MINI METROLOGY LAB

Build a Kelvin-Varley voltage divider to complete the mini metrology lab.

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THE FIRST TWO PARTS OF THIS SERIES showed how to build a voltage standard and a null detector. This final article shows how to build a precision voltage divider to complete the mini metrology lab. The voltage divider is a key component of the measurement lab because it allows both larger and smaller voltages to be compared to the voltage standard. It can also act as one side of an ultra-precise resistance bridge, allowing many different values of resistance to be compared to a single known resistance standard.

Of the many types of divider schemes, the Kelvin-Varley divider (KVD) is one of the most useful and desirable because it combines both superb ratio accuracy and high resolution. Found almost exclusively in calibration labs, the KVD is used for the most critical calibrations and measurements.

Commercial KVDs are often accurate to 1 part per million (PPM) or even 0.1 PPM. Unfortunately prices for commercial units start at about $4000, and can easily exceed $10,000. The cost of precision wirewound or bulk metal-foil resistors, multi-deck switches, and substantial hand labor, conspire to keep commercial KVDs beyond the reach of experimenters.

So can you build a decent KVD without breaking the bank? Absolutely! We'll get into the details shortly, but here are a few specifications to whet your appetite. Our KVD is a full six-decade device, just like the commercial ones. It will resolve 1 PPM. Though the design goal was an absolute accuracy of 20 PPM or .002%, the prototype was twice as good—it was better than 10 PPM at all settings! The total cost of the project is under $75, but a well-stocked junk box can reduce that substantially.

How does it work?

The best way to understand how a Kelvin-Varley divider works is to look at just one decade, shown in Fig 1. There are 11 resistors in the main divider string, but two of them are in parallel with the output divider, in this case, a potentiometer. The value of the output divider is chosen so that the parallel combination of it and the other two resistors is equal to one step of the main divider. Thus, the circuit is the equivalent of a simple ten-resistor divider.

No matter where on the main divider the output divider is placed, the circuit that results is always a ten-resistor divider. Since the output divider is a potentiometer, any voltage between the two tap voltages can be selected.

The simple output divider (potentiometer) can be replaced by another decade constructed in the same manner as the first.

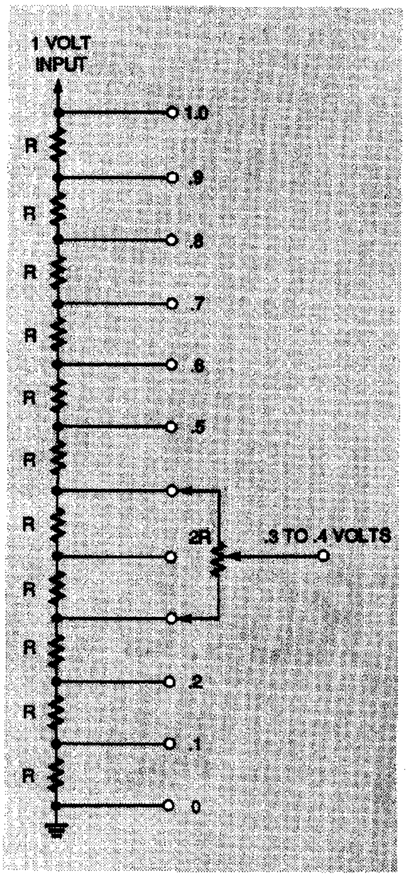

FIG. 1—A SINGLE KVD DECADE. Note that the circuit is equivalent to a 10-resistor divider.

The decade must, of course, have a total resistance equal to twice the resistor value used to construct the first decade. Each additional decade increases the *resolution* by a factor of ten. In theory you can add as many decades as you want, but the divider *accuracy* is always limited by the first decade.

The last decade is a simple ten-resistor divider, since there is no divider in parallel with any of its elements. The top position is the "carry" position, so full output from the KVD will be 9-9-9-9-9-10. Sometimes, a potentiometer is used for the last decade, giving continuous resolution over the full range of the divider.

Figure 2 shows the full KVD configuration. Trimmer networks have been added so that any decade can be shunted to the correct total value. That way you have to be concerned only with resistor matching, not exact resistor values.

You might notice that the resistor values used in each decade set an absolute minimum value for the following decade. The traditional series is 10K, 2K, 400, 80, 16, and 3.2 ohms, with no shunts. This KVD is designed to use standard value resistors, and to have reasonable value shunts. Thus, the values are somewhat different. Remember, you can only shunt a decade one way—down!

PARTS LIST

All fixed resistors are metal film, RN55D, 1%, or better. See text for selection process.

R1–R11—10,000 ohms, selected
R12–R22—2050 ohms, selected
R23–R33—412 ohms, selected
R34–R44—100 ohms
R45–R65—24.9 ohms
R66—806,000 ohms
R67—825,000 ohms
R68—4220 ohms
R69—499 ohms
R70—100 ohm multiturn trimmer
R71, R72—50,000 ohm multiturn trimmer
R73, R74—1000 ohm multiturn trimmer

Connectors

J1–J6—12 Pin Header, Molex 26-48-1121
P1–P8—3-Position Connector, Molex 09-50-8031
J7,J8—5-way Binding Posts, Red
J9,J10—5-way Binding Posts, Black

Miscellaneous

Terminals, Molex 08-52-0072, (Digikey WM2302-ND), case, small rubber grommets, epoxy, hot glue or cyanoacrylate, hookup wire, 22 AWG, insulated, multistrand (two colors required) 9V batteries (3), resistors for comparison bridge (2K, 49.9K), trimmer potentiometer for comparison bridge (1K, multiturn), brass strip (.015" thick, or similar)

Note: For those needing lower temperature coefficient and greater stability, precision bulk metal foil resistors can be ordered in small quantities from: Vishay East, #1 Precision Place, Hagerstown, MD 21742; (301) 739-8722 or Vishay West, 3431-I Pomona Blvd., Pomona, CA 91768; (909) 594-6737. High quality ceramic rotary switches are available for this project from the author. Please inquire as to price and availability: Conrad Hoffman, 4391 County Road #1, Canandaigua, NY 14424-9611; E-mail 73260.2255 @compuserve.com

Design issues

One of the biggest problems in designing this project was finding an affordable way to do the switching. Older KVDs used unique rotary switches which had dual multiple leaf wipers and large brass lugs for contacts. The high contact pressure resulted in very low resistance. Most modern KVDs use high quality two deck wafer switches. Unfortunately, the old switches are no longer available, and the modern replacements are quite expensive. However, the switch design presented here will fit anyone's budget- the "switches" cost just over a dollar each!

The decade resistors are mounted on six twelve-pin headers. Switching is done by moving a plug up and down the header. A three-hole plug is used, with only the end holes connected to the next decade. The physical layout very much resembles the schematic, helping to reinforce the principles of KVD operation. It is also reminiscent of early dividers and bridges that used brass plugs to make connections between adjacent resistors.

The other design issue is the type of resistors to use. Wirewound or bulk metal-foil resistors would be ideal, but they would cost several dollars each, pushing the cost of the KVD out of many people's reach because of the tolerances and quantities required.

The best easily obtainable resistor is the 1% metal-film type. Its temperature coefficient or tempco is not the best, and its stability isn't well characterized, but those factors can be worked around. If the resistors are selected carefully, and they are put to work over a reasonable temperature range, they can provide quite acceptable performance. However, it is important to check the ratio accuracy occasionally. Although I had some doubts about

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tempting this project with commonly available resistors, the results have been excellent.

Selecting resistors

You must select resistors for the divider out of a batch of ordinary 1% metal-films devices. Even though 1% is more than two orders of magnitude worse than what we need, any given bag of 200 resistors is almost certain to contain at least one suitable set, and usually more than one.

The process of selecting eleven resistors that are matched to better than 40 PPM is not difficult, merely tedious. To make the job as easy as possible, you can build a comparison bridge with "quick insertion" clips, just like commercial bridges use.

A simple comparison bridge circuit is shown in Fig. 3. Build it on some scrap perforated construction board, and be sure to use a multi-turn trimmer potentiometer, or the bridge will be impossible to zero. The resistor clips are made from .015-inch brass, cut with scissors and bent with needle nosed pliers. Drill the brass strips, deburr them, then clean them with steel wool before bending.

Bridge power is supplied from three 9-volt batteries in series. The best detector is the null detector described last month. However a DVM that can resolve 0.1 millivolt is also acceptable. With a resistor installed on the

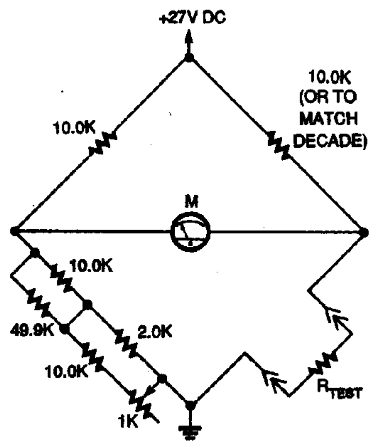


FIG. 3—BUILD THIS COMPARISON BRIDGE to match resistors for the KVD.

clips, you should be able to zero the bridge by adjusting the trimmer potentiometer. Note

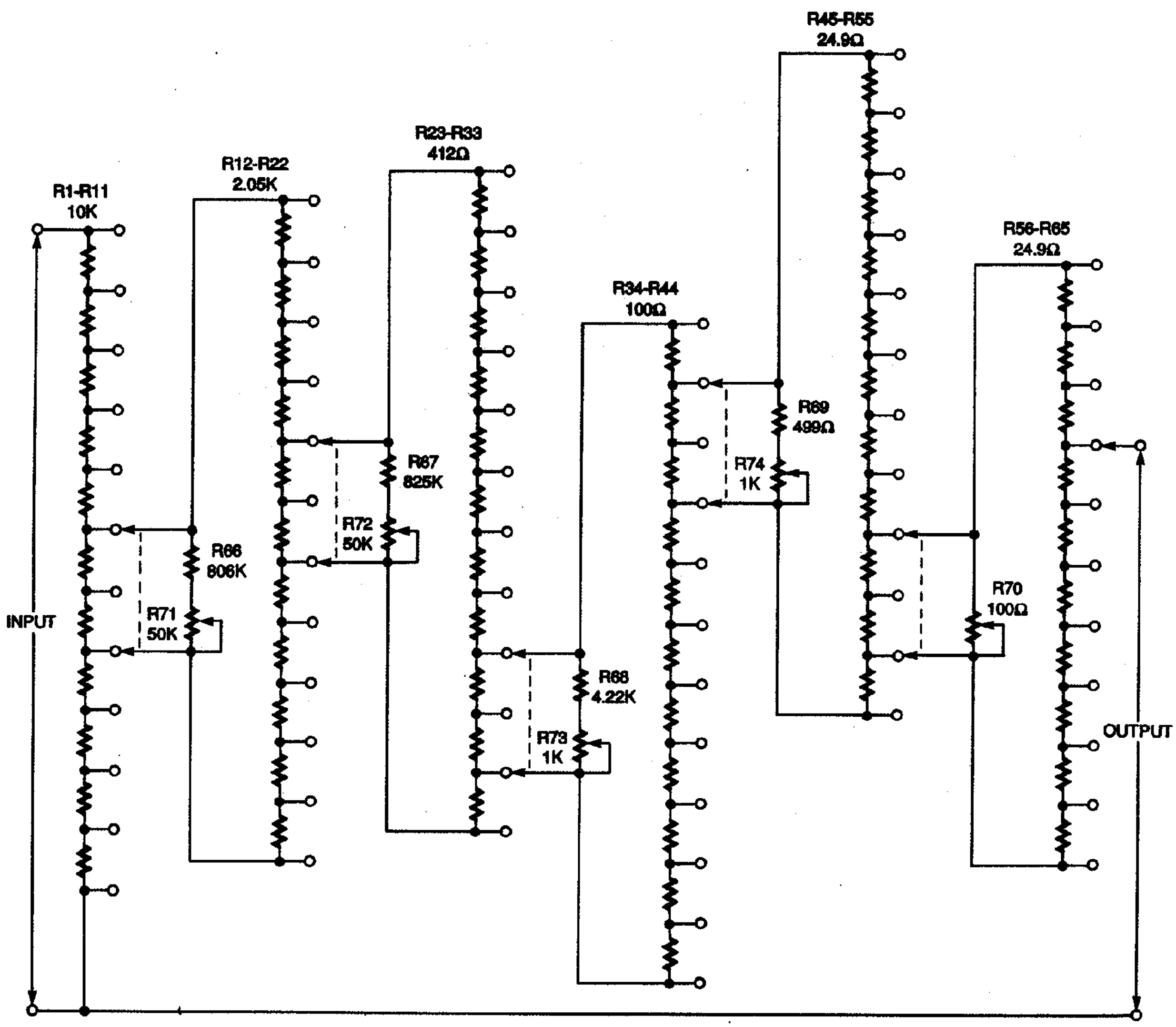


FIG. 2—THE COMPLETE KELVIN-VARLEY DIVIDER. The setting shown equals 0.45187.

that it takes 10–20 seconds to get a stable reading to the precision you need.

The first order of business is to get an idea of the average value of your resistors, and sort them into roughly matched groups. Since all of the resistors have values within 1%, the bridge will be nearly balanced at all times. You will not have to re-zero it; instead, just read the deviation on the null detector (or DVM). The bridge has a very narrow range of adjustment. You might have to pad one of the upper legs slightly if it won't zero.

An excellent way to keep track of the resistors is to use a piece of perforated construction board as a sorting board. Put a piece of masking tape on the long edge and label the holes. Start with zero in the center, then 10 millivolts per hole, going outwards from zero each way. Minus should be on the left. You will soon see where most of the resistors fall, and can re-zero the bridge to put this value in the center. I find that a four by six inch board is enough. If the average value is near the center, resistors off the edge are unlikely to match, and can be put aside.

Measure each resistor, put it into the appropriate hole in the sorting board. As you test more and more resistors, the sorting board becomes a visual histogram of the resistor values!

With luck, there should be several columns with high numbers of resistors. Separate these columns, combining them with the columns on either side. Measure these resistors again, increasing the sensitivity of the detector, and sorting them every 1/2 millivolt.

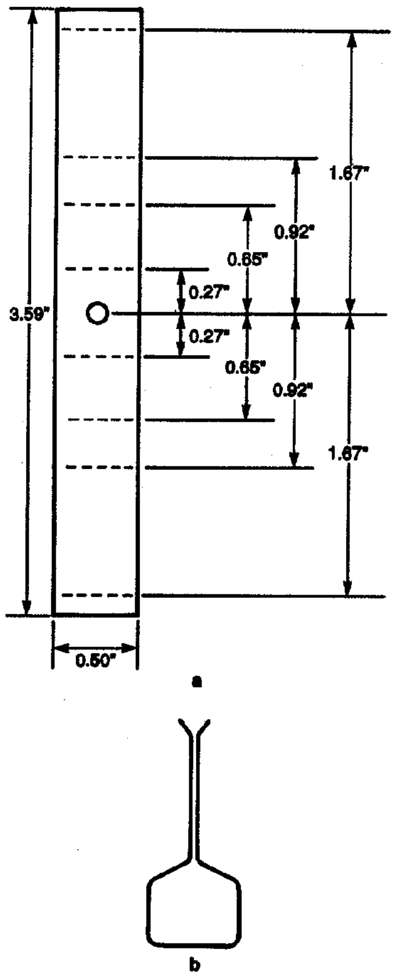


FIG. 4—BEND A 0.015-inch BRASS STRIP as show to form a clip for inserting resistors into the comparison bridge.

From adjacent columns, it should be possible to find 11 resistors that are all within 1/2 millivolt of each other, and hopefully, a few spares. No doubt there will be a few people who don't "win" on the first bag of resistors. If this is your fate, either order another bag, or live with a bit lower accuracy.

Once you have resistors for the first decade selected, remeasure them a few times until you have confidence that all the parts are within a 1/2 -millivolt window. Congratulations, the hardest part is over!

Select the resistor sets for each subsequent decade in the same manner. You will have to change the reference resistor in the bridge for each value. The required match for each succeeding decade becomes less critical. The last three decades don't require matching, but I like to check them on a DVM just to be sure they are close. See Table 1 for values and matching requirements.

Assembly

The connector headers are epoxied to the top panel of the enclosure. I used a piece of phenolic sheet, but a piece of circuit board material would work equally as well. Remove the copper by etching or peeling it off.

Figure 5, a 1:1 copy of the panel layout, makes a handy drill template. Just tape a copy of it in position on the panel, then use a center punch to mark the holes. Drill on the punch marks. Clean everything carefully, then epoxy the connector headers in place. Try to keep the epoxy off the pins. Small rubber grommets in the wire exit holes will protect the wires and give the unit a more finished appearance.

Solder the decade resistors to the underside of each header as shown in the photo. Since excessive heat can change the resistor values, be sure to leave the leads long and heat-sink each lead while soldering. A pair of long nose pliers can be used as a heat sink.

The padding networks are at-

TABLE 1—MATCHING REQUIREMENTS

KVD Decade	Resistor Value	Resistor Match	Bridge Offset with 27V Applied	Padding Network (Typical)	Padded Value
1	10KΩ	±0.0037%	±0.25 mV	-	-
2	2.05KΩ	±0.037&	±2.5 mV	820K (806K+50K pot)	20K
3	412Ω	±0.37%	±25 mV	844.6K (825K+50K pot)	4.1K
4	100Ω	±1%	-	4.68K (4.22K+1K pot)	824Ω
5	24.9Ω	±1%	-	1.01K (499Ω+1K pot)	200Ω
6	24.9Ω	±1%	-	62.25Ω (100Ω pot)	49.8Ω

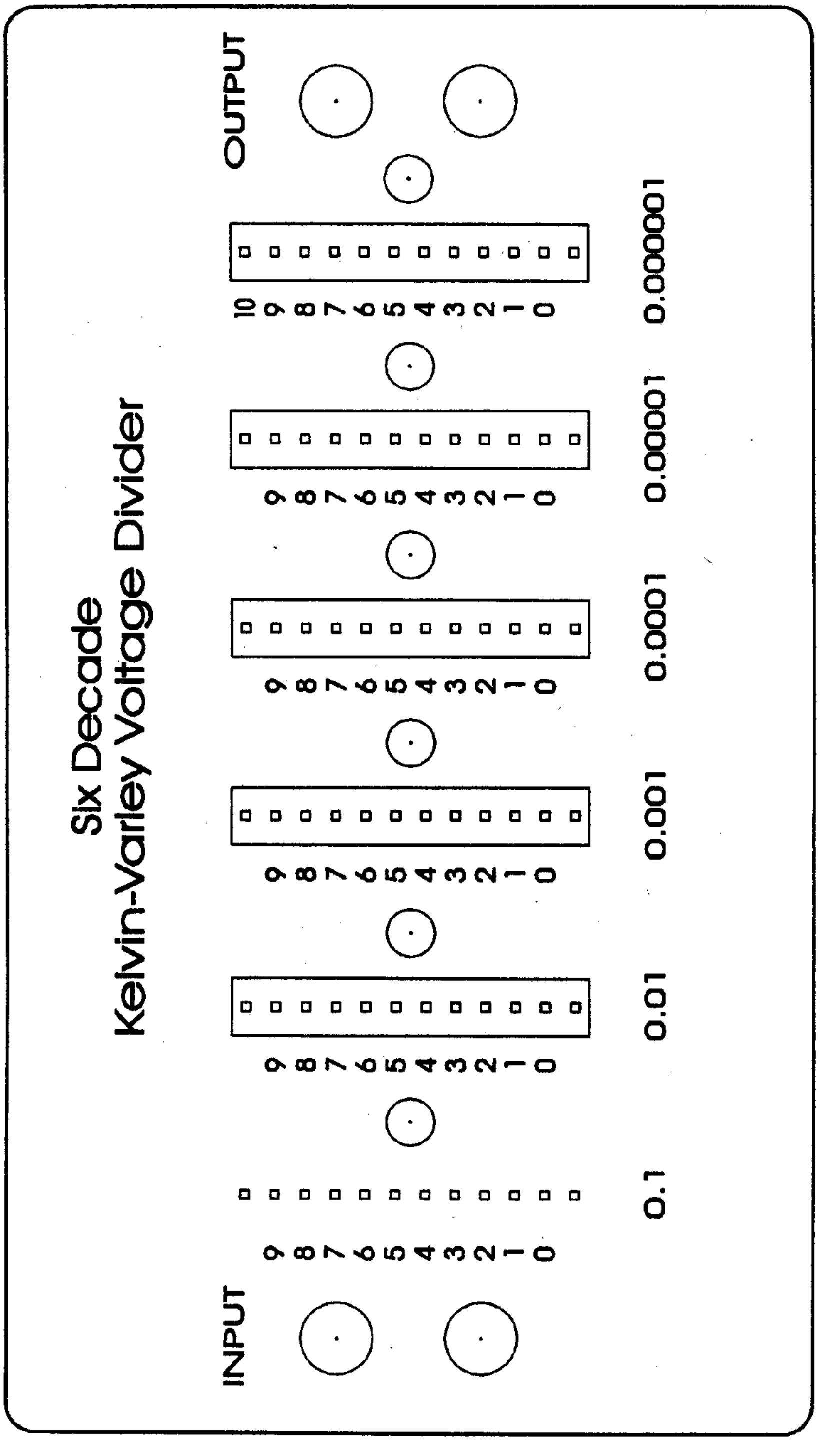


FIG. 5—THE KVD FRONT PANEL makes a handy drilling guide. It is shown full-size here.

tached across the full decades, and can be held in place with a drop of hot glue or epoxy. Each decade connects to its plug via a 6" twisted wire pair. Since the plugs are reversible, use two different colors of wire to avoid confusion. The plug for the last decade uses only one wire, so you may want to saw off the unneeded portion. Also, cut off the unused header pin from the same decade.

If you build a KVD using rotary switches, you will have to work out the connections for the particular switches you use. Generally, the resistors will be mounted in series around one of the decks, and the other deck will be wired in parallel, but offset by two positions.

Adjustment

The final step is to adjust the padding networks. This step has the potential to be confusing, so study the figures and instructions carefully. What you will do is attach clip-leads to turn each decade into a Wheatstone bridge, with the previous decade included as one of the bridge's arms. It is then a simple matter to adjust the previous decade and null the bridge.

This technique isolates each decade, and is the only way to accurately adjust the KVD. Do not attempt to adjust the decades with an ohmmeter, because it is not accurate enough, and the multiple current paths will give incorrect readings. Note that the voltages used are common battery voltages, if you don't have a suitable power supply handy.

1. Start with the output decade (No. 6). Attach power supply, the null detector, and a shorting lead to decade No. 5, as shown in Fig. 6. Because the resistances are low, do not apply more than 3 volts DC. Adjust the trimmer network on decade No. 6 for null.
2. Shut off the power and carefully move all of the clip-leads to the next decade (No. 4). Apply 3 volts DC and adjust the trimmer network on decade No. 5 for a null reading.
3. Move to decade No. 3 and adjust the trimmer network on decade No. 4, using about 9 volts DC.
4. Move to decade No. 2 and adjust decade No. 3, using about 18 volts DC.
5. Finally, move to decade No. 1 and adjust decade No. 2. Use 27 volts DC and make this adjustment as carefully as possible.
6. Recheck all the decades until you are confident that they are stable and correctly adjusted.
7. Finish up by installing the KVD in its enclosure

Making precision measurements

The simplest application of the KVD is to measure voltages

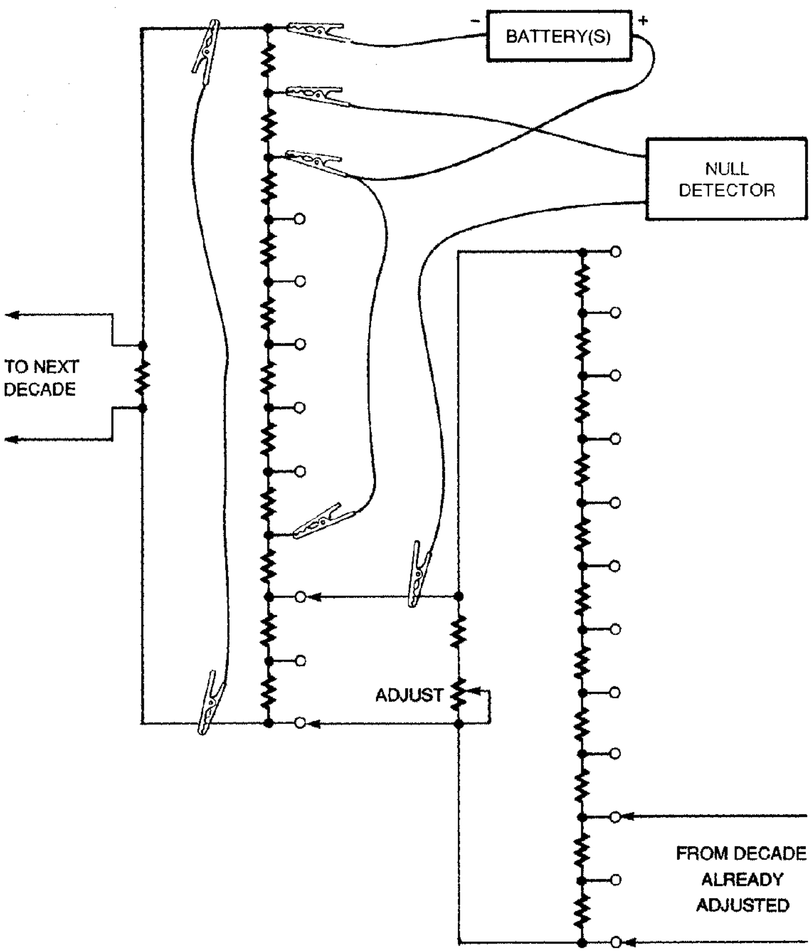
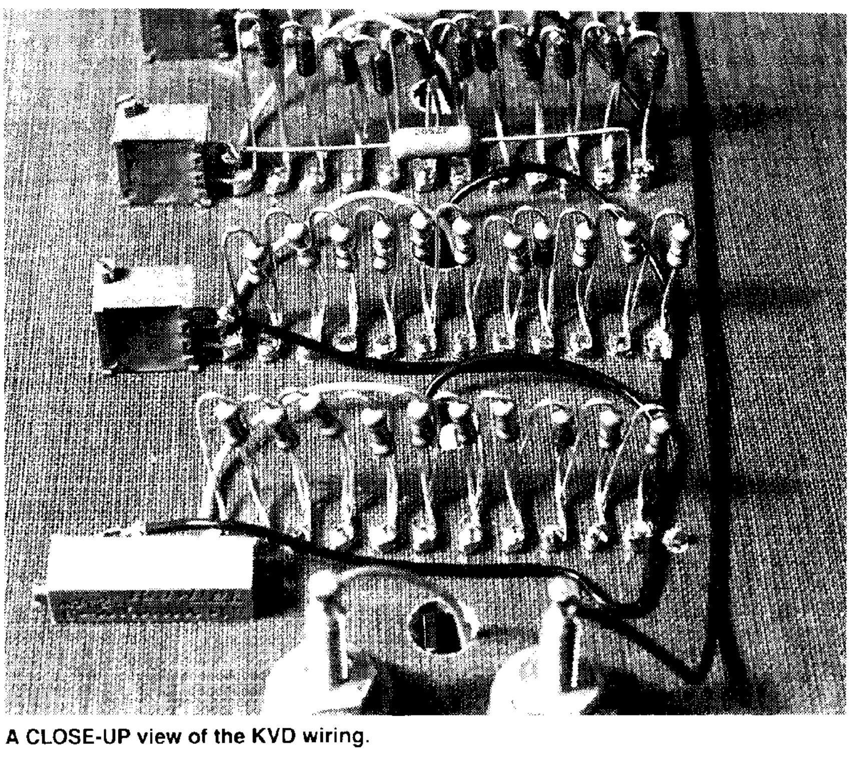


FIG. 6—HOOK UP CLIP LEADS AS SHOWN to adjust the padding networks.



A CLOSE-UP view of the KVD wiring.

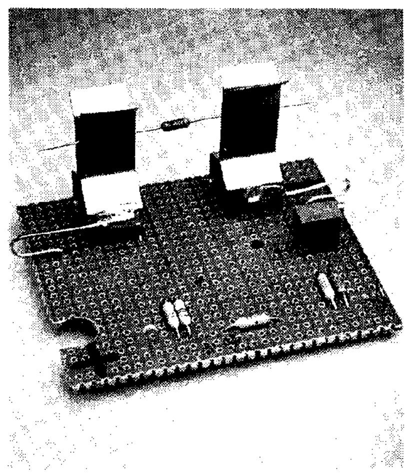
from zero up to the value of your voltage standard. The setup is shown in Fig. 7. Adjust the KVD settings until the null meter reads zero, then multiply the KVD reading times the exact value of the voltage standard.

Warning: Because the divider connections are exposed, do not use this divider with high voltages (above 40 volts), as there would be a risk of shock.

Using the voltage standard from the first installment of the series, this setup will easily check or calibrate the references used in 14-bit digital systems.

Remember: *The KVD is only accurate if no current is flowing in the output leg*. Thus, it is always used for null measurements, never as a source of current. For example, you cannot accurately measure the output of the KVD with a voltmeter, because the resistance of the meter would form a divider with the KVD, lowering the voltage slightly.

To measure voltages higher than the voltage standard, you can divide them down with the KVD, then null to the voltage standard. See Fig. 8.



THE COMPARISON BRIDGE can be built on perforated construction board.

This method does load the source. To avoid that, another stable voltage source can be used. The source drives the KVD, and is adjusted to null with the voltage standard. The unknown voltage is then measured as in Fig. 7, but with the higher temporary standard.

The KVD can also be used as

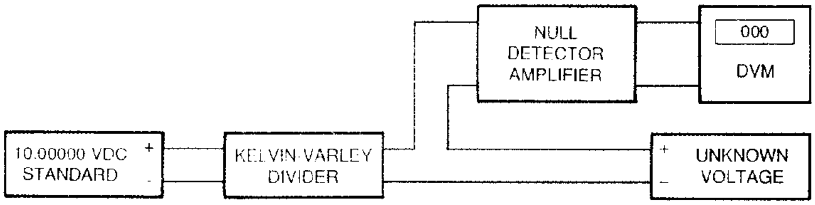


FIG. 7—THE SIMPLEST KVD MEASUREMENT SETUP.

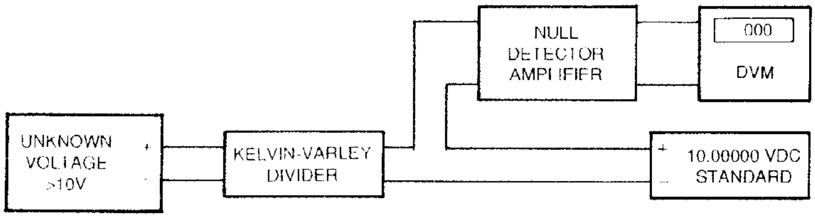
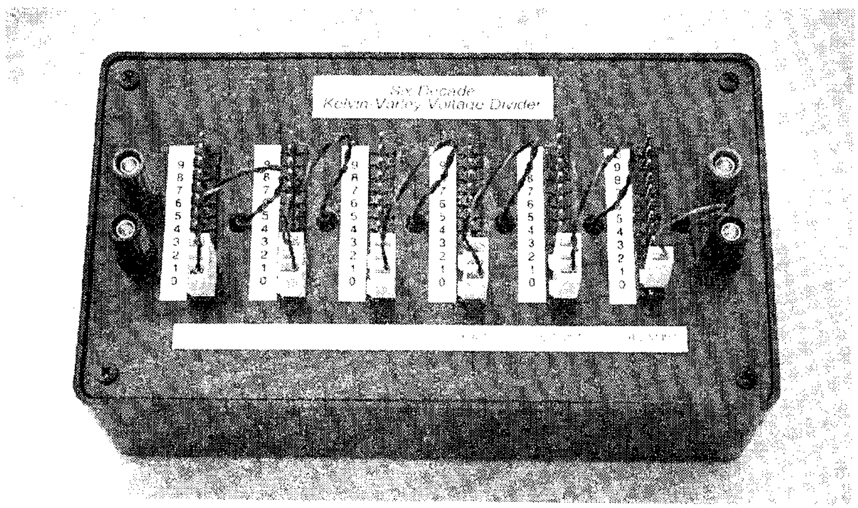


FIG. 8—THE KVD CAN BE USED TO MEASURE VOLTAGES above 10 volts with this setup.



THE COMPLETE SIX-DECADE KVD installed in its case.

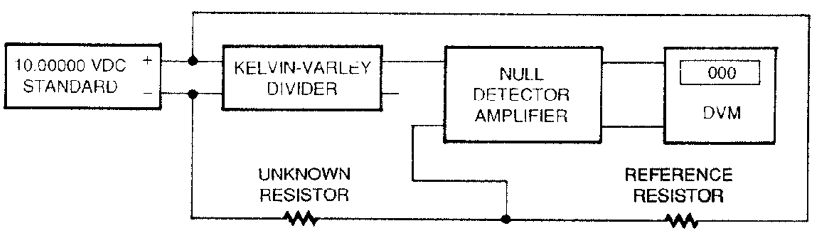


FIG. 9—USING THE KVD AS A BRIDGE.

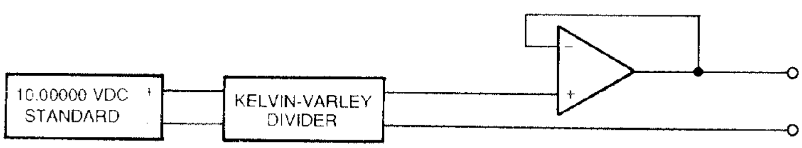


FIG. 10—THE KVD CAN BE USED AS A VOLTAGE SOURCE with this setup.

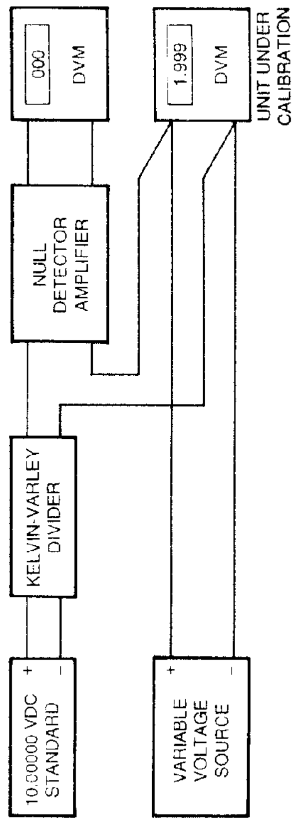


FIG. 11—TYPICAL CALIBRATION SETUP for the KVD.

one half of a Wheatstone bridge. If you have one or more precisely known resistors, you can accurately compare many different values to them. See Fig. 9.

Finally, the voltage standard and KVD can make a superb low current voltage source. The KVD is accurate only if no current is flowing in the output tap, so it must be buffered. See Fig. 10. This is a particularly useful arrangement for checking analog-to-digital converters.

We hope you enjoy building the equipment presented, and increasing your knowledge of traditional metrology techniques and making measurements that are accurate! Ω

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