The Kelvin Four-Wire Resistance Measurement Method

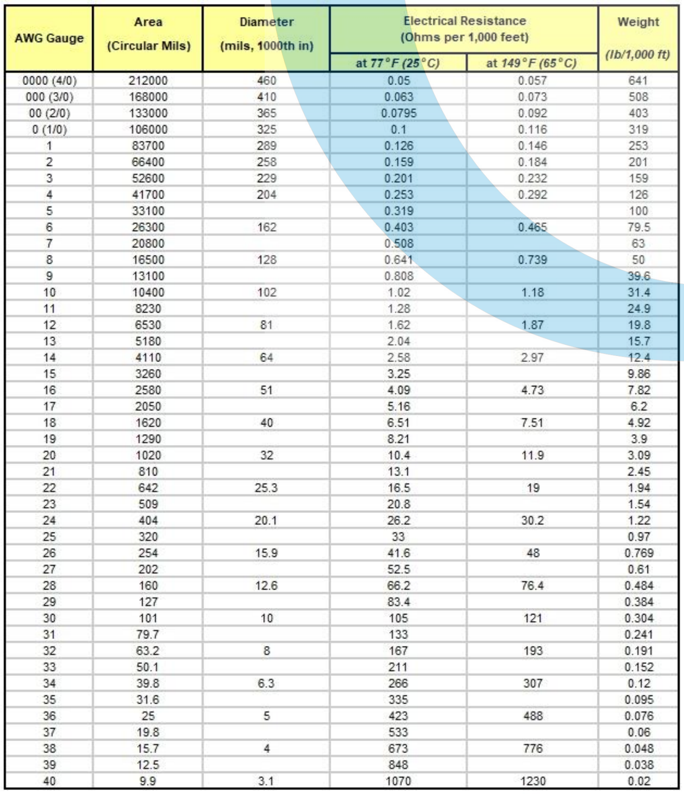
Resistance measurement is one of those things that we often tend to take for granted, and don't think much about. However, it is exactly that mindset that can cause errors to creep into our work without our ever noticing that the errors are present at all. This can happen quite easily, and we might not ever be aware that it is happening, because we have come to expect and accept the erroneous readings as valid and factual. What is this guy talking about, you ask? Read on…

Figure 1 - Kelvin test lead set

Consider the conventional measurement of a 0.2Ω resistance with an ohmmeter whose leads each have a resistance of 0.1Ω. This means that the test leads have as much resistance as the actual device under test, meaning that the meter will indicate a reading of 0.4Ω, or a 100% error. This is unacceptable and is to be avoided if possible.

Now consider a 0.773µH toroidal coil wound on a T50-6 core using 0.6mm diameter enameled copper wire. If measured with a conventional ohmmeter, this inductor would yield a resistance measurement of zero ohms, and in fact would cause a tonal continuity tester to emit the indicating tone. However, when measured using my Ascel Æ20218 milli-ohmmeter, which uses the Kelvin resistance measuring method, we get a quite different picture. Now we see that this inductor actually has a measurable resistance of 0.0226 ohms.

Table 1 – Copper wire resistance by AWG size, solid wire



AWG Gauge	Area (Circular Mils)	Diameter (mils, 1000th in)	Electrical Resistance (Ohms per 1,000 feet)		Weight (lb/1,000 ft)
			at 77°F (25°C)	at 149°F (65°C)	
0000 (4/0)	212000	460	0.05	0.057	641
000 (3/0)	168000	410	0.063	0.073	508
00 (2/0)	133000	365	0.0795	0.092	403
0 (1/0)	106000	325	0.1	0.116	319
1	83700	289	0.126	0.146	253
2	66400	258	0.159	0.184	201
3	52600	229	0.201	0.232	159
4	41700	204	0.253	0.292	126
5	33100		0.319		100
6	26300	162	0.403	0.465	79.5
7	20800		0.508		63
8	16500	128	0.641	0.739	50
9	13100		0.808		39.6
10	10400	102	1.02	1.18	31.4
11	8230		1.28		24.9
12	6530	81	1.62	1.87	19.8
13	5180		2.04		15.7
14	4110	64	2.58	2.97	12.4
15	3260		3.25		9.86
16	2580	51	4.09	4.73	7.82
17	2050		5.16		6.2
18	1620	40	6.51	7.51	4.92
19	1290		8.21		3.9
20	1020	32	10.4	11.9	3.09
21	810		13.1		2.45
22	642	25.3	16.5	19	1.94
23	509		20.8		1.54
24	404	20.1	26.2	30.2	1.22
25	320		33		0.97
26	254	15.9	41.6	48	0.769
27	202		52.5		0.61
28	160	12.6	66.2	76.4	0.484
29	127		83.4		0.384
30	101	10	105	121	0.304
31	79.7		133		0.241
32	63.2	8	167	193	0.191
33	50.1		211		0.152
34	39.8	6.3	266	307	0.12
35	31.6		335		0.095
36	25	5	423	488	0.076
37	19.8		533		0.06
38	15.7	4	673	776	0.048
39	12.5		848		0.038
40	9.9	3.1	1070	1230	0.02

OK – 0.0226 ohms does not seem like a whole lot of resistance, but it is *clearly* more than we originally measured with the less-capable meter system. So, what is it about the Æ20218 that makes it "more capable" than the standard ohmmeter as found in my Greenlee DM-510A DVOM? In short, the answer is the four-wire Kelvin measurement method, which is what we are going to explore in this article.

To begin, we have to accept some truths right up front. The first of these is that any test lead will have some inherent resistance within the lead, as a function of the physics of the test lead. The test lead is made of wire, and wire – any wire – has a given amount of resistance per foot (or inch) of that wire. The data in Table 1 provides some insight into these inherent resistances. As the caption reveals, these values are for solid copper wire. Similar tables are available for wires that are stranded with various stranding schemes. Because of the wide variety of different stranding schemes on the market, it was decided to ignore the stranded wires and illustrate the solid wire for this discussion.

As the Table 1 data shows, 22AWG solid copper wire will have an approximate resistance of 16.5 ohms per thousand feet of wire. This works out to 0.0165 ohms per foot of that wire. That is how this table works. Bear with me here, because now I am going to do some magic with the table.

Take a look at the 23AWG wire. It is listed as having a 509 circular mils area, which works out to 22.56 mils diameter. Compare that to the 0.6mm diameter wire used to wind the toroidal coil referenced earlier in this article. A diameter of 0.6mm is equivalent to a diameter of 23.62 mils – very close to our 22.56 mils of the 23 AWG wire. Now let’s look at the resistance of the 23AWG wire, which is listed as 20.8 ohms per one thousand feet of length, equivalent to 0.0208 ohms per foot. Now look at the measured resistance of the toroidal coil referenced earlier. That resistance was 0.0226 ohms. This is remarkably close to the resistance of one foot of 23 AWG solid copper wire, which is remarkably close to the diameter of the 0.6mm diameter magnet wire used for the coil in the first place.

Why did I just go through all of this? I did this to clearly illustrate that these “zero ohms” inductors do in fact have a measurable – and predictable – resistance based on the physics of the wire used to manufacture the inductor. Concept number one is now out of the way, and we can move on to concept number two.

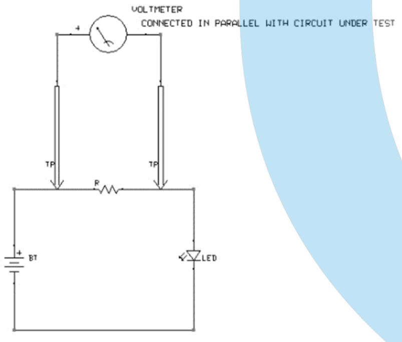


Figure 2 - Voltmeter connected in parallel

I said earlier that any test lead will have *“some inherent resistance within the lead, as a function of the physics of the test lead”*, a statement that we have just validated with the above explanation and illustration. The next truth that we have to accept is that for all intents and purposes, the resistance of the leads of a quality voltmeter can largely be ignored when considering the effect on the accuracy of a voltmeter reading. Let’s look at why this is so.

A voltmeter is connected in parallel (Figure 2) with the circuit or device under test. A quality (read: *accurate*) voltmeter will have a very high input impedance as indicated by the meter’s ohms per volt rating. In the bad old days of analog voltmeters, an ohms per volt rating of 20,000 ohms per volt was considered to be a trait of a good meter. That was, and still is, the DC Volts input impedance rating of the venerable Simpson 260 analog VOM. The AC Volts scale, however, dropped to an input impedance of only 5,000 ohms per volt with the Simpson 260.

A more accurate analog VOM was typically found in the form of a vacuum-tube voltmeter (VTVM), which had input impedances on the order of ten or eleven megohms per volt, a considerable increase over the previous impedances discussed. Modern digital voltmeters also have ten- or eleven-megohm per volt input impedances, due to the fact that they typically employ a field-effect transistor-based amplifier circuit. The FETVOM was the portable, battery-operated successor to the VTVM, again using a FET circuit in place of the vacuum tube amplifier circuit.

The bottom line to all of this is that the connection of a quality voltmeter to an operating circuit should have an extremely limited effect on the working circuit, because we are adding such an immense resistance in parallel to the working circuit. The circuit loading will be nil and the voltmeter reading will be as accurate as possible.

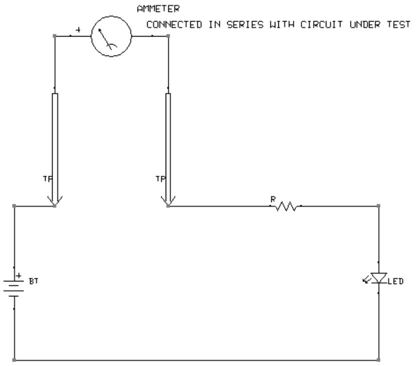


Figure 3 - Ammeter connected in series

Now for the third truth that must be accepted. In a series circuit, any current flowing in that circuit will pass as the same current value through all series-connected components of the circuit. This is a basic concept, but it is important that it is understood in order to understand the operation of the Kelvin resistance measurement method. It is equally important to understand that an ammeter is always connected in series (Figure 3) with the circuit whose current is being measured, and therefore becomes one of the series components in that circuit and the full series current will therefore flow through the ammeter.

Let’s now move on to the physical aspect of Kelvin resistance measurement. We start out with the fact that this method requires making two separate measurements and then using the results of those measurements to calculate the resistance.

The Kelvin method uses a set of four test leads, each of which has some inherent resistance. At one end of each test lead is a connector that makes the circuit into the ohmmeter, *e.g.,* a banana plug or some similar connector. The meter, of course, has a mating receptacle for each of the four test leads. Two of the test leads are voltage leads, and two are current leads. At the working end of the test leads, each pair of leads is brought together to a specialized type of test clip similar to an alligator clip, but the similarity is in general appearance only.

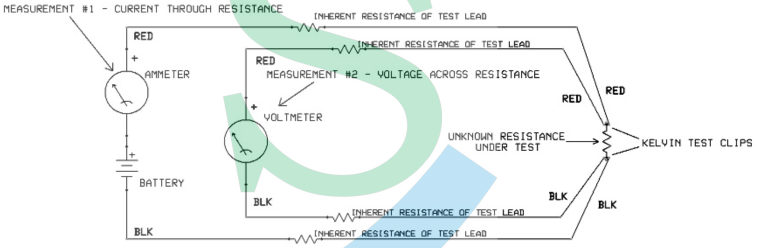


Figure 4 - Diagram of Kelvin test lead connections

A standard alligator clip is a single connection for a single lead, with both “jaws” of the clip connected to each other whether the clip is open or closed. The Kelvin test clips are quite different in that the two opposing “jaws” are insulated from each other. The clip body is of an insulating material. The two separate test leads are connected separately, one lead to each jaw of the Kelvin test clip. When the test clip is open, the two test leads are isolated from each other.

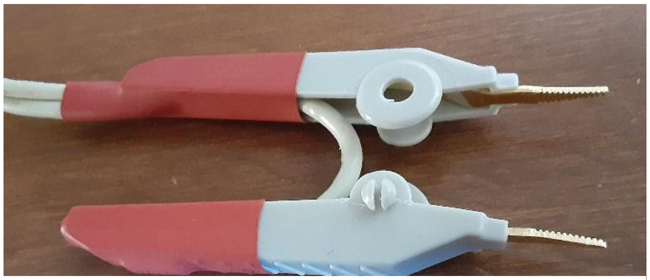


Figure 5 - Kelvin test clip disassembled

The typical Kelvin test lead set consists of two leads having red banana plugs on one end of each lead and two leads having black banana plugs on one end of each lead. The two leads with the red banana plugs come together to a Kelvin test clip having red insulation on the handles, and as stated earlier, are isolated from each other when the test clip is held open. The photograph in Figure 5 shows the Kelvin test clip with its halves separated, showing that one of the test leads is connected to each half of the test clip, and that when the test clip is open, the leads are isolated from each other. The two leads with the black banana plugs come together to a Kelvin test clip having black insulation on the handles in a manner that is the same as that for the red test leads, and as stated earlier, are isolated from each other when that test clip is held open.

At the test instrument, the banana jacks are labeled *Current OUT* and *Voltage IN*. There is one red and one black banana jack each for current and voltage. So long as the colors are matched, it makes no difference which lead is connected to which banana jack as regards current versus voltage. Figure 6 shows the front panel of the Ascel Electronic Æ20218 Milliohm Meter, a test instrument that uses the Kelvin resistance measurement method.

Figure 6 - The Ascel Electronic Æ20218

When the Kelvin resistance measurement method is in use, the test instrument sends a DC current out to the resistor under test, using one pair of the connected test leads. The test instrument then precisely measures the current that flows through the unknown resistance. At the same time, a precise measurement of the voltage drop across the unknown resistance is made by the test instrument, using the second set of connected test leads. These two measured values are used to calculate the resistance of the device under test using the Ohm's Law equation for resistance, $R = \frac{E}{I}$.

As an example, suppose that the test instrument measures a current of 783mA and a voltage drop of 3.85V. In that case…

$$R = \frac{3.85}{0.783} = 4.917\Omega.$$

A quick look at the diagram in Figure 7 might help to make this whole concept a little bit more clearly understood. In the Figure 7 example, a current of 335mA is measured through the unknown resistance, across which a voltage drop of 6.7 volts is measured. Apply these values into the Ohm's Law equation as shown in the diagram and we get a calculated resistance of 20 ohms for the device under test. Note that the two red leads are connected to the positive sides of the two meters, and the two black test leads are connected to the negative terminals of the two meters.

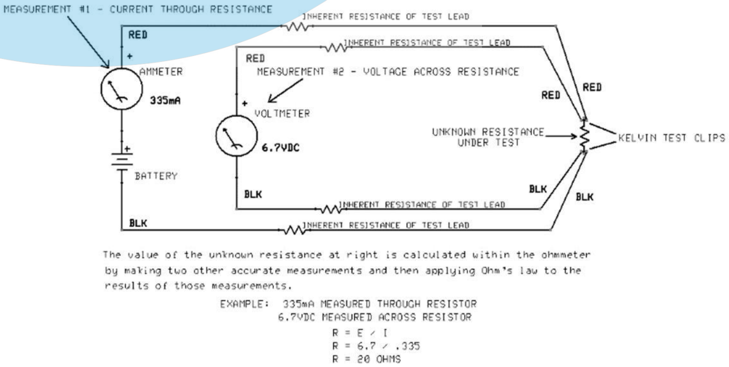


Figure 7 - Kelvin resistance measurement method example

The inherent resistance of the test leads is nullified differently in the two measurements. In the current measurement, it is a moot point, because the current flowing through the resistance under test is the same as the series current throughout the entire circuit, including the test leads. In the voltage measurement, as has already been explained, the extremely high input impedance of the voltmeter circuit causes minimal loading to the circuit under test, making the resistance of the test leads negligible.

Because of the fact that the lead resistance is taken out of the measurement, the remaining resistance is purely that of the device under test. Because that resistance is calculated arithmetically using two other non-resistive measurements as the basis for the calculation, we have the strength of Ohm's Law to support the accuracy of the ultimate resistance determination. These two measurements, as we have seen, are largely unaffected by the inherent resistance of the test leads, reducing the error almost to the point of non-existence. We cannot get much better than that. The Kelvin four-wire or four-terminal resistance measurement method gives us the most accurate resistance measurement we can obtain without spending thousands of dollars on high-level laboratory test equipment.