Basics of High Voltage Probe Design

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[Document Version: **1.21**] [Last Updated: **05/25/1998**]

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1. About the Author & Copyright

Basics of High Voltage Probe Design

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2. Personal Safety

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Read the associated document: "Safety Guidelines for High Voltage and/or line
power equipment" before attempting to work with high voltage systems.  High
voltage can jump amazing distances when you least expect it.  The direct or
indirect consequences of this can ruin your entire day or a whole lot more.
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3. Basic Considerations

Warning: DMMs may not be particularly forgiving of voltages on their inputs exceeding their specifications. Autoranging DMMs may be even more likely to blowout as they are selecting the correct range - if there even is one. Depending on your electrical and mechanical components, the chance of excess voltage due to arcover, leakage, or component breakdown may be a major consideration. My analog VOM has survived many close encounters with HV. You should not assume the same for the typical low cost or even expensive DMM. There is a reason for the high cost of commercial HV probes - these kinds of factors are incorporated (hopefully) in their design.

A simple high voltage probe for a DMM or VOM may be constructed from a pair of resistors. This is suitable for DC measurements but without compensation, will have a unknown AC response due to the very high impedance and stray capacitance forming a filter - low pass or high pass depending on the amount of stray capacitance and input capacitance of your meter or scope. However, this simple design is sufficient for the majority of consumer electronics work which are mostly DC measurements. I have not characterized the AC response of this probe design. However, if there is AC riding on your high voltage, it may mess up your readings if there is no compensation provided as it may act as a high pass filter.

To design the voltage divider, the input impedance of the meter must be taken into account. There is a minor but significant difference between DMMs and VOMs.

DMM: Z-in is usually constant, often 10 M ohms.

VOM: Z-in is the voltage range (full scale) times the ohms/volt rating of the meter.

Here is the basic circuit:

```
  High Voltage <------/\/\/\/\/\/--------+-------------> + to DMM/VOM
                           R1            |                      |
                                         \                      \
                                      R2 /                   R3 /
                                         \                      \
                                         /                      /
                                         |                      |
  Ground Clip  <-------------------------+-------------> - to DMM/VOM
```

R1 together with R2//R3 form a voltage divider where R3 is the internal resistance of the DMM or VOM on the scale for which the probe is designed.

While R2 is not strictly needed, it is recommended that it be included and approximately equal to the Z-in of the meter on the scale you will be using. The reason to include R2 is to insure that high voltage never can reach the meter. The ground clip should be securely connected to the metal chassis of the device being tested - the frame of a microwave oven or CRT grounding/mounting strap of a TV or monitor - before it is powered up. Both R1 and R2 should be located in the probe head.

The only difficult part is locating a suitable resistor for R1 that has high enough resistance and physically is long enough such that arcover is avoided. One company that comes to mind has a name something like Victoreen - they make/made radiation measuring instruments among other things that require really high value resistors. It can be constructed from several equal lower value resistors in series if they are all approximately the same size. Another possibility is salvaging the focus divider networks from dead flybacks or TV/monitor voltage multiplier assemblies. Even if the unit was discarded as being faulty, where there are no internal shorts in the HV rectifier or resistive network itself, the entire unit can be used intact.

In addition to basic safety precautions when working around high voltages, some form of equipment protection should be considered in provide an arcover path to ground should there be arcing over the surface of the resistor as well as if the resistor should somehow decrease in value. There is no telling what can happen under less than ideal damp or dirty conditions.

A 'corona','arc', or 'discharge' ring could be placed around the resistor near the low voltage end securely connected to the ground cable. The idea is that any arcing over the surface should find this as its destination before obliterating your meter.

A variety of devices could be placed across R2 to limit the maximum voltage present in the event of a breakdown. Suitable devices include neon light bulbs (NE2s without resistors); zener, avalanche, or ordinary diodes; or other semiconductor junction devices. Traditional surge suppressors like MOVs and Tranzorbs may work but their off-state impedance may be too low compared to R2). The neon bulb is good since its impedance is essentially infinite until its breakdown of 90 volts or so is reached. In some cases, these devices will be destroyed (semiconductors may short) but they will have served their protective function and are a small price to pay to protect you and your meter.

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4. Frequency Response Considerations

Probe compensation similar to that used on oscilloscope probes can be implemented. However, the determination of the capacitor values is beyond the scope of this note. To put it simply, the ratio of the capacitance C1:C2 (where C1 is across R1 and C2 is across R2//R3) needs to be equal to the ratio of R2//R3 to R1 (or equivalently, to the inverse of the voltage divider ratio). C2 includes the stray capacitance and input capacitance of the meter or scope probe. The capacitor across R1 would need to sustain the HV so that is another complication. Since a 10x scope probe usually has an input impedance of 10 M, the same design as used for the DMM would work with a scope. Although I have not pursued this issue, it sounds like based on the ratio (1000:1 would mean that C1 would need to be extremely small, probably smaller than the stray capacitance of the R1 and the associated wire) you would need to add a capacitance for C2 and that there will be enough stray capacitance such that no physical C1 will be needed.

If you are only interested in DC measurements, putting a .1 uF capacitor across R2 should smooth out any 50/60 Hz or higher frequency ripple.

The implementation of full probe compensation is left as an exercise for the motivated student.

Design example: 50,000 V maximum using a 10 M ohm Z-in DMM.

By my rule above, I will select R2 to be 10 M ohms. Fine adjustment of calibration could be made by making R2 out of a combination of a fixed resistor and a multiturn pot.

To minimally load the circuit under test, R1 should be as high as practical. Practical here means (1) low enough so that leakage over its surface is not a problem, (2) low enough that a reasonable voltage can be developed across R2//R3, and high enough so that loading of equipment being tested will not change the readings by more than a few percent.

R2//R3 is 5 M ohm. Selecting R1 to be 5,000 M ohm will give a 1000:1 ratio so that 50,000 volts will read out as 50 V on the DMM. 5,000 M ohm is high enough that loading of a 250 M ohm focus network should not be an issue (5%). 1000:1 is a nice easy to remember ratio. You could go to something higher if loading is still a concern but then leakage current over the surface of R1 becomes an even greater concern. Even 5,000 M ohm is about as close to an open circuit as you can get - any contamination whatsoever will change the calibration significantly. You may find that using a 1,000 M ohm resistor will result in less of a problem and accept the circuit loading that this value implies.

Design example: 50,000 V maximum using a 30K/V VOM.

This is a little more complicated because you need to pick a range and then calculate the Z-in for that range. for example, for the 100 V range of a 30K/V VOM, the Z-in will be 3 M ohms. For the same 5,000 M ohm R1 and 10 M ohm R2, you would get a reading of 23 V (roughly) on the 100 V scale for a 50 KV input. The divide ratio in this case is about 218.

It is a simple matter to determine a scale and an R2 such that the actual high voltage measurement is easily calculated from the meter reading. What you want is the ratio of R1 to R2//R3 to be a nice round number. Note that switching ranges will produce some peculiar behavior due to this current division between R2 and R3. A unique R2 must be selected for each range of interest. You are already using nearly the maximum sensitivity of the meter and switching to a lower range will only slightly change the position of the needle unless you construct a range switch box as shown below.

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5. Calibration

Unless you have a calibrated HV supply, a working TV for which you have the service manual makes a good starting point. The proper high voltage is usually specified to within 5-10%. If you have a line-transformer based HV supply (e.g., neon sign transformer, rectifier, capacitor), then this would be pretty accurate based on your power line voltage. For a DMM with a constant input resistance, you can use a low voltage (like a few hundred V) on a lower range and extrapolate for the HV range. However, for a VOM, you cannot use this technique since changing ranges also changes the parallel resistance of R2//R3. You are already using nearly the full sensitivity of the meter.

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6. Sample Circuit

I have constructed a high voltage probe from the surplus bleeder resistor from a defunct video terminal. For the probe tip, I used a discarded probe from a VOM. The resistor and probe tip were mounted inside an insulating plastic tube with R2 included at its base. A ground cable with an allegator clip provided the connection to the chassis. A second pair of wires with banana plugs connected to the meter via a switchbox which could select between a DMM or a couple of different scales on a VOM. Potting the entire HV head is a good idea to minimize the possibility of arcover. Remember that 50,000 V can jump several inches (2 inches in dry air approximately). See above text for other suggestions on equipment/you protection (which is not shown).

This circuit uses only a 203 M ohm high voltage resistor. Since the internal resistance of a typical focus divider network is 200-300 M ohm, this probe would obviously load such a circuit excessively.

```
                                       .
 High Voltage <----/\/\/\/\/-------+--------+-------------+-----o + to DMM/VOM
                      R1           |    .   |             |
                     203 M         |    .   \             |
               (15 W HV rated)     |    .   / R4          |
                                   \    .   \ 360K    SW1 |
                                R2 /    .   /            /
                                1M \    .   |         3 o o o 1
                                   /    .   |           | 2 |
                                   |    .   \           \   \
                                   |    .   / R5    R6  /   / R7
                                   |    .   \ 25K   1M  \   \ 810K
                                   |    .   / Adj       /   /
                                   |    .   |           |   |
 Ground Clip  <--------------------+--------+-----------+---+---o - to DMM/VOM
                                        .
                      Probe Head        .    Range Switch Box
                                        .
```

SW1 - SPDT Center Off Toggle Switch.
All resistors except R1 are 1/4 watt 2%.

50,000 V maximum based on the particular R1 I had laying around. 1000:1 voltage division.

SW1-1 = Radio Shack DMM on 3, 30, or 300 V scale (10 M Zin).
SW1-2 = VOM, 25 V scale (30K ohms/V, 750 K Zin).
SW1-3 = VOM, 100 V scale (30K ohms/V, 3 M Zin).

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7. General construction comments

(From: Duane C. Johnson (redrok@pclink.com)).

1. When you make the resister strings make sure that the maximum voltage rating of the resisters is not exceded. Most resisters have a maximum rating of 200 volts. In this case I would not excede 100 volts per resister.

2. Don't place the scope directly in series with the higher resisters. The first resister should be in parallel with the scope and and ground or the scope chasis.

   This detail is important for safety reasons. If the connection to the scope becomes disconnected then their will not be a dangerious shock hazard as would be the case if the scope was in series.

(From: Larry G. Nelson Sr. (nr@ma.ultranet.com)).

You can do this with a high voltage resistor divider network. That is what is in a high voltage probe you would buy. This can be very dangerous to you and your equipment in the event of a failure. Please be very careful. I suggest a fuse at the probe input and an MOV across the resistor to ground that will connect to the scope and use a plexiglass tube to put it all in to contain the bits if anything blows up.

(From: Kevin Astir (kferguson@aquilagroup.com)).

With respect to preventing high voltage arcing and corona, *do not* use RTV.

Places that carry the GC line will have some 'anti corona discharge dope' often called 'Q-dope'. This is *the* stuff to use at HV. You can clean it off with acetone when you discover that you didn't clean flux off good enough and have an arc underneath. Epoxy and RTV have no such advantage, and RTV releases corrosive acid while curing to boot.

Heed the warnings of other respondants WRT resistor voltage. As they said 100 V per for garden variety resistors will yield a safe margin. 200V is typical max rating.

There are special HV resistors (up to 10 KV or so) made, available into the G Ohm range. I don't know of a hobbiest source however. If you know anyone who works in nuclear instrumentation field they may be able to snag one for you. (HV used as detector and PMT bias in radiation detectors). This is what will be inside "real" HV probe from Fluke, or Tektronix.

Finally, I have a lot of experience, and am fairly blase around HV, but in addition to "normal" 115V AC rules, (no rings, one hand in pocket, etc.) I *never* work on HV stuff (not even a TV or hi-pot test) alone. And, I make sure the 'observer' knows CPR, even if I have to wait 2 days to fix TV, so girlfriend can 'help'.

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8. High voltage probe frequency response

(From: Winfield Hill (hill@rowland.org)).

You can calculate this for yourself. The parasitic lead-to-lead capacitance of a typical small resistor is 0.05 to 0.2pF. The capacitance from the *middle* of the resistor and from any connection node between series resistors, to ground, may range from 1pF to 5pF or more depending upon your choice of a sheilding scheme. Longer glass resistors intended for high voltages have lower lead-to-lead capacitance, but higher distributed parallel capacitance.

As a worst case, imagine a 1000 M ohm probe made with a 2-inch long resistor. To start, place the capacitance to ground from the midpoint. If you assume 5pF of parallel capacitance, you'll see you're in trouble even at 60Hz!

* HV probes with usable high frequency response may have cleverly arranged sheilds which can be connected to ground, the attenuated signal output, and the input. Some shields may overlap and may be adjustable, to provide an adjustable capacitive divider that can swamp the remaining effects of the resistor's capacitance.

* These probes can be very accurate at DC and high frequencies, but the skill of the designer is tested in the transition between resistive and capacitive divider action. They can be very badly behaved in this transistion region. Basically the "center" of the resistor experiences a bypass to ground (a severe dip in gain) or due to other HF components, a severe peak in gain. This can easily be 50% and cover a decade. Typically it'll happen at 20 to 100 KHz.

  One solution invokes the capacitance from a few carefully-placed concentric sleeves connected to the input and the signal output, plus an overall shield or guard connected to ground.

* Poorly designed probes can suffer from mid- or high-frequency errors and from severe pickup sensitivity to nearby rapidly-changing voltages. For example, I've seen probes that provide an output even when the measuring tip is grounded!

The classic low-voltage probe architecture of a pair pf RCs doesn't work for HV scope probes, unless (1) you're willing to have an overly high capacitive loading, or (2) you don't care about mid-frequency or pulse-shape response accuracy. This is because the RES1 value will be very high, 100M or more likely 1000 M ohms, and physically long and large. So the real circuit is like:

```
                +------------ CAP1 -------------+
                |                               |
Probe tip o--------- Rs -*- Rs -*- Rs -*- Rs -------- etc
                         |      |      |
                         Cs     Cs     Cs
                         |      |      |
                        Gnd    Gnd    Gnd
```

Because the Rs are so high, the probe becomes a good antenna, and a shield is mandantory. Therefore the Cs "stray" capacitance is higher than you might think. I think you see the problem.

One solution is to make C1 very large, but it's just a matter of specs - if you want 1% performance over the whole range, C1 is a severe load. There is a good overall solution, which I think is fairly clever (after thinking of it, I discovered the experts had beat me to it!).

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9. High voltage probes for AC measurements

(From Winfield Hill (hill@rowland.org)).

The usual method is simply to use a capacitive divider, a small 1 kV capacitor, etc., or make the HV capacitor yourself for really high voltages, like 5 to 20 kV, use an air neutralizing capacitor, etc.

Say for example, its a 3pF capacitor. With shields. With another more conventional capacitor, say 3000pF for the bottom of the attenuator, followed with a voltage buffer if desired, and you've got a nice wideband 1000:1 HV probe installed in the system, good for mucho kV.

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10. Commercial high voltage probes

(From: Frank Miles (fpm@u.washington.edu)).

Both Tektronix and Hewlett Packard sell HV probes rated at 5kV and up. Bandwidths are (at least) into the 100kHz area, probably more. I imagine there are others.

The older Tek probes even had ports to refill with now-banned chemicals. The newer ones don't, but are more expensive.

Frequency response is a significant concern. Designing and manufacturing a decent HV probe is definitely non-trivial if you need flat frequency response. Many parts have significant voltage coefficients, too, as well as breakdown voltages.

(From Winfield Hill (hill@rowland.org)).

A significant part of the design effort (and cost) deals with, the problem of how to go smoothly from a resistive divider at low frequencies, to a capacitive divider at high frequencies, while keeping a constant attenuation value at mid-frequencies. This isn't easy. Consider for example, that an overall shield is clearly needed and must properly prevent the high-Z end of the probe from simply acting as an antenna (as some HV probes do! i.e. ground the tip of the probe and *still* see large signals at the output). This shield acts as a capacitance to ground for the HV resistor, routing some of the high-frequency current which is supposed to go to the output, to ground.

```
Hence at some middle frequency there's a dip!  This is solved in various ways
- with shields connected to the probe tip (but inside the ground), capacitors
bypassing the resistor, special resistor construction, etc.  Most solutions
can just as easily cause a region with a response hump, as well as a dip, or
even both.  BTW, these problems are much harder if one seeks to make a probe
with very low capacitive loading and high frequency response.  The Tek P6015A
probe is 3pF, and you'll also note it has a veritable raft of response
adjustments on the scope-input end.

Much of the cost of the probe is knowing how to do all this!

Incidentally, a low-cost intermediate-range HV probe is the Fluke PM9100,
which is a 4kV 100:1 probe with a 200MHz bandwidth.  Also the Tek P5100 is
rated to 2.5kV.  Most of these probes also have a derating above some d
frequency.

Most of this mess you can avoid entirely by not attempting to make the probe
measure DC (or at least not the whole frequency range).
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