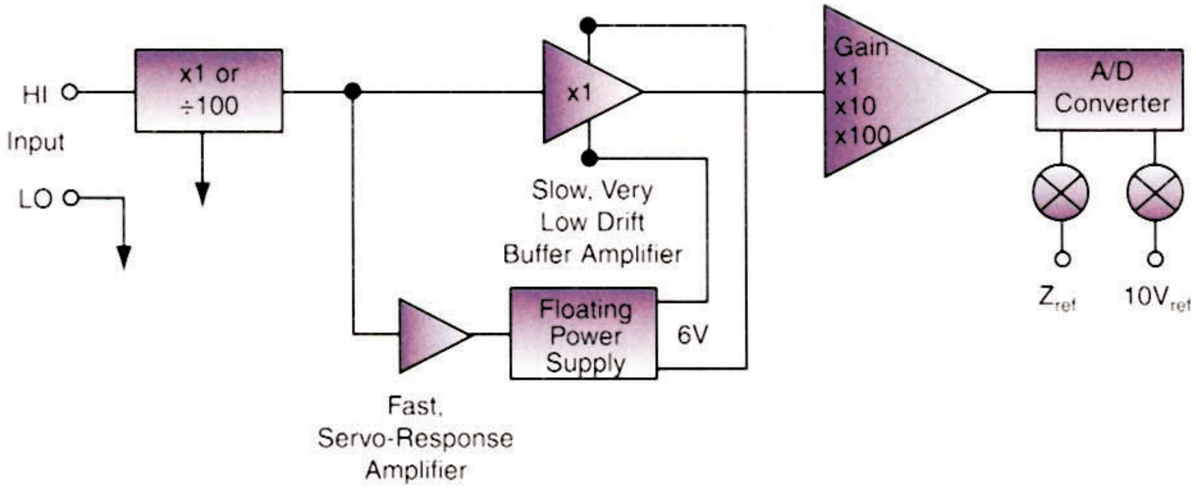



**Figure 2 — By eliminating zero offset due to drift, a servo correction amplifier eliminates time normally required to perform an autozero function.**

• Normal mode rejection ratio (NMRR) – This is the ability of an instrument to reject interference (usually of line frequency) across its input terminals. It is expressed in decibels (dB), where 60dB is typical for a DMM.

• Common mode rejection ratio (CMRR) – This is the ability of an instrument to reject interference from a common voltage at it input terminals with respect to ground. It is expressed in dB, where typical specifications for a DMM are 140dB at slow reading rates and 80dB at fast rates (less than one power line cycle).

• RMS noise – This is the noise floor, that is, the noise present on a measurement range at a specific reading rate and resolution. A low-noise DMM operating with its most sensitive settings might have a noise floor of 100 nV. With less sensitive settings, this could be as high as a 100 microvolts or more.

• System DC noise – For data acquisition cards, this specification is frequently listed under DC Accuracy and expressed in terms of a maximum uncertainty in the Least Significant Bit (for example, 0.2 LSB). With a 12-bit A/D converter, one LSB is equivalent to one part in 4096 ($2^{12}$). If the input signal varies between zero and 1.0 V, and the maximum noise level is 0.2 LSB,

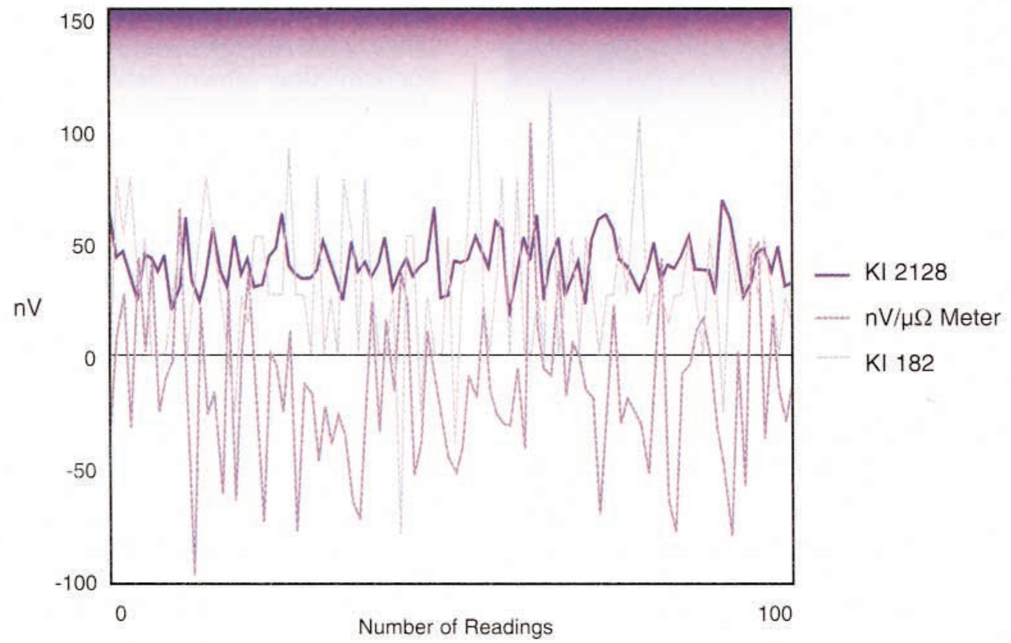


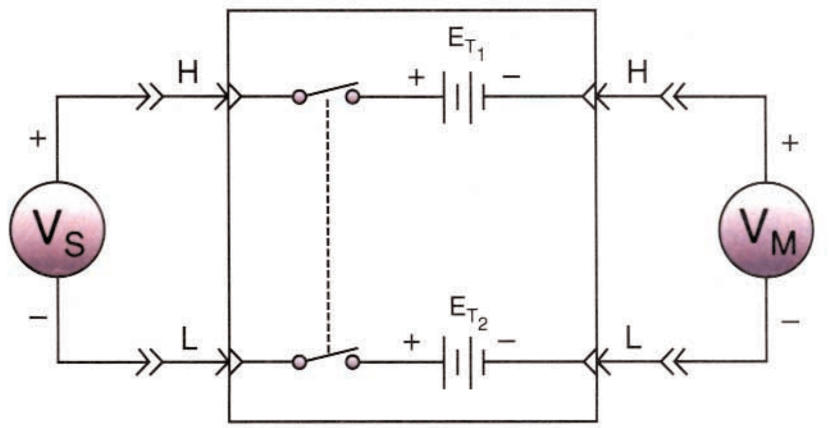

**Figure 3 – Noise specifications vary widely, even within the same class of instrument, as shown here for three different nanovoltmeters.**

then the maximum noise magnitude is (0.2 x 1) / 4096 = 48.8 μV.

• AC noise – The AC accuracy spec for a data acquisition card may list total harmonic distortion and channel crosstalk. The first term expresses in dB the magnitude of all harmonic frequencies relative to the fundamental frequency, for example, -60 dB. Crosstalk is the degree to which signals on different channels interfere with one another and is also expressed as a signal level in dB lower than the one on the selected channel.

the voltage produced between contact terminals due to the temperature gradient across the relay contacts, and the reed-to-terminal junctions of dissimilar metals. Cards designed for low voltage measurements might specify as low as 1 μV per channel contact pair. Also, 2-pole switch designs and symmetrical measurement loops minimize the effects of contact potential (Figure 4).

• Offset current – This is the current generated within a switching card even though no user signals are applied. It is caused by triboelectric, piezoelectric and




If $E_{T_2} = E_{T_1}$

then $V_M = V_S$

Similarly, each connection in circuit HI is cancelled by an identical connection in circuit LO.

**Figure 4 – Two-pole switching and a symmetrical measurement loop minimize reading errors due to contact potential.**

## ERRORS INTRODUCED BY SWITCHES

In a typical test or data acquisition device there are at least a few switches that a signal must pass through before its value is computed and displayed. For example, in a benchtop instrument, dry reed relays are commonly used to change ranges. Some switching mainframe systems may use solid-state switches to route the signal from the DUT to the measurement instrument. Regardless of type, any switched path degrades a signal. Low-level signals and those from high impedance sources are the most susceptible to errors.

For mainframe switching systems and instruments with their own internal switching cards, switch specifications are largely determined by the relays or solid-state devices used to make the signal connections. Other factors include how the traces are laid out on the switching card, both spacing and path length, and the type of connectors used, which could be anything from a screw-terminal block to a coaxial connector.

When comparing switch cards, make sure the specifications are given for the entire path from input terminal to output terminal, not just for the relay itself. For low-level measurements, check the following specifications:

• Contact potential (contact offset voltage) – This is galvanic effects, plus finite coil to contact impedance. For low current measurements, look for offset current specifications on the order of 1 pA.

Since a switch or data acquisition card can have many types and levels of signal present, isolation is important. Isolation is defined as the insulation resistance between signal paths, i.e., two different channels on a data acquisition card or two different poles on a switching relay. Again, the switching device is the primary determinant of the specification. Table 3 lists typical isolation values for common relay types.

## A/D CONVERTER TYPES

Speed, resolution, and noise are three tradeoffs in A/D converter designs. For example, the high speed of a flash converter is offset by its lower resolution and higher noise susceptibility. And the higher resolution and good noise immunity of an integrating A/D is compromised by its lower speed.

A more precise A/D converter can correct for drift errors associated with resistor networks used for signal conditioning ahead of the converter. This provides higher accuracy over a wider operating temperature range.

In any case, make sure the specified digits of resolution

**Table 3 - Relay isolation specifications**

| Relay Type | Isolation (Ω) |
|---|---|
| Electromechanical | $10^7$ - $10^{10}$ |
| Contactor | $10^6$ - $10^9$ |
| Dry Reed | $10^9$ - $10^{14}$ |
| Mercury-Wetted Reed | $10^8$ - $10^{12}$ |
| Solid State | $10^6$ - $10^9$ |

is not based on an average of multiple readings. Achieving this resolution comes at the price of a significantly lower reading rate. By contrast, a DMM with 7.5 digits of resolution based on a 28-bit A/D converter does not require averaging to discern small signal level changes.

## DESIGN ISSUES AFFECTING THROUGHPUT

Since most test systems use a PC to control and manipulate data, the method used to move digitized data between the PC and measurement devices is a major determinant of system throughput. Where and how data is stored also is important.

*Data communication bus* – Many data acquisition systems utilize cards installed in an ISA or PCI bus slot inside a PC. However, the PC may also act as a controller and be connected to other test system devices on an external data communication bus. While the data acquisition card may be able to scan inputs at a rate of 1 MHz, the RS-232 serial communication port of a PC is limited to data communication rate of about 20 kHz. Faster parallel communication interfaces are possible, such as IEEE-488 (general purpose instrumentation bus, or GPIB), but that requires a separate interface card in another slot inside the PC.

Frequently, benchtop instruments have both an RS-232 and GPIB interface, the latter moving data at a maximum rate of about 1 MB/s. Since both benchtop and PC card systems have the IEEE-488 bus available as a design option, the speed/accuracy dichotomy between the two is determined by other design issues. For example, benchtop instruments rarely take advantage of the maximum data rate available with IEEE-488, opting instead for slower internal signal processing that dramatically increases accuracy.

Getting the signal, now expressed digitally, out of the instrument to the PC controller is the function of the data communication bus. Probably the most common instrumentation interface is IEEE-488, also known as GPIB (general purpose instrumentation bus), a parallel interface standard.

*Data storage methods* – Another parameter affecting throughput is data storage time. Using an internal buffer is faster than sending data over an external communication bus to the PC, although that may be required at some point in the test cycle. Ideally, the buffer memory size should be large enough to hold all collected data until the end of a measurement cycle. Then it can be sent to the PC while other time consuming functions are being performed, such as removing the DUT from a test fixture.

*Equipment integration* – Combining several measurement functions in a single instrument tightens integration and tends to decrease the combined trigger latencies of separate instruments. Also, as mentioned in Part 1, internal or hardware triggering is usually faster than external or software triggering. Look for instruments that have all, or most, of the functions and features required in your test system. For example, some DMMs have special functions, such as channel scanning, measure temperature with thermocouples and RTDs, perform total harmonic distortion measurements, etc. Also, source and measure functions can be combined, and you will find instruments that include both voltage and current source-measure capabilities covering a wide range of values. Frequently, these source-measurement units also conserve rack space.

## A LOOK AHEAD TO PART 3 – EXTERNAL ERROR SOURCES

The next installment of this series will describe external error sources and measurement techniques to reduce those errors. Techniques for low impedance and high impedance measurements will be presented.

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