1x.2 Resistors

Figure 1.2 in AoE3 shows the range of resistor types, from tiny surface-mount chips to giant wirewound power resistors. The most important characteristics are ***resistance***, ***power rating***, ***tolerance*** (accuracy), ***stability*** (over time), and ***temperature coefficient*** of resistance. But resistors (like all electronic components) are imperfect – electrically they exhibit some ***series inductance*** and some ***parallel capacitance***,[34] which become important in high-frequency circuits and in power-switching circuits. Additional departures from ideal performance include ***voltage coefficient*** of resistance and ***excess noise***; these are important in low-distortion, low-noise, and precision circuits.

We touched briefly on these less-than-sterling attributes of the humble resistor in several places in AoE3; see for example the Box ("Resistors") on page 5, the Table ("Selected Resistor Types") on page 1106, and discussion on pages 300, 476, and 697–98. Here we elaborate on some of these neglected aspects of a component often taken for granted.

1x.2.1 Temperature coefficient

The ubiquitous thick-film SMT chip resistor (e.g., Vishay CRCW-series) typically has a specified tempco of ±200 or ±100 ppm/°C (designated in the manufacturer's part number). But if you need better, you can get low tempco SMT resistors, for example the inexpensive Panasonic ERJ-xRBD or -xRHD series (±50 ppm/°C), which cost about $0.07 in full-reel quantities (compared with $0.003 for the commodity CRCW types). Still better are some thin-film SMT parts, for example the Panasonic ERA-xAR series or Yageo RTxxxxxRB series (±10 ppm/°C), which cost about $0.18 in full-reel quantities, or the Vishay TNPU-Z series (±5 ppm/°C, $1 in full-reel qty).

For the absolute lowest tempco you can get metal-foil ("Z-foil") SMT resistors from Vishay (VSMP-series, ±0.2 ppm/°C), which exploit a clever thermal compensation trick by bonding the metal foil element to a carefully chosen ceramic substrate whose mechanical coefficient of expansion causes the combined object to exhibit extraordinarily low tempco; these things cost plenty, though, about $10 apiece.

The above are SMT types; you can, of course, get through-hole (axial or radial lead) resistors with analogous performance. Additional types are available, for example wirewound resistors, which come with tempcos as low as ±20 ppm/°C (though typically they are in the ordinary range of ±100 ppm/°C or so).

1x.2.2 Self-capacitance and self-inductance

Real resistors have some equivalent series inductance and some distributed shunt capacitance (Fig. 1x.27). Typical values for SMT resistors are in the range of tens to hundreds of femtofarads, and 0.01–2 nanohenrys.[35] Depending on the physical construction, the overall effect may be a rise in impedance with frequency (e.g., wirewound resistors), or, if the parallel capacitance dominates, a falling impedance. Both trends can be seen in the measured $|Z(f)|$ plots of Figure 1x.28.

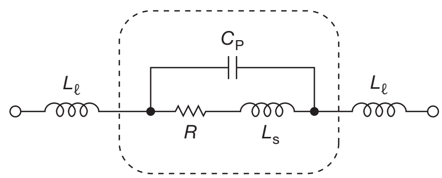

Figure 1x.27. Simplified resistor model, showing parasitic inductances and capacitance. The external inductances L_l represent the inductive contributions of the leads to the impedance of the resistor body (enclosed in dashes).

To explore this further, we measured the impedance of a set of wirewound resistors of the same construction (the classic Ohmite Brown Devil®), with the results plotted in Figure 1x.29. Evidently the inductive contribution dominates at megahertz frequencies, more so for the lower resistor values. For applications at high frequencies, non-inductive wirewound resistor types largely eliminate the problem.

What about the parallel capacitance C_p of the model of Figure 1x.27? At some frequency it should form a (damped) parallel resonant circuit, an effect that can be seen in the measured data of Figure 1x.31, where we've extended the frequencies out to 300 MHz for three of the wirewound resistors of Figure 1x.29. You can use a trick to largely compensate for this unseemly behavior, namely

[34] Which may be more complicated than a single series L and parallel C, because they are distributed throughout the resistor.

[35] See, for example, Vishay Technical Note 60107, "Frequency Response of Thin Film Chip Resistors."

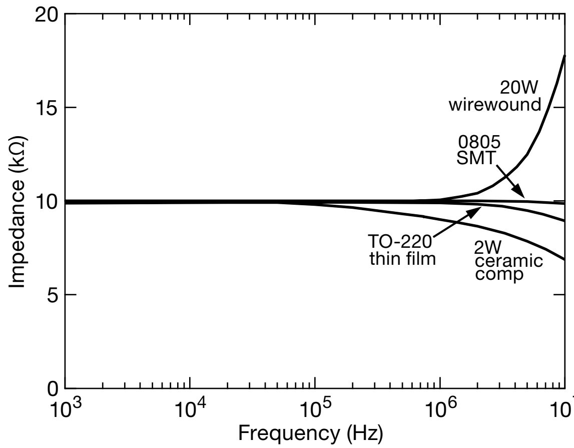

Figure 1x.28. Measured impedance (magnitude) versus frequency for four resistor types. At high frequencies the effects of parasitic inductance and capacitance cause a deviation: upward for wirewound resistors (inductance dominates), downward for non-inductive construction (capacitance dominates).

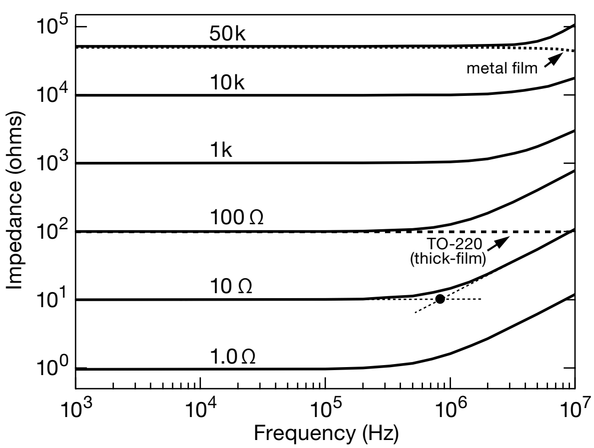

Figure 1x.29. The inductance of wirewound resistors causes the total impedance to rise at high frequencies, as seen in measured data of 20 W "brown devil" types. If this matters in your application, you can get non-inductive wirewound resistors that use bifilar (two windings, connected together at one end), or Ayrton–Perry (two counterwound windings in parallel) winding geometries; the simpler bifilar winding suffers from much higher parasitic capacitance. A "breakpoint" frequency (black dot) fully characterizes a resistor with series inductance (see the wirewound resistor zoo in Fig. 1x.30).

a series *RC* attached across the offending resistor, with *R* equal to the nominal resistance, and *C* selected to flatten the impedance curve.

Once we had the measurement rig set up, we couldn't resist (pun) running a bunch of resistors (of various resistances, and various construction) through it. They all exhibit curves similar to those in Figure 1x.29; to keep the figure uncluttered we plotted just the breakpoints (intersection of nominal resistance with the extrapolated upward slope, see the example in Fig. 1x.29). Figure 1x.30 shows the resulting scatterplot.

The best performers (breakpoints at the highest frequencies) are the carbon composition (RC07 type), the non-inductive Ohmite WN-type (Ayrton–Perry zigzag winding), and the surface-mount small wirewound type. By contrast, the losers are the traditional large-geometry wirewound power resistors. However, some of the latter are available in non-inductive versions: for the Vishay/Dale RS, RH, and LVR types you can get NS, NH, and NI as Ayrton–Perry non-inductive variants.

1x.2.3 Nonlinearity (voltage coefficient)

An ideal resistor maintains $I=V/R$ over time, temperature, frequency, and applied voltage. In the real world resistors exhibit deviations from perfection. A not-insignificant effect is *nonlinearity* – an effective change of resistance with applied voltage.

You can find worst-case specifications in some datasheets: for example, although the commodity Vishay CRCW-style thick-film SMT resistors do not specify a voltage coefficient, their PCAN-series thin-film resistors specify a worst-case resistance change of 0.1 ppm/V, the same as the best-in-class metal foil or metal film types such as the Vishay VSMP and Z-foil series resistors.

Out of curiosity we measured the resistance change versus voltage for a selection of resistor types. You often use a high-resistance voltage divider to monitor a high-voltage dc supply, so we tested high-resistance parts at voltages to 1000 V. Figure 1x.32 shows the results, plotted as log–log and log–linear. The thick-film resistors (curves C–H) are better by some two to three orders of magnitude, compared with the traditional carbon composition type.

Carbon-composition resistors are largely a relic of the past (though they excel in peak power endurance, see §1x.2.6). Sticking with the thick-film types, we explored the nonlinearity versus resistance (for a fixed size), and nonlinearity versus size (for a fixed resistance). Figures 1x.33 and 1x.34 plot the measured results, showing that the nonlinearity increases dramatically with increasing resistance and with decreasing physical size.

When does nonlinearity matter? For low-distortion amplifiers and oscillators, certainly. Also for precision low-voltage monitoring and control of a high voltage source. Note, however, that for the latter what you care about is a

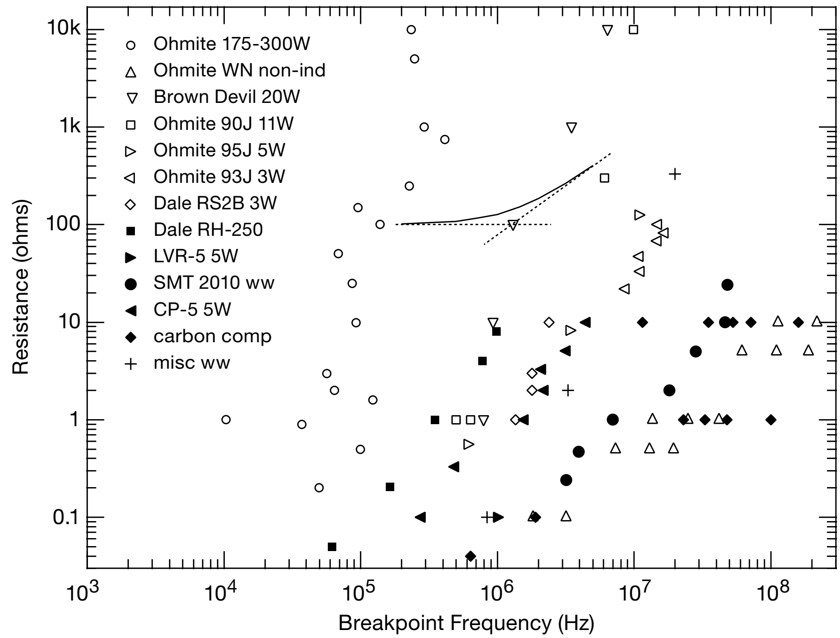

Figure 1x.30. Measured *RL* breakpoints (see Fig. 1x.29) for a sampling of power resistor types. All are through-hole wirewound, except as indicated.

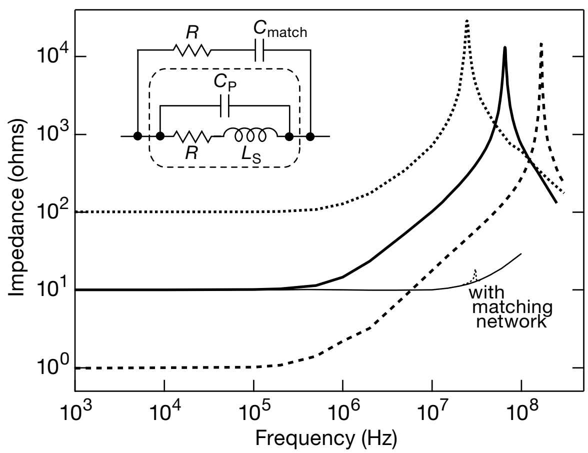

Figure 1x.31. Extending the measurements to 300 MHz reveals *LC* parallel resonances. The high-frequency artifacts are largely suppressed by attaching a matching network of 10 Ω in series with 16.5 nF in parallel with the 10 Ω wirewound resistor. Watch out for the amount of power dissipated in the matching resistor.

precise resistor *ratio*, for which you should probably be using a resistive divider that is designed to maintain a stable ratio as the applied voltage varies – see §1x.2.7, below.

1x.2.4 Excess noise

In our extensive discussion of noise in Chapter 8 we introduced the business of *excess noise* in resistors (§8.1.3); this effect is essentially a fluctuation in resistance, which manifests itself as an added noise voltage (i.e., in addition to Johnson noise, which depends only on the resistance) when current is flowing through the resistor. We've been visited by this phenomenon in some recent instruments we designed; here is the story:

We built a high-voltage amplifier with ±1200 V of operating range, and with less than 1 ppm of output voltage noise.[36] For some experiments at CERN, 160 of these were machine assembled. About 10% of them failed to meet the low-noise goals, with an excess noise level that increased with output voltage. The amplifiers used an Ohmite 150M 1.25 W SM103 high-voltage resistor in the feedback loop. This "Slim-Mox" thick-film-on-Alumina precision planar resistor is 15 mm long and is rated at 7.5 kV. After replacing the offenders we wound up with a small collection of noisy 7.5 kV resistors. Evidently the resistive material has domains that change under the influence of electric fields. (Perhaps the problem would have been avoided if we had made the feedback resistor from fifteen standard 10.0M re-

[36] To learn more about the amplifier, ask about the AMP-37 UberElvis project.

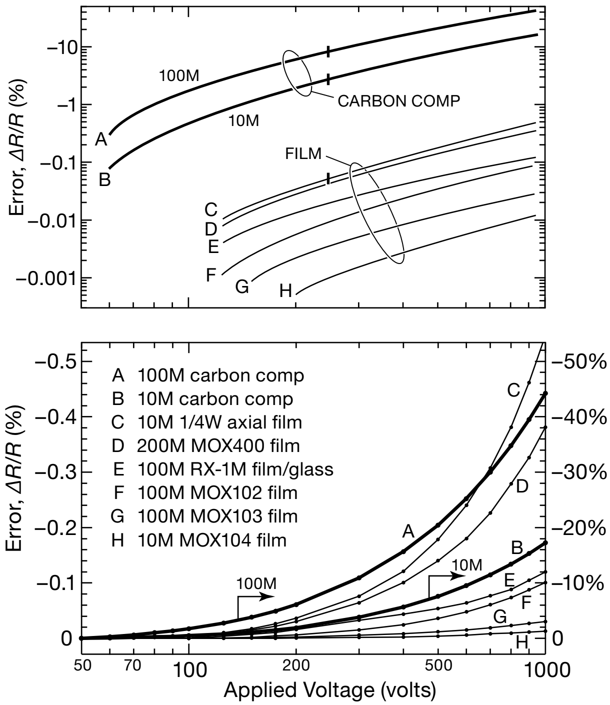

Figure 1x.32. Measured change of resistance versus applied voltage for eight resistor types. The 1/4-watt carbon composition (RC07, plots A and B, scale on right) and film (plot C) resistors are rated only to 250 V (marked with vertical stroke), a limit we ignored in our enthusiasm.

sistors in series, each limited to less than 80 V in operation.)

1x.2.5 Current-sense resistors and Kelvin connection

We discussed the business of 4-wire sensing ("Kelvin connection") in many places in AoE3; see, for example, pp. 277–78, 294, 350, 365–67, 898, and 1070–71. The basic idea is to eliminate the error in a current measurement by sensing the voltage drop across the current-sensing resistor (often of very low resistance, less than an ohm) with a separate pair of wires (Fig. 1x.35). In that figure, for example, you would suffer a +20% error in the measured current, if you had (foolishly) used the voltage drop between the pair of terminals themselves. Measuring instead the drop between the sense terminals eliminates this error. The assumption, of course, is that the sensing circuit (here the difference amplifier) draws negligible current; this is easily satisfied, especially in high-current circuits where

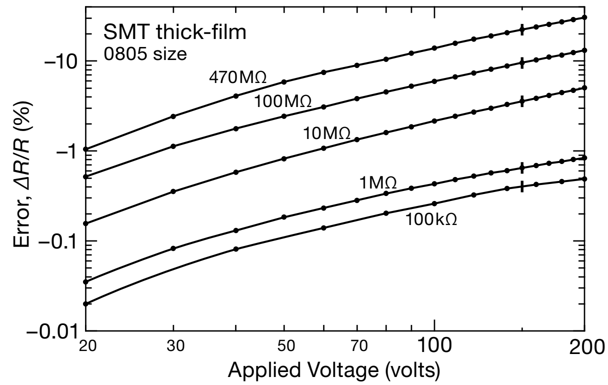

Figure 1x.33. Measured change of resistance for 0805-size thick-film surface-mount resistors, officially rated to 150 V maximum. The nonlinearity increases with resistor value.

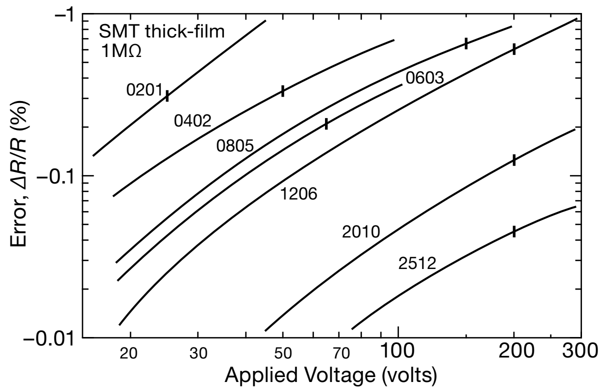

Figure 1x.34. Measured change of resistance for 1 MΩ thick-film surface-mount resistors of different sizes; the rated voltage for each is indicated by vertical strokes. The nonlinearity decreases with increasing physical size.

the sense resistor is of low resistance (and thus prone to error in a 2-wire configuration).

Current-sensing resistors come in an enormous range of current capabilities and physical sizes – see the montage in Figure 1x.36, photoshopped by the authors from datasheets of a half dozen manufacturers, where the scaling varies wildly among the specimens (the little guys labeled "R010" are 40 times smaller than the big one on the top row, second from right).

1x.2.6 Power-handling capability and transient power

In circuits with pulse waveforms you frequently have situations where components (resistors, diodes, transistors)

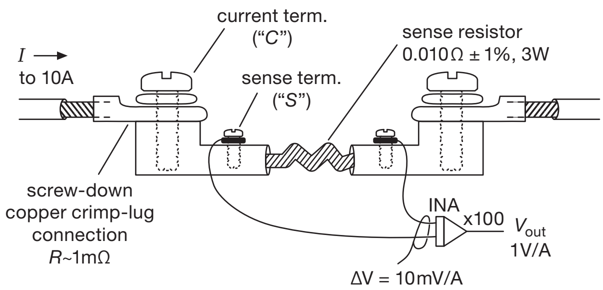

Figure 1x.35. A 4-wire (Kelvin) current-sensing resistor eliminates errors caused by imperfect connections. Here, for example, 4-wire sensing eliminates a 20% error that would be caused by just a milliohm of bolt-on lug resistance.

are subjected to peak power (during the pulse) that is well above the steady-state power rating. That's OK as long as the thermal pulse does not cause the component's temperature to exceed allowable limits. We discuss this further in §9x.25.8 in the context of semiconductor devices (MOSFETs, TVSs), where allowable pulse power is described by the *transient thermal resistance* as a function of pulse duration, $R_{\Theta JC}(\tau)$.

Here we are interested in the humble resistor, where the same effect applies: the peak power during the pulse can be absorbed by the heat capacity of the resistor's mass, as long as the average power does not exceed the part's power rating. Some resistors are designed and specified for such "pulse-withstanding" service. This is usually specified with a graph of peak power (or "pulse load") $\hat{P}_{max}$ versus pulse duration. Figure 1x.37, shows such curves for resistors from seven datasheets, mostly of similar size (1206 SMT for all but curves A and F).

You can see some interesting trends in these plots. Curve B is a Vishay "pulse-proof" resistor, which does considerably better for short pulses than its more conventional curve B′ sibling. Resistor C exploits the thermal conductivity of aluminum nitride to permit high steady-state power (2 W), but with no special attention to short-pulse endurance. Resistor F uses a solid resistive carbon slug (rather than a resistive film), whose mass is able to absorb prodigious peak power (35 kW!) for up to a microsecond – not bad for a quarter-watt resistor. Yet, in spite of its larger size (roughly triple the footprint of the other resistors), it falls below the rest of the pack for pulse durations greater than 10 ms.

In Figure 1x.38 we adapted datasheet plots for some larger pulse-rated resistor types. Here you can see the impressive performance of ceramic composition resistors (the worthy successor to the once-ubiquitous carbon comp), plots B1–B3; Tyco's CCR-series (plotted) are similar to Ohmite's OX (1 W) and OY (2 W), though the latter do not provide $\hat{P}_{max}$ versus t_i plots.

A word of caution: It is our belief that one should not place complete reliance on the kind of curves provided by manufacturers (Figs. 1x.37 and 1x.38); in part our skepticism is based on their qualitatively different shapes and slopes. For example, in Figure 1x.38 curves B–D have $P_{max} \propto 1/t_i$, whereas curves A, E, and F have $P_{max} \propto 1/\sqrt{t_i}$. If you intend to push these parts close to their limits, you may need to subject sample parts to your own testing (which, conveniently, we discuss next). Generally, though, it's better not to "twist the dragon's tail"; our advice is to derate resistors by 50%. Resistors of higher power rating can cost considerably more – in that case you can use the trick of connecting several low-power (and inexpensive) resistors in series or in parallel (the choice depending on whether you would be happier with "fail open" or "fail short.")

A. Do-it-yourself testing

The ever-creative John Larkin needed to find out the best choice for a 0.33 Ω resistor for a pulse-stress application. Not wanting to rely completely on datasheets, he built the apparatus of Figure 1x.39, which switches a bank of charged energy-storage capacitors across the victim resistor for a known duration, at a known repetition rate.[37] Being a friendly chap, he loaned us his gadget (Fig. 1x.40), which we promised to take good care of. But, um, the very first resistor we blasted emitted a fiery arc downward, causing a cascade that etched away the foil adjacent to the insulating gap (Fig. 1x.41). So much for taking care of valuable (and unique) borrowed equipment (sorry John). To make amends, we built a set of expendable bolt-on "mezzanine" daughterboards; as luck would have it, we have not experienced another foil-destroying explosion.

We tested to destruction many resistors with Larkin's toy, recording their final moments (with a 'scope), and their resting places (with a camera). Read on . . .

B. Overload to failure

At Larkin's suggestion, we modified the test jig to capture the current-vs-time waveform during extreme overload of a resistor; in this case we applied a 32 V dc step across several types of small 50 Ω resistors (thus 20 W dissipation in resistors rated from 0.25 W to 2 W). All but one were

[37] Based upon a set of measurements, he settled on the Vishay/Draloric type AC05 axial-lead 5 W cemented wirewound resistors.

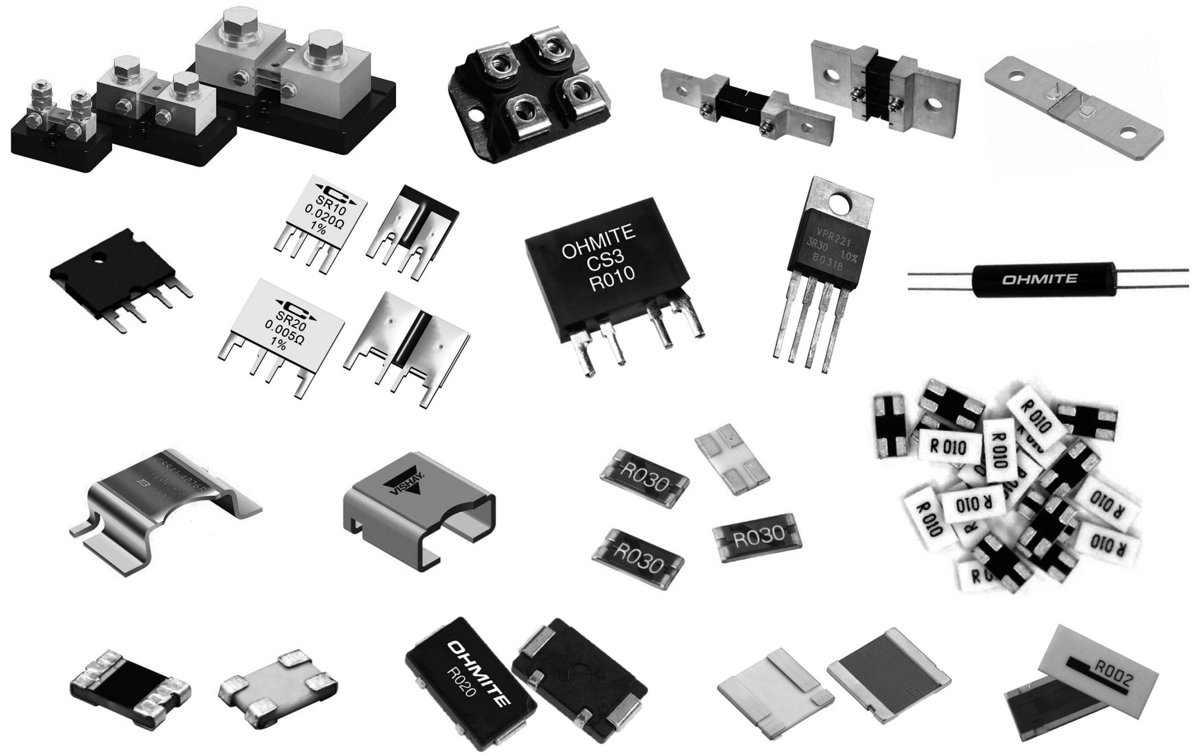

Figure 1x.36. Current-sensing 4-wire resistors range from tiny SMT parts to giant bolt-down 1000 A units. Shown here (not to scale!) are representative parts from six manufacturers (Bourns, Caddock, Ohmite, Riedon, Vishay Intertechnology, and VPG Foil Resistors; photographs used with written permission of the respective manufacturers).

surface-mount types, of size 1206 or similar, soldered to a pair of copper pads each 1″ square (6.5 cm^2).

The tests were, uh, both noisy and smelly, in most cases becoming incandescent while belching noxious fumes. Figure 1x.42 includes some carcasses, and Figure 1x.43 shows the death throes of five victims. In the latter figure the initial current of 640 mA corresponds to 3.2 vertical divisions.

Trace A is a "commodity thick-film" chip resistor ($0.005 each in full-reel quantity!), rated at 0.25 W, with no pulse-load specifications; it failed quickly (to an open circuit) at this 80× overload. Trace B is a 0.75 W "pulse-proof" variant ($0.05 each in full-reel quantity) from the same supplier (Vishay), which fares considerably better (lasting about 200 ms before partial opening, followed by arcing (the current spike around 1 s), some sputtering, and final failure. Its specified pulse endurance is curve B in Figure 1x.37.

Trace C is Vishay's 0.4 W CMA "high pulse-load" carbon-film resistor ($0.10 each in full-reel quantity), in a MELF (cylindrical SMT) package that is only slightly larger than the 1206-size rectangular SMT packages of traces A, B, and D. It does not fare any better than the CRCW-HP (trace B), but, interestingly, it fails through a low-resistance phase (off-scale current spike) before finally opening up. Its specified pulse endurance is curve A in Figure 1x.37.

Trace D is Vishay's 2 W PCAN "high-power aluminum-nitride" SMT resistor ($0.87 each in full-reel quantity), with enlarged terminations to carry heat to the mounting foils; here we're punishing it with a 10× overload, causing some intermittent current dips, but not enough to cause it to fail (even after 10 s). Its specified pulse endurance is curve C in Figure 1x.37.

Finally, trace E is the humble 0.25 W RC07-style (Ohmite OD-series) carbon-composition axial-lead (through-hole) resistor of yesteryear, with claimed "high surge capability" (curve F of Fig. 1x.37). These things used to be inexpensive, but nowadays you'll pay about $0.30 in quantity (50 times as much as a commodity SMT

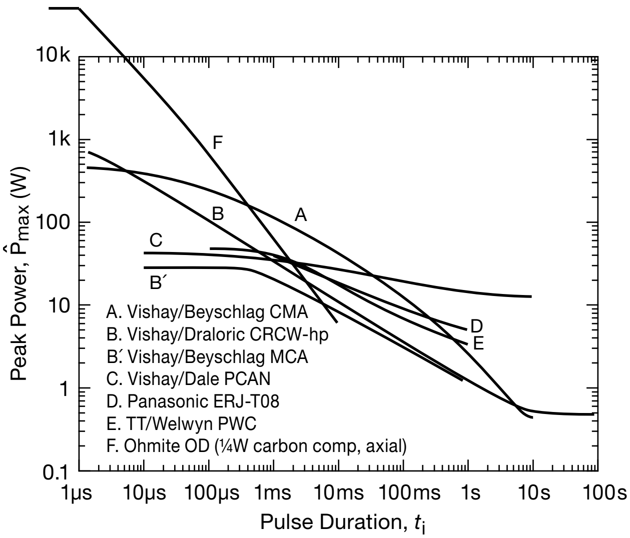

Figure 1x.37. Datasheet plots of single-pulse peak power versus pulse duration, for several pulse-rated SMT resistors. All are 1206 size (3.2×1.6 mm) except the CMA (plot A), which is a similarly sized MELF "0204" (cylindrical, 1.4 mm dia × 3.6 mm long) and the OD (plot F), which is an axial-lead carbon-composition resistor of approximate size "2510" (2.4 mm dia × 6.3 mm long).

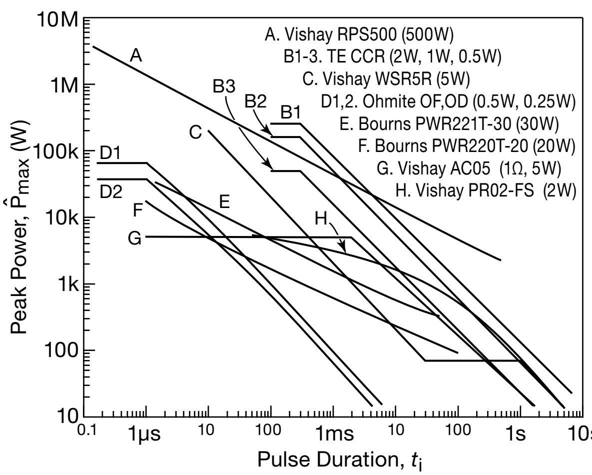

Figure 1x.38. Datasheet plots of single-pulse peak power versus pulse duration, for some larger pulse-rated resistors. Note that the "composition" types (B – ceramic comp, D – carbon comp) battle mightily their larger brethren, in spite of their diminutive size.

resistor). Its failure mode, like the carbon-film CMA, includes a low-resistance current surge and a fail-short endpoint. Its specified pulse endurance is curve F in Figure 1x.37.

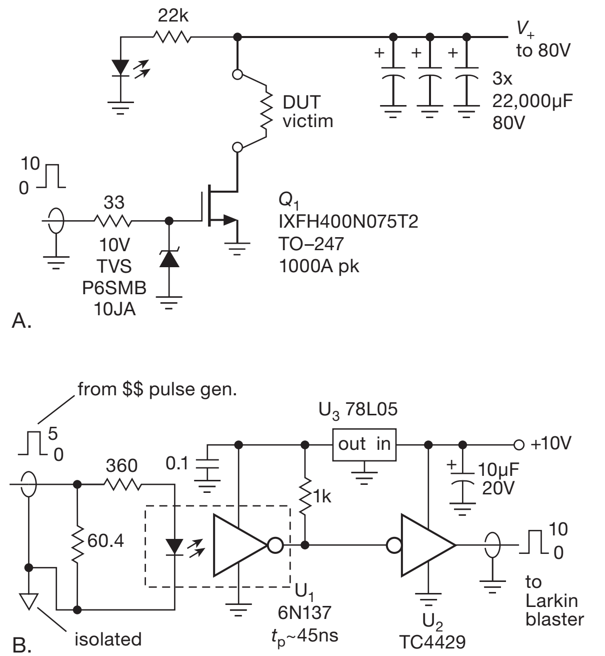

Figure 1x.39. John Larkin's pulse-power torture machine. A. A power MOSFET with plenty of muscle switches V_+ across the victim when the gate is pulsed. B. With hundreds of amps flowing (and hundreds of joules of stored energy), we added this isolated driver to protect our expensive pulse generator in the event of a catastrophic fault. (Larkin accused us of excessive caution – but he didn't offer to buy a new pulse generator.)

1x.2.7 Resistor dividers

In §1x.2.3, above, we pointed out that run-of-the-mill film resistors have voltage coefficients of order 10–100 ppm/V (see Figs. 1x.33 and 1x.34), making them unsuitable for precision voltage dividers, especially in high-voltage applications; the best (and pricey!) metal foil types do considerably better, with voltage coefficients in the 0.1 ppm/V range.

But if what you want is a precise voltage *ratio* that does not vary with applied voltage (and, what the heck, stable with temperature as well), you can do no better than a pre-built precision voltage divider. Manufacturers like Caddock are happy to oblige: their 1776-C68 series of precision decade voltage dividers, which cost about $10–15 in unit quantities, have a ratio voltage coefficient of 0.04 ppm/V max (100 to 1200 V), and a ratio tempco of 5 ppm/°C max. These parts have several taps, for example a 9 MΩ part has taps at 900k, 90k, 9k, and 1k (thus voltage ratios of 10:1, 100:1, 1000:1, and 10000:1). And their USVD2 and HVD "ultra-precision voltage dividers"

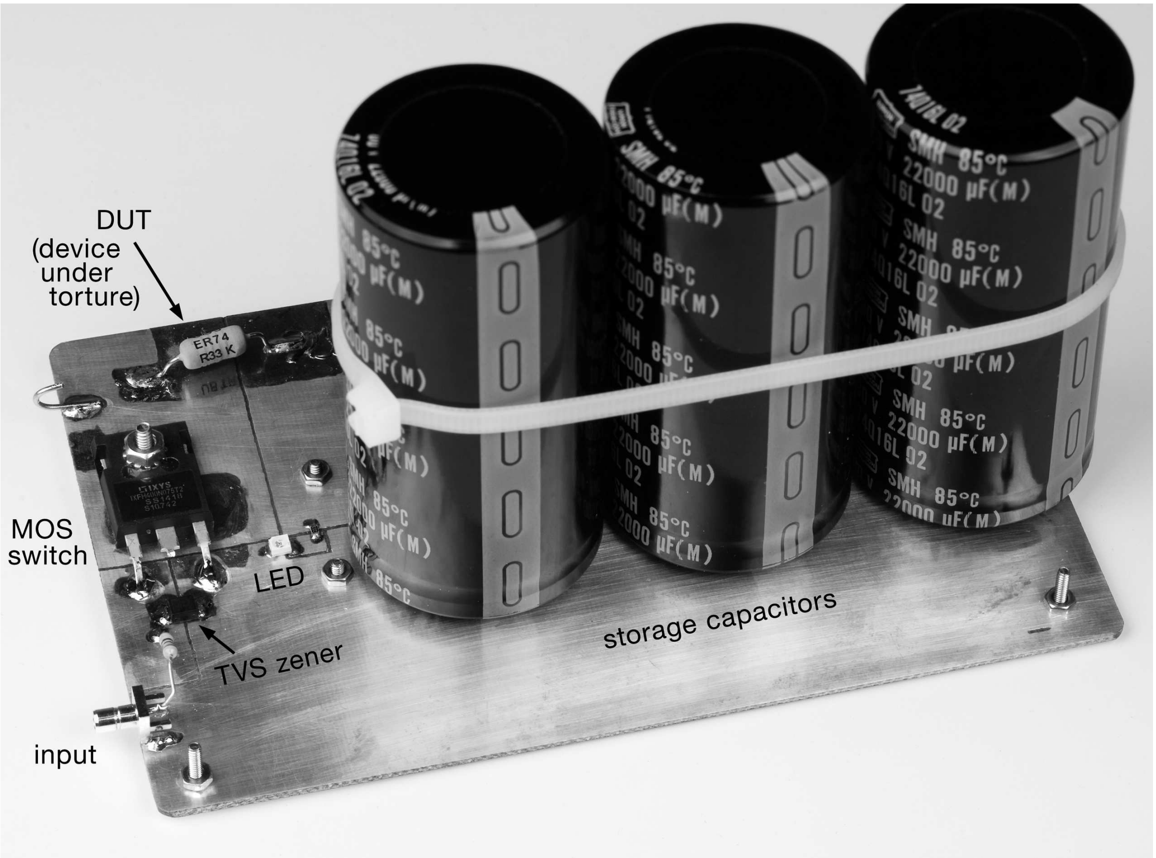

Figure 1x.40. Photo of the Larkin-blaster. An input pulse train switches on the hefty MOSFET (good for 1000 A peak current), putting the bank of charged capacitors across the resistor.

offer even better linearity: 0.02 ppm/V ratio linearity, and 2 ppm/°C ratio tempco. These go up to 5000 V ratings, with a single ratio (choice of 100:1 or 1000:1); they cost about $40 in unit quantities.

The above parts are intended for high-voltage dividers. At the other end of the spectrum, there are lots of precision dividers intended for low-voltage applications, such as single-ended and difference amplifiers, low-voltage dc supplies, and bridge circuits. You can get these from some semiconductor manufacturers (LTC/ADI, Maxim) and, of course, from the all-encompassing Vishay group. Some examples of the former are Maxim's MAX5490 series, and LTC's LT5400 series, both in surface-mount packages. The MAX5490 is a 100k SOT23-3 surface-mount part with standard ratios (set by the part number) of 1:1, 2:1, 5:1, 10:1, and 25:1, ratio tempco of 2–4 ppm/°C max, and ratio voltage coefficient of 0.1 ppm/V typ. LTC/ADI's part has four separate resistors (two matched pairs) in an MSOP-8 package, with ratios of 1:1, 4:1, 5:1, and 9:1, ratio tempco of 1 ppm/°C max, and ratio voltage coefficient of 0.1 ppm/V typ. These parts cost about $4 (Maxim) and $7–$20 or more, depending on grade (LTC/ADI).

Vishay aims at ultimate performance, with its metal foil (Z-foil) products (but you have to pay the price: $15 to $40 or more, depending on grade). Their wide selection comes in surface-mount (DSMZ, VFCD1505 series) and through-hole varieties (VFD244Z, VSH144Z, 300144Z, 300145Z, 300190Z–300212Z), with ratio tempcos from 0.1 ppm/°C to 4 ppm/°C typ (depending on resistance, ratio, and grade), and ratio voltage coefficients of 0.1 ppm/V max. Because these are constructed from metal foil elements, the resistance range is limited to a maximum of 100 kΩ. By contrast, the Caddock high-voltage parts go to 10 MΩ (1776 and USVD2 series) and 50 MΩ (HVD5 series).

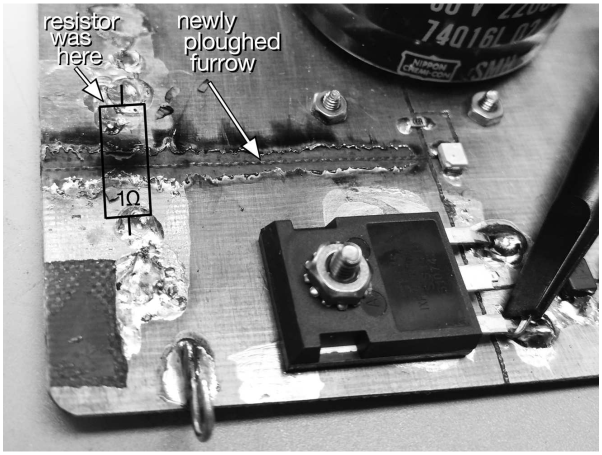

Figure 1x.41. Unexpected result of a 1 Ω 3 W resistor's final fire-belching act – the plasma erupted downward, causing a cascading arc that devoured the foil on facing sides of the gap (compare with Fig. 1x.40).

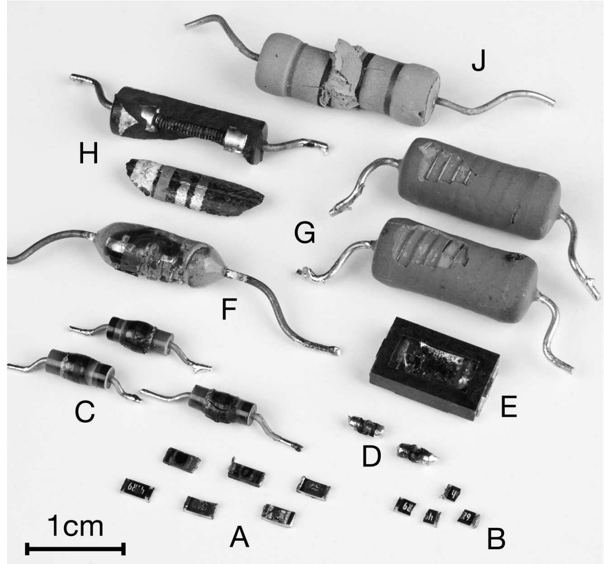

Figure 1x.42. Resistor graveyard: here are some residues of our resistor-torture experiments. A. SMT 1206-size parts that burned but were not consumed. B. SMT 1206 parts that blew into pieces. C. RC07-style 0.25 W carbon-composition resistors developed mid-section bulge. D. MELF carbon-film SMT parts also bulged. E. 5 W SMT 4527-size "power metal strip" resistor blew its top off. F. 3 W wirewound resistor belched fire. G. 5 W wirewound resistors exfoliated some of their skins. H. 2 W wirewound resistor exploded with a bang. J. 2 W ceramic composition was hard to kill, but 250 W for a half minute did the trick.

1x.2.8 "Digital" Resistors

The traditional mechanical potentiometer type of control has largely been superseded by the so-called digital potentiometer – an integrated series-connected array of fixed resistors, with the "wiper" replaced by an array of CMOS switches (Fig. 1x.44).[38] This has many advantages, some of which are (a) elimination of wiper noise, aging effects, and susceptibility to vibration, (b) electronic (digital) control, (c) cold switching, thus elimination of susceptible signal-carrying wiring, (d) accurate tracking of multi-ganged sections, and (e) small size. There are a few drawbacks, also – switch ON-resistance, distributed capacitance, digital signal coupling, limited voltage range, limited choice of resistance – but these are generally minor annoyances, certainly compared with the flaws of the traditional mechanically adjusted panel pot. Some manufacturers of digipots include Analog Devices, Intersil/Renesas, Maxim, and Microchip.

To give some perspective, old-timers will remember (and not with fondness) the early attempts to implement remote control of volume in amplifiers and TVs: a *motor-driven* panel pot! These graybeards will remember, also, the scratchy noise that accompanied rotation of volume controls in audio equipment (hence the admonition "never adjust a volume control while making a professional recording"). Digital potentiometers ("digipots") make it easy to control the setting with logic signals (SPI, I^2C, or UP/DOWN inputs); and they are free of scratchy-wiper noise (though they do exhibit switch-transition clicks). But don't confine your attention to panel-mounted controls – in fact, most digipots are used in trimming applications: sensor calibration, offset trim, current-source setpoint, voltage regulators, bias setpoint, laser drive current, and the like.

A. The digipot zoo

Digital pots come in a bewildering variety of styles and parameters, which we'll attempt to untangle in this section. Some choices include (a) total resistance, (b) number of steps, (c) volatile or non-volatile memory, (d) number of sections ("gangs"), (e) operating voltage range, (f) bandwidth, (g) linear or log steps, (h) digital interface, (i) ratio tolerance, resistance tolerance, and gang matching, (j) tempco, (k) wiper resistance, and (l) distortion. You can get an idea of the digipot family tree from Figure 1x.45, adapted from a figure found on Intersil/Renesas's 2017 product brochure.

[38] There are variations on this single-string theme, notably ADI's "segmented architecture," which reduces greatly the number of CMOS switches needed; see *Analog Dialog*, **45-08**, August 2011.

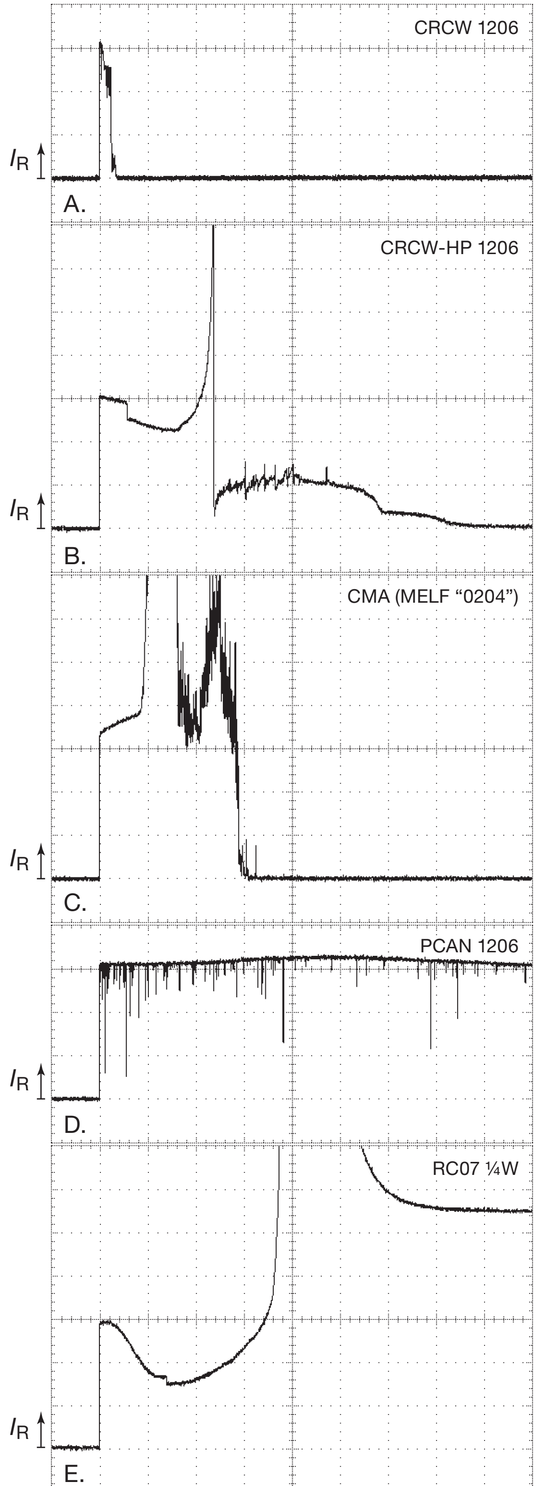

Figure 1x.43. We applied 32 V across a selection of 50 Ω resistors and watched their final moments. Vertical: 200 mA/div; Horizontal: 400 ms/div.

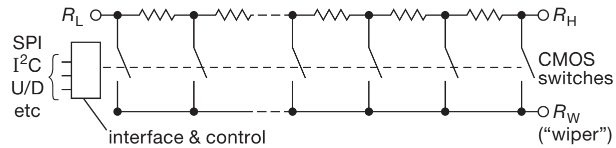

Figure 1x.44. A digital potentiometer IC consists of a series-connected string of resistors, with an array of digitally controlled CMOS analog switches to select the tap. The resistors may be of equal value ("linear taper") or configured to create steps of equal decibels ("log taper" or "audio taper").

Total resistance

Digipots are available in just a few total (end-to-end) resistance choices, ranging from 1 kΩ to 200 kΩ (and, rarely, 1 MΩ). Because many digipots are intended for voltage-divider use, they can have very loose tolerances of total resistance, up to ±25% or more; see below.

Number of steps

Most digipots have 64 to 256 taps, but you can get some with 1024 taps.

Volatile/non-volatile tap register memory

A mechanical pot remembers where you set it, and for many applications that's essential; hence the non-volatile (NV) digipot. Digipots lacking NV memory usually power-up to midscale or bottom.

Number of sections

For applications such as a stereo volume control, or tuning an analog active filter or Wien-bridge sinewave oscillator, you need at least two ganged pot sections. You can get mechanical multisection pots, and digipots offer the same option, usually duals or quads (or, rarely, six sections, e.g., the AD5206). Because of their simple digital control, you can always have as many sections as you want, by commanding multiple digipots to the same tap setting.

Voltage range

Digipots are CMOS devices, usually restricted to rather low total voltage ranges; typical are 5 V total (0 to 5 V, or ±2.5 V, with some "low-voltage" types specified down to 1.7 V total supply), but there are digipots available (particularly from ADI) that run up to 16 V total supply, and even to 33 V (e.g., AD5290, AD5293, AD7376).

Bandwidth

Digipots have internal capacitance, which creates an inherent *RC* roll-off that can be at surprisingly low frequencies. See, for example, Figure 1x.46, which plots the attenuation

NON-VOLATILE (EEPROM MEMORY)

- **Single 16-Tap (4-Bits)**
  X9116 - 10kΩ, Up-Down
- **Single 32-Tap (5-Bits)**
  $\boxed{D}$ X9314 - 10kΩ, Log Taper, Up-Down
  X9315 - 10kΩ / 50kΩ / 100kΩ, Up-Down
  $\boxed{D}$ X9511 - 10kΩ, Push Button
- **Single 100-Tap (~6.65-Bits)**
  X9317 - 10kΩ / 50kΩ / 100kΩ, Up-Down
  X9318 - 10kΩ, Up-Down
  X9319 - 10kΩ / 50kΩ, Up-Down
  $\boxed{D}$ X9C102 - 1kΩ, Up-Down
  $\boxed{D}$ X9C103 - 10kΩ, Up-Down
  $\boxed{D}$ X9C104 - 100kΩ, Up-Down
  $\boxed{D}$ X9C503 - 50kΩ, Up-Down
  $\boxed{D}$ X9C303 - 32kΩ, Log Taper, Up-Down
- **Single 128-Tap (7-Bits)**
  ISL22316 - 10kΩ, I^2C
  ISL22317 - 10kΩ, 1% Tolerance, I^2C
  $\boxed{E}$ ISL95311 - 10kΩ, I^2C
  $\boxed{E}$ ISL95310 - 50kΩ, Up-Down
- **Single 256-Tap (8-Bits)**
  ISL95810 - 10kΩ / 50kΩ, I^2C
- **Single 1024-Tap (10-Bits)**
  $\boxed{D}$ X9110 - 100kΩ, SPI
  X9111 - 100kΩ, SPI
  $\boxed{D}$ X9118 - 100kΩ, 2-Wire
  X9119 - 100kΩ, 2-Wire
- **Dual 128-Tap (7-Bits)**
  ISL22326 - 10kΩ, I^2C
- **Dual 256-Tap (8-Bits)**
  X95820 - 10kΩ / 50kΩ, I^2C
  $\boxed{D}$ X9268 - 50kΩ / 100kΩ, 2-Wire
  $\boxed{D}$ ISL22424 - 10kΩ, SPI
- **Quad 64-Tap (6-Bits)**
  $\boxed{D}$ X9408 - 2.5kΩ / 10kΩ, 2-Wire
- **Quad 128-Tap (7-Bits)**
  ISL22346 - 10kΩ / 50kΩ, I^2C
- **Quad 256-Tap (8-Bits)**
  X95840 - 10kΩ / 50kΩ, I^2C
  $\boxed{D}$ X9250 - 50kΩ / 100kΩ, SPI
  X9251 - 50kΩ, SPI
  X9252 - 2kΩ / 10kΩ, 2-Wire
  $\boxed{D}$ X9258 - 50kΩ / 100kΩ, 2-Wire
  X9259 - 50kΩ, 2-Wire

SPECIAL FUNCTION DCPs

- **Dual Audio DCP - Integrated Output Buffer Amps and Audio Detect**
  ISL22102 - 32kΩ, Log Taper, Push Button, 0 to -72dB Dynamic Range
- **Low Voltage 1% Tolerant Precision DCP & Low Temperature Coefficient**
  ISL22317 - 10kΩ, I^2C
- **TFT/LCD Programmable VCOM Calibrator (128 Step)**
  ISL45041 - I^2C
  ISL45042 - Up-Down
- **Military Temperature (-55°C to 125°C) Non-Volatile DCP**
  ISL22316WM (Single) - 10kΩ, I^2C
  ISL22326WM (Dual) - 10kΩ, I^2C
  ISL22346WM (Quad) - 10kΩ, I^2C

VOLATILE (NO EEPROM MEMORY)

- **Single 32-Tap (5-Bits)**
  ISL23511 - 10kΩ, Push Button
  ISL90461 - 10kΩ/50kΩ/100kΩ, Up-Down, 2-Pin, Rheostat
  ISL90462 - 10kΩ / 50kΩ, Up-Down, 2-Pin, Voltage Divider Only
- **Single 128-Tap (7-Bits)**
  ISL90726 - 10kΩ / 50kΩ, I^2C, Rheostat
  ISL90727/28 - 10kΩ / 50kΩ, I^2C, Voltage Divider Only
  ISL23318 - 10kΩ / 50kΩ / 100kΩ, I^2C, Low Voltage
  ISL23418 - 100kΩ, SPI, Low Voltage
- **Single 256-Tap (8-Bits)**
  ISL23315 - 100kΩ, I^2C, Low Voltage
  ISL23415 - 100kΩ, SPI, Low Voltage
- **Dual 32-Tap (5-Bits)**
  ISL22102 - 32kΩ, Log Taper, Audio Detect, Push Button
- **Dual 128-Tap (7-Bits)**
  ISL23328 - 10kΩ / 100kΩ, I^2C, Low Voltage
  ISL23428 - 10kΩ / 100kΩ, SPI, Low Voltage
- **Dual 256-Tap (8-Bits)**
  ISL23325 - 10kΩ / 100kΩ, I^2C, Low Voltage
  ISL23425 - 10kΩ / 100kΩ, SPI, Low Voltage
- **Quad 256-Tap (8-Bits)**
  ISL90841 - 50kΩ, I^2C
  ISL90842 - 10kΩ / 50kΩ, I^2C

$\boxed{E}$ Extended positive terminal voltage
$\boxed{D}$ Positive and negative terminal voltage

Figure 1x.45. This family tree of Intersil digital pots, adapted from their 2017 product brochure, illustrates a nice selection of parameters: resistance, resolution, interface, linear vs log taper, and volatility. Analog Devices offers an even larger selection (74 devices, each available with two to four resistance values as of this writing), but no handsome genealogical graphic.

versus frequency of a typical digipot, when set to attenuate 6 dB (code 40_H of a 128-tap pot). Digipots of lower resistance roll-off at higher frequencies, as expected, so you might feel comfortable choosing a 100 k digipot for an audio application. But beware – for a given digipot, the frequency at which its attenuation departs from what you expect depends on the tap setting, as seen in Figure 1x.47.

Taper

Most digipots (like most mechanical pots) have a linear “taper,” that is, the steps are of equal resistance increments. However, for audio applications you want a logarithmic (or “audio”) taper, corresponding to equal ratios, i.e., equal numbers of decibels. There are a few digipots with log tapers, as can be seen in Figure 1x.45. You may wonder why there are not more, given the common use of digipots in audio/video equipment. Good question! There

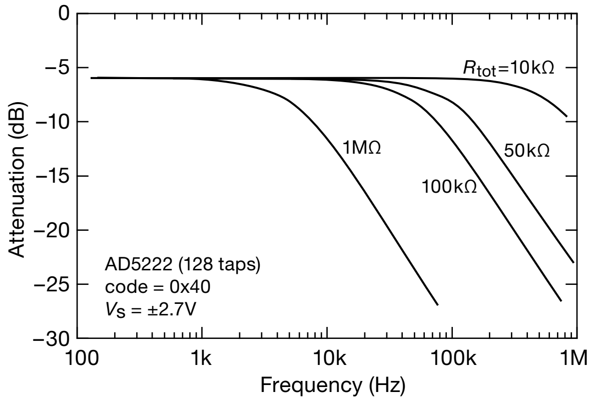

Figure 1x.46. Frequency response of the 128-step AD5222 digipot, in its four available total resistances, when set at half of full-scale.

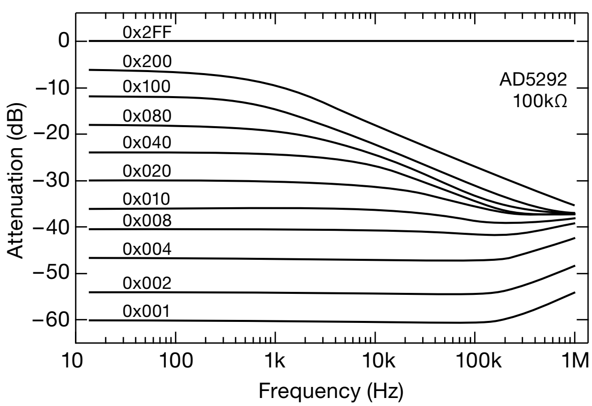

Figure 1x.47. The high-frequency behavior of digipots depends on wiper position, as seen in these curves from the AD5292 1024-tap digipot. This is reminiscent of analogous behavior in MDACs (§13.2.4).

are several reasons: (a) It's far easier to make a linear-step digipot, and that's often good enough for log steps – see Figure 1x.48, where we plot the error from perfect dB steps when using nearest-integer steps of a linear taper digipot. (b) For many audio/video applications, the signals are digital along the way, so an attenuator is just a digital multiplier, at zero cost! (c) Also, digipots exhibit unpleasant switch-transition spikes (see below); so even for analog audio gain stages, circuit designers sometimes use impulse-free variable-gain amplifier stages (such as the THAT2181) or digital programmable-gain amplifiers, microcontroller-adjusted from the setting of a (linear) digipot.

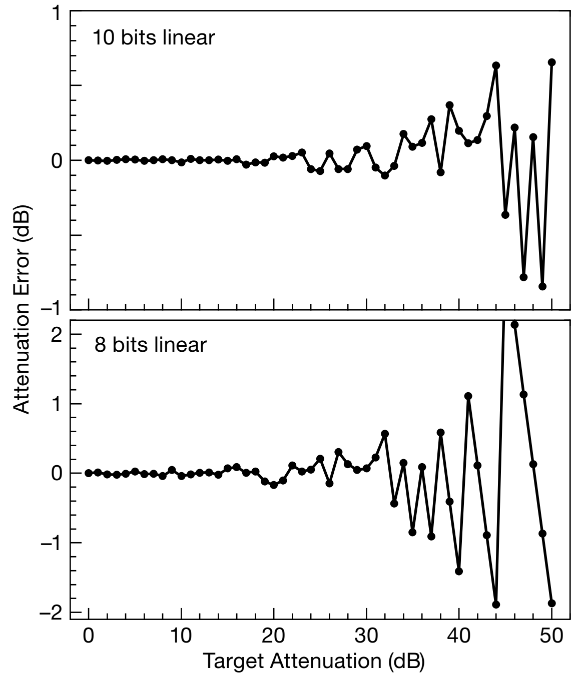

Figure 1x.48. You can get reasonably accurate log (i.e., dB) steps of attenuation from a linear decapot of 256 or 1024 taps, as seen in these plots of error. Note change of vertical scale.

Digital interface

Digipots are controlled digitally, with either the usual SPI or I^2C serial bus protocols, or with UP/DOWN control. The latter comes in two forms: one has a CLK input and a U/D′ input, and clocks up or down accordingly; the other kind (sometime called a "push-button" interface) has an UP input and a DOWN input, and connects easily to a pair of buttons (which may have to be debounced, check the specs).

Ratio tolerance, resistance tolerance, and gang matching

The majority of digipots are aimed at potentiometer use, that is, as adjustable voltage dividers; so they tend to have mediocre resistance tolerances, often ±25% or worse (if you want to use a digipot as a 2-wire adjustable resistor, you can get parts with far better resistance tolerance, 1% or so). But digipots do quite well in delivering accurate resistance *ratios*, usually specified in terms of differential and integral nonlinearity (DNL, INL), with typical values around ±0.1 LSB (and rarely worse than 0.5 LSB). Multi-gang digipots specify matching tolerances, typically 0.5 LSB.

Temperature coefficient

You'll usually see two values specified, one for "resistance tempco" (or "rheostat-mode" tempco) and one for "voltage-divider tempco" (or "ratiometric-mode" tempco). When used as a variable resistor, the tempco will be somewhere around either 20–40 ppm/°C or 500–800 ppm/°C (thin-film or polysilicon resistors, respectively), so be sure to check the specs carefully if you want a stable 2-terminal adjustable resistor. As you might expect, when used as a voltage divider these things are better, with typical ratio tempcos of ±5–20 ppm/°C. There are some standouts, for example the AD5291–92 (256 or 1024 steps), which specifies a ratio tempco of ±1.5 ppm/°C (typ), or the MCP42xxx-series from Microchip, with its ±1 ppm/°C (typ); the latter is particularly impressive, given its poor resistance tempco of 800 ppm/°C (typ).

Wiper resistance

The tap ("wiper") is a CMOS switch, with all the benefits and gremlins that accrue thereby. So it's got some series resistance (usually in the range of 10–100 Ω), which (as with all CMOS analog switches) depends on the rail-to-rail supply voltage (discussed extensively in §3.4.2B in AoE3). This rarely matters when you're using a digipot as a voltage divider with a high-impedance load, but it can be serious in 2-terminal (rheostat) mode, particularly for low-voltage digipots. Figure 1x.49 shows a nice example of the increasing R_W with decreasing supply voltage, and also the characteristic peak near the middle of the signal voltage range (when both nMOS and pMOS transistors find themselves with a V_{GS} of only half the supply voltage).

Distortion

For audio or precision applications you care about device linearity (i.e., change of resistance with applied voltage). Distortion specs are often omitted from digipot datasheets; Analog Devices, breaking this code of silence, is pleasantly forthcoming, with typical THD (total harmonic distortion) figures in the neighborhood of 0.01% for many of their parts. If you need better, try their AD5293, with THD of 0.0005% typ (1 Vrms and 1 kHz, a sweet spot for lowest THD); it boasts some other nice features, also, such as operation from 9–33 V total supply, ±1% resistor tolerance max, and 100 kHz bandwidth (flat, all codes).

B. Digipot cautions

Digipots are not perfect, as described above. Here we summarize some additional cautions – things to think about when considering using them (rather than a mechanical trimpot or panel pot) in a circuit.

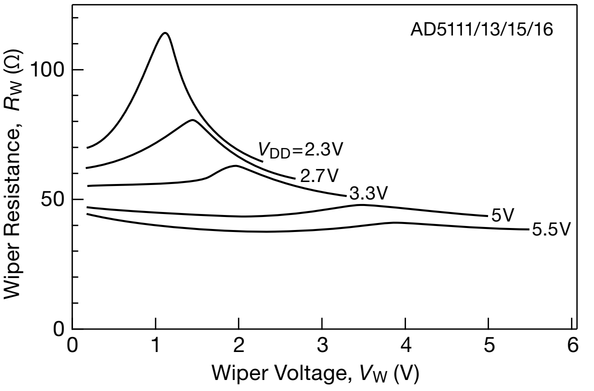

Figure 1x.49. Wiper resistance versus signal voltage, for several supply voltages, for the AD5111/13/15/16-series decapots.

Voltage, current, and power ratings

Most digipots are limited to swings between the supply rails, typically the CMOS value of 5.5 V total supply, whereas mechanical pots can handle far more, up to hundreds of volts (generally limited by power dissipation). Likewise, digipots are good only to a few milliamps and a few tens of milliwatts. Stick with mechanical pots if you need more.

Bandwidth–distortion tradeoff

High-resistance digipots roll off at distressingly low frequencies, but low-resistance digipots suffer from nonlinearity (owing to varying R_{on} of the CMOS switches). Both effects are largely absent in mechanical pots.

Zipper noise

Digipots exhibit switch-transition spikes, typically of microsecond-scale and in the neighborhood of tens of millivolts (but as much as a volt for some higher resistance parts). This is not good in an application such as a volume control. There are tricks to circumvent this problem, such as delaying the switching until the signal's next zero crossing. Mechanical pots are immune from zipper noise, but they get scratchy with time.[39]

C. Wrapup

Digital potentiometers really hit the spot when you want digital control of trims (amplifier or converter offsets, sensor calibration, bias or current setpoints) and where those

[39] We find that spinning them back and forth a few dozen times (or much more) can clean them up, especially if you can get some DeoxIT® Gold G-series contact cleaner into the guts. But more often they just refuse to return to their once silky-quiet state.

settings are within low-voltage and low-current circuitry. They are also excellent in applications where you need to have matching (multi-gang) adjustments. The least expensive digipots are hardly more expensive than analogous mechanical trimpots ($0.50 versus $0.30, in unit quantities), and they are compact and reliable. But there are plenty of applications where a simple mechanical trimpot works just fine, requires no interfacing or programming, is available in a wider range of resistance, and can handle much wider ranges of voltage, current, and power.