Practical Aspects of High Resistance Measurements

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We can observe an increased interest in high resistance measurements in the range of MΩ to TΩ. This may be related to recent inter-laboratory comparisons in this area, or to increasing activities in HiPot testing and insulation resistance measurements in industry, which of course requires availability of appropriate calibrated high resistance standards. As there are many metrologists with experience in the low resistance measurements (up to about 100k Ohm) who are now facing the need to extend their range of measurements to higher values, we offer some information that hopefully shall help to make it easier.

Terminology

Isolation resistance *– resistance between two points at a measurement circuit – e.g. two conductors at cable, or two terminals. It is the result of a finite value of the resistance of the material which the terminals are mounted on.*

Leakage resistance *– resistance between a particular place of the measurement circuit and ground terminal, respectively the point connected to zero potential.*

GUARD source *– additional active (regulated) or passive (non-regulated) voltage source of VG, used for elimination of influence of insulation or leakage resistances*

Guard of the resistance standard *– additional screening or similar part of the construction of the resistance standard, which is intended to be connected to the guard source* VG

High Resistance Measurement

There are various methods of high resistance measurement. The most frequently used are either a terraohmmeter for direct reading of the resistance, dual source bridge (DSB) or binary voltage divider (BVD) using the potentiometric method. Regardless of the method used, the high resistance measurement deals with a number of additional effects that have to be taken into account as compared to low resistance measurements. These are namely insulation resistances and leakage effects (although, in the TΩ range these can still influence the measurement if proper care is not taken), but also voltage coefficients of the resistance standards (which may be determined using different voltages for measurement) and the cleanness of connectors, etc.

Although manufacturers of high resistance standards use construction and materials which help limit the insulation and leakage resistance effects, is not possible to eliminate them completely. Therefore, it is necessary to take appropriate care when designing the measurement circuit for high resistance measurements in such a way that allows elimination of these effects as much as possible.

One of the common methods of eliminating leakage effects is through use of a "guard" connection which means that the point where the current leakage may flow is connected to the same potential as the measurement point, so that the leakage current is then minimized or eliminated (as the current flows only when there is a difference in potential).

The following paragraphs discuss in more detail ways to eliminate the effects of insulation or leakage resistances when using a bridge for high resistance measurements based on the binary voltage divider, designed according the Cutkosky principle. Although this particular measurement method is discussed, the solutions or hints shown here are applicable to other methods too and the aim of the article is to show where the problems originate and what one has to take into account in order to achieve good and unbiased results.

To conduct a resistance measurement, two resistors (a known standard and unknown DUT) are connected in series and supplied from the same voltage

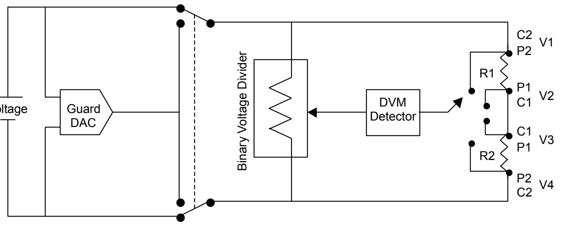

Figure 1. Principle of measurement with binary voltage divider.

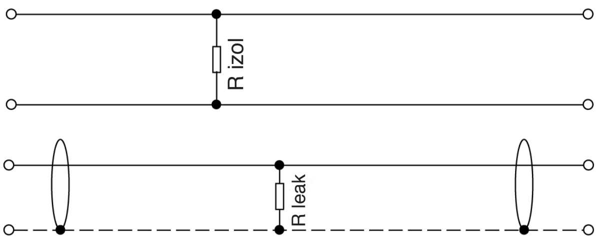

Figure 2. Unshielded two-wire cable (or shielded single wire cable).

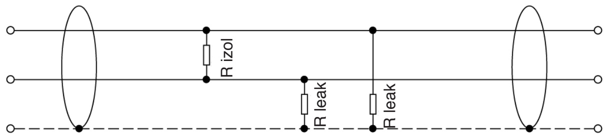

Figure 3. Shielded two wire cable.

source (Figure 1). The voltage is divided at the ratio of the resistors and the individual voltages V1, V2, V3 and V4 at points P2(R1), P1(R1), P1(R2) and P2(R2) are measured by the compensation method, where the measured voltage is balanced with the voltage from the BVD and the DVM acts only as the null detector (high resolution DVM is typically used).

Specific measurement design helps to cancel the influence of the input current of the DVM. The current passing through both resistors is the same, which means that the higher power is dissipated at the resistor with the higher value. The source voltage is considered to be constant during the measurement. The unknown resistance is calculated from the measured voltage ratios and known value of the standard resistor.

Resistors are connected to the bridge using four-terminal connections. If the resistors being measured are two-terminal, the appropriate pairs of terminals at the bridge (P1, C1 and also P2, C2) must be connected together. The bridge construction allows easy and automated switching of the resistor's position at the divider (called a resistance interchange); shown in Figure 13. The voltages measured at points V2 and V3 are sensitive to any leakage caused by the finite insulation of resistors against the ground or common point of the measurement circuit. These leakages are minimized using an isolated guard source that follows the voltage being measured and keeps the guard circuit at the same potential. The resulting leakage current is then practically zero.

The following paragraphs discuss the potential measurement setups and considerations when designing a measurement circuit for high resistance measurements.

Analysis of Leakage and Insulation Resistances for Various Constructions of Cables and Resistors

Unshielded Single-Wire Cable

One simple method of resistance measurement uses an unshielded (usually isolated) single wire connection only. Here the insulation properties of the surrounding environment (usually the air) are most important. This connection is acceptable, providing that the configuration of the equipment allows it. Nevertheless, whenever this wire comes in contact with anything (other wires; metal or isolated parts of standards or equipment, or anything else), the mutual resistance of the wire insulation and the touched part starts to play a role. The values are usually changing and hard to define; therefore elimination of their influence is very difficult.

Unshielded Two-Wire Cable (or Shielded Single-Wire Cable)

The insulation resistance between individual wires or leakage resistance between an inner wire and a shield applies, depending on the insulation material (Figure 2). Use of a shielded wire brings the advantage of elimination of the outside RF noise (e.g. from mobile communication sources), but more importantly, the elimination of leakage current from the inner wire using a guard method sets the potential of the shield to the same level as the potential of the inner wire. This makes the insulation properties of the cable less important; therefore it is possible to use regular, easily available coaxial cables. The same applies to coaxial connectors since they are often used in the construction of precision high resistance standards.

Shielded Two-Wire Cable

The insulation resistance between individual conductors and the leakage resistance between individual wires and the shield applies, depending on the insulation material and cable construction (Figure 3). If the inner wires are used to connect the two-terminal high resistance standard to the bridge, the combination of all leakage and insulation resistances are connected in parallel to it.

Connection of the screen to the same potential as one of the wires will make the problem smaller, but cannot eliminate it – the measurement result will be affected by systematic error at any case. At the other side, this cable can be used for connection of one pair of terminals (e.g. P1 and C1) in the case of four-terminal resistance standards.

In this case the insulation resistance between wires does not play a role, as they are practically shorted inside of the resistor. Leakage to the shield may be eliminated the same way like at case of the single wire shielded cable.

Unshielded Four-Wire Cable

The insulation resistance between individual conductors depends on the insulation material and cable construction.

Use of such cable for connection of high resistance standards with four-terminal construction means that the combination of the insulation resistances will be connected again in parallel with the standard and the result will be affected by systematic error. This type of cable is not suitable for high resistance measurements connections. In contrast, they offer very good properties when used for low resistance measurements. It is also one of the most frequent errors encountered when people with experience in low resistance measurements start to do high resistance measurement.

Shielded Four-Wire Cable

The insulation resistance between individual conductors and leakage resistance between individual conductors and shield applies, depending on the insulation material and cable construction (Figure 5). The same reasons as in the previous case make this type of cable unsuitable for high resistance measurements.

The only exception would be the use of this type of cable for connection of one side of the two resistors with four-wire construction to the BVD bridge – one cable would be used for connection of terminals C1(R1), P1(R1), C1(R2) and P1(R2), while the other will connect to terminals C2(R1), P2(R1), C2(R2) a P2(R2) (see Figure 13 for illustration).

The leakages between wires and shields can be eliminated the same way as single-wire shielded cables. Nevertheless, such a connection requires higher care for connection to individual terminals (do not mix them together) and often represents other difficulties (e.g. very short unshielded parts of cables, making connection of the resistors difficult).

Two-Terminal Unshielded Resistance Standard

Only the insulation between terminals applies, if mounted on some insulation material. It then appears to be an integral part of the measured resistor value.

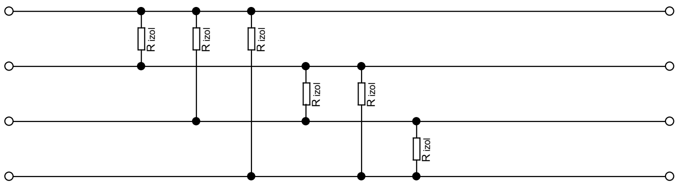

Figure 4. Unshielded four wire cable.

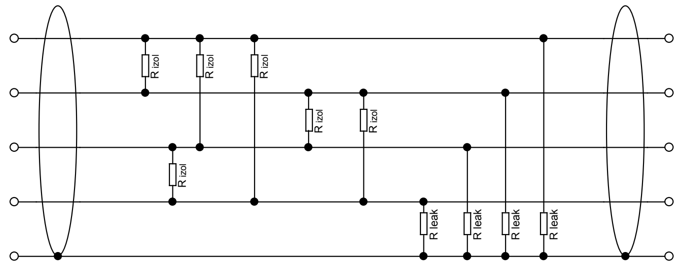

Figure 5. Shielded four wire cable.

Two-Terminal Resistance Standard in Metal Shield (e.g. GL 65206)

The leakage resistance between terminals and the metal shield (Figure 6) are practically connected in parallel to the standard. This may not cause a problem when the terraohmmeter is used for its measurement, but when used with the BVD bridge, the only way to eliminate it is to connect the shield to the guard source, thus maintaining the shield at the same potential as the potential of the point where the voltage is being measured. Any other connection (grounding the shield, or leaving it not connected) will result in measurement errors.

Four-Terminal Unshielded Resistance Standard (e.g. Tinsley 5685A)

Insulation resistance among individual terminal pairs (C1, P1 and C2, P2) applies, which will appear as an integral part of the measured resistance value. The possible effect of leakage between the insulation of the terminal board and the metal box of the resistance standard can usually be considered negligible (depending on material used and its cleanness). This additional leakage may apply when the metal container is grounded (e.g. by touching the metal parts of the oil bath). Connecting the container to the guard source would help to eliminate this leakage.

Four-Terminal Resistance Standard With Metal Shield (e.g. MIL 9331)

In some resistor construction, insulation resistance between the metal shield and the resistance element occurs – e.g. when the resistance elements are glued to the metal shield. (Figure 7) The situation is therefore practically identical to the previous case except that the most important factor is the insulation of the terminals and the metal shield.

Two-Terminal Resistance Standard With Metal Shield and Unsplit Additional guard (e.g. older MIL 9331S)

This is an old construction of MIL high resistance standards. The insulation resistance of terminals against the additional guard applies and also insulation resistance of terminals against the shield – the outside screen of the BPO terminals is connected with the metal shield (Figure 8). Effects of the insulation resistance against the inner guard are possible; eliminate using the guarding method described earlier. Nevertheless, the insulation resistance of the BPO connectors against the metal shield cannot be eliminated during measurement on the BVD bridge, unless the guard voltage is connected to the outside metal box of the standard too, which of course cannot be grounded at the same time.

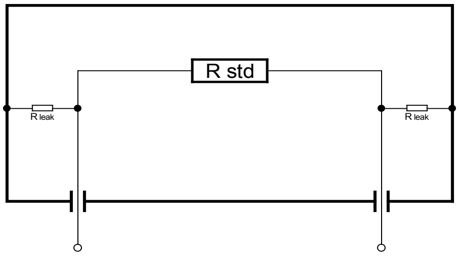

Figure 6. Leakage model of two terminal resistance standard type GL 65206.

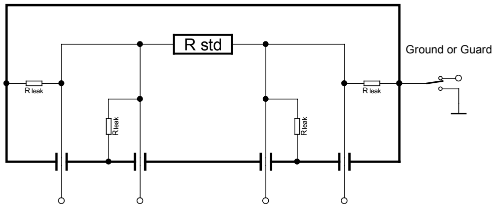

Figure 7. Leakage model of the four terminal resistance standard type MIL 9331.

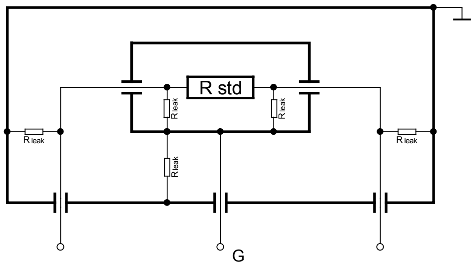

Figure 8. Leakage model of the Two terminal resistance standard type MIL 9331S.

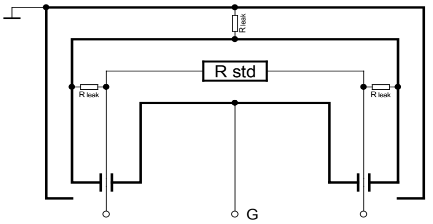

Figure 9. Leakage model of two terminal resistance standard at dual metal shield, e.g. type P4013.

Two-Terminal Resistance Standard With Dual Metal Shield – Inner Shield Acts As Guard and Holds the Resistance Terminals (e.g. P4013)

The insulation resistance of terminals against the inner shield applies, as well as the leakage between the inner and outside shield (Figure 9). This construction seems to be very well suited for measurement using the BVD bridge. Leakage between inner guard and terminals is possible. To eliminate use guarding as described above. Outside shield can be grounded and serves as electrical shielding.

Two-Terminal Resistance Standard With Metal Shield and Additional Split Guard (e.g. MIL 9331G)

The construction of this type of standard follows the NIST design. The outside part of the N connector is connected with the appropriate part of the inner split guard and is isolated from the shield of the resistance standard (Figure 10). Each part of the inner guard can be connected to a different potential, this improves the elimination of insulation and leakage effects and makes the connection to the BVD bridge easier.

Nevertheless the split guard may need to be interconnected when using other measurement methods like the Terraohmmeter, or bridges with passive guard sources. In this case the additional guard terminals represent an advantage and the passive resistive divider can be used to create an appropriate ratio of guard voltages. The leakage resistance between guard and shield is maintained high due to the appropriate construction and materials used. Older units do not have additional guard terminals, which were added in response to customers' comments and as to address some specific applications.

Two-Terminal Resistance Standard With Metal Shield, Additional Split Guard and Auxiliary Resistance Between Guard Parts (e.g. Ω-Labs)

The outside part of the BPO connector is connected with an appropriate part of the inner split guard and is isolated from the shield of the resistance standard. The guard parts are connected using an auxiliary resistor of high value (Raux = 100 MΩ) (Figure 11). Insulation resistance occurs between the terminals and guard and at the connectors. The leakage resistance between the guard and shield is kept high through construction. Use of this type of standard is very similar to the previous case. An additional auxiliary resistor eliminates the need for connection guard parts in some applications, and can be also used as part of passive divider in case of the measurement with passive guard source, but only when the resistors of the same value are measured (ratio 1:1).

In addition to the above mentioned common construction of the high resistance standards, there are also standards using a three-terminal configuration, containing a so-called "T" cell, consisting of the two resistors in series and a third connecting their common point and ground (e.g. model GL9337 or older standards from Russia series P4085). These standards actually simulate high resistance values and are usable only with some measurement methods (e.g. with terraohmmeter). Direct measurement of these standards using the BVD Bridge is not possible. It is of course possible to measure the individual resistances of the three resistors inside, or measure series combination of pairs between each pair of terminals and calculate the simulated value of the standard and appropriate uncertainty of such indirectly measured value. However, a detailed description of such calibration procedure is not the subject of this text.

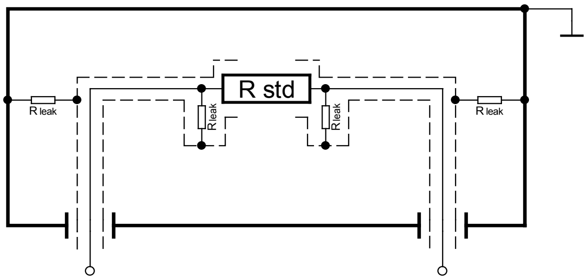

Figure 10. Leakage model of two terminal resistance standard at metal shield with additional split guard, e.g. type MIL 9331G.

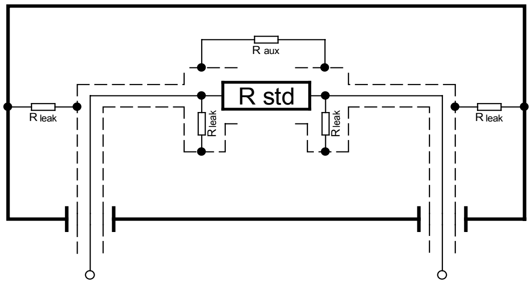

Figure 11. Leakage model of two terminal resistance standard at metal shield with additional split guard and auxiliary resistance between guard parts, e.g. Ω-Labs type.

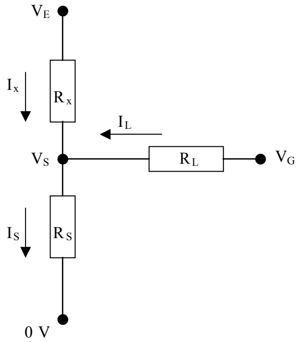

Figure 12. Schematics for calculation of leakage effects on a resistive divider.

Theoretical Calculation of Possible Errors Caused by Leakage

The excellent theoretical analysis of possible errors caused by leakages and their elimination using an active guard source made Tore Sørsdal from the Norwegian National Lab Justervesenet in his article "Current leakage error in calibration when doing potentiometric ratio measurement on two series connected resistors."

The result of his analysis is demonstrated in the simplified schematics shown in Figure 12.

The formulas that apply are:

$$dV_G = V_G - V_S$$

$$I_x - I_S + I_L = 0$$

$$V_E - I_x \cdot R_x = V_S$$

$$I_L \cdot R_L = dV_G$$

$$I_S \cdot R_S = V_S$$

The resulting formula for relative error of measurement of R_x caused by leakage resistance R_L as result of the difference of V_S and V_G, which Tore Sørsdal derived is:

$$E_{RxL} = -\frac{dV_G}{V_E} \cdot \frac{R_x + R_S}{R_L + R_x \cdot dV_G / V_E}$$

Typical Connection to a High Resistance BVD Bridge (Resistors With Split Guard)

A typical connection scheme for two resistors with a split guard is shown in Figure 13. When considering leakage and insulation effects, the following conclusions can be made:

— Terminals P2(R1) and P2(R2) are connected to the H and L terminals of the source, and therefore any leakage or insulation effects at these points are negligible – the low internal impedance of the source will cause the leakage currents, but will not cause any change of the source voltage and therefore will not affect the result of measurements. This means that the shields of cables connected here and appropriate parts of the inner guard of the resistors can be grounded to the ground terminal of the BVD Bridge.

On the other side, the terminals P1(R1) and P1(R2) are at high impedance created by measured resistors and therefore any leakage current here through insulation or leakage resistances will cause a problem and will directly affect the results of measurements. Therefore the shields of the cables connected to these points, as well as the appropriate parts of the inner guard of resistors, are connected to the guard source of the BVD bridge to eliminate any possible leakage.

The same applies when using a null detector (DVM) — the shield of its cable as well as the internal guard of the DVM is connected to the guard source of the BVD bridge. (Note that some DVM's have an internal guard connected through a resistor to the Lo terminal – e.g. Datron 1281, and therefore the guarding cannot be used in such units to eliminate leakage when measuring at BVD bridge. It is better to select another DVM as the null detector.)

Insulation resistance between the inner wires of the null detector cable does not apply, as they are at practically the same potential when the balance is reached, not speaking about the fact that this insulation resistance is usually far higher than the internal impedance of the DVM.

This connection configuration is most often used for measurements of the resistance values up to 1G ohm. Measurements of higher values are made using a special measurement setup, where the unknown resistor is connected in parallel with a known standard of the value of 100MΩ or 1GΩ.

The connection shown in Figure 13 is designed for two resistors with a split guard. When other models of resistors are used, the connection has to be appropriately modified to eliminate as much as possible the leakage and insulation effects. The blank connection scheme may be used to document a particular measurement setup and keep it for future use with the same configuration.

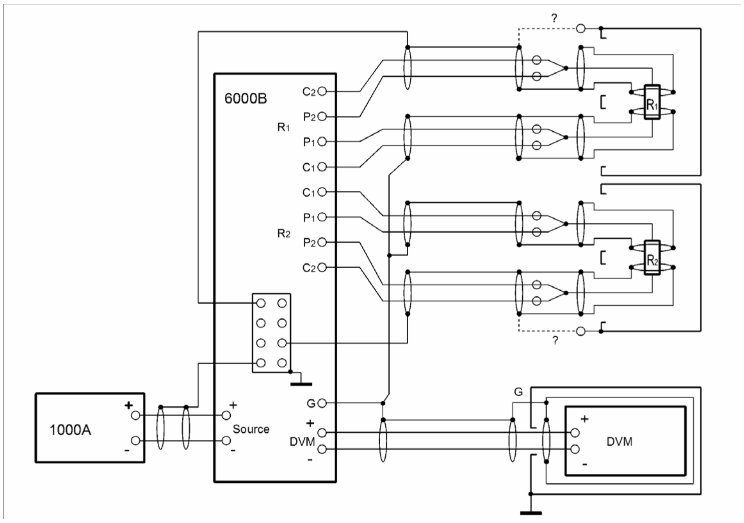

Figure 13. Typical connection to a high resistance bridge (resistors with split guard).

Connection Design

When designing a particular connection setup for measurement with a BVD bridge, one has to avoid connection of any additional resistance parallel to the measured resistors. This means not using four-wire cables in a typical connection for four-terminal standards, as it is used when the low resistance measurement is made, or avoiding the use of two-wire cable for connection of two-terminal standards. Any resistance that is connected in parallel with a measured resistor cannot be eliminated by any means of guarding or shielding.

It is preferred to use shielded two-wire cables for connection of each pair of terminals P1-C1 and P2-C2 for four-terminal resistance standards. Connection of two-terminal resistance standards is possible using shielded coaxial cable (it is necessary to connect together terminals P1 with C1 and also P2 with C2 at the appropriate input channel of the BVD bridge).

Usually it is recommended to avoid creating any ground loops – therefore all grounding connections should be made to the common point, using grounding bar at the rear panel of the bridge.

The next goal is to design the connection in such a way that it will eliminate or minimize any influence of the leakage or insulation resistances at connection points P1(R1) and P1(R2). Depending on the construction details of the individual resistors (as discussed above) one needs to select connection of the guard source in such a way that it helps isolate the connection points P1(R1) and P1(R2).

As discussed earlier, the best results can be achieved when using the resistors with split guard, connected also to the outside shields of the coaxial connectors (Figure 10) – the voltage VG of the GUARD source is connected to the guard of P1(R1) and the guard of P1(R2) as well as the outside parts of the terminals P1(R1) and P1(R2) and also the shield of the cables connected to these terminals (this is automatically made when using coaxial cables).

The same connection is used for standards with a split guard connected with the auxiliary resistor (Figure 11) – low impedance of the GUARD source will assure that the auxiliary resistor will not cause any problem. This is, of course, only valid for measurements where the guard source is active. If the passive, fixed guard voltage source is used, then the appropriate function of guarding is assured only for measurement of two resistors of the same value and same construction (ratio 1:1).

If the ratio of resistors is different, then the passive divider created from auxiliary resistors will create the wrong guarding voltage and the leakage elimination will not work – it may happen that the results of the measurement in this case will be even worse than if no guarding is used (see Tore Sørsdal’s calculation for more understanding).

When connecting the resistors without split inner guard, connect to the guard source. Connection of resistors with a simple shield (two-wire or four-wire connection) is good to connect guard source to this outside shield, but high care must be taken, as the guard voltage will appear at the outside (often bare metal) surface of the resistor! It is necessary to note that high care and specific safety precautions apply when using the guard source – its voltage, which may reach up to 120 V may appear at the metal parts of connectors, shields of cables or even metal parts of the resistor shields. Therefore it is important to never touch any metal parts at the measurement setup when the measurement is running!!!

Parallel Combination Measurement

As was already mentioned, the BVD bridge is suitable for direct measurements of resistors up to about 1GΩ. Measurement of resistors with values higher than 1GΩ requires a special parallel configuration when the unknown resistor is connected in parallel to the known standard resistor

(Figure 14). The value of the unknown resistor is calculated automatically by the BVD bridge SW from the change of the known value of the standard resistor in the parallel combination. The best results are achieved when the value of the standard resistor is measured first and immediately after this fresh value is used for measurement at a parallel configuration. Any leakage at this type of measurement is, of course, critical and can cause large errors. Proper connection design is really important. This configuration is usable up to 1 TΩ values, although some users have reported successful measurements up to 100 TΩ.

Aside of these detailed discussed effects of leakage and insulation resistances, there are other additional effects that will influence results of high resistance measurements and their uncertainties. We can list for example:

- stability of standards, elapsed time since their last calibration, knowledge of their history and possibility to predict their actual values
- voltage dependence, temperature and power coefficients of the standards, stability of the temperature at the thermostat used, relative humidity of air
- thermal voltages at terminals
- static charges, microphone effects on cables
- correct adjustment of the guard source voltage V_G

In order to illustrate some effects discussed in this article, we made a few measurements on the BVD bridge model 6000B from Measurements International. The resistors R_1=100MΩ and R_2=10MΩ, both MIL model 9331 with a metal shield box and four-terminal connection (Figure 7) were measured in the first experiment. The measurement was made with a source voltage of 10V, so the voltages at the resistors were 9.1V at R_1 and 0.9V at R_2. Each result was the average of five measured values. In the first case the metal shield boxes were connected to the guard source of the bridge (results marked as guarded in Table 1). The second measurement setup was with metal shields not connected (results marked as floating in Table 1) and finally the metal shield boxes were grounded (results marked as grounded in Table 1). Measurement cables were connected according to the schematics in Figure 13.

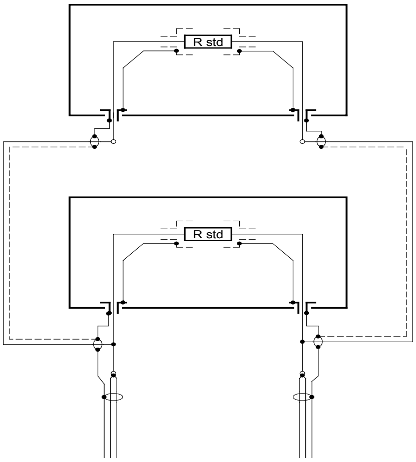

Figure 14. Schematics of connections for parallel combination measurement.

Then the resistors R_1=1GΩ and R_2=100MΩ, both MIL, R_2 model 9331 with a metal shield box and four-terminal connection (Figure 7) and R_1 model 9331G with metal shield and additional split guard with two-terminal connection (Figure 10) were measured in the second experiment. The measurement was made with a source voltage of 100V, so the voltages at resistors were 91V at R_1 and 9V at R_2. Each result was the average of five measured values. In the first case R_1 was connected according to Figure 13 and the metal shield box of R_2 was connected to the guard source of the bridge (results marked as guarded in Table 1). The second measurement setup was with guard connections and metal shield not connected (results marked as floating in Table 1) and finally the guard of R_1 and metal shield box of R_2 were grounded (results marked as grounded at Table 1). Measurement cables were connected according to the schematics in Figure 13.

It was illustrated that in the case of improper connection setup, the measurement errors can easily reach levels that are higher than the specifications of the BVD bridge.

100M/10M	**Ratio R1/R2**	**R1 Value**	**Error ppm**
guarded	10,00030613	100002561,2	-
floating	9,99986849	99998184,9	-43,8
grounded	10,00031374	100002637,3	0,8
1G/100M	**Ratio R1/R2**	**R1 Value**	**Error ppm**
guarded	10,00000379	1000025991	-
floating	10,00032103	1000057716	31,7
grounded	9,99990013	1000015625	-10,4

Conclusion

The purpose of this text was to turn the attention to possible difficulties that can be experienced during high resistance measurements, which are not present during low resistance measurements (up to about 100kΩ), where the standard four-wire connection is able to eliminate most of the problems. The possible sources of problems were discussed and several hints for design of appropriate measurement setup for high resistance measurements were offered. It was illustrated that when higher care and appropriate knowledge is not used for measurement connection design, the results will be most likely affected with systematic errors caused by improper elimination of leakage and insulation effects. The author hopes that proper analysis of connection may help to improve measurement results and help to make high resistance measurements easier and more correct.

Roman Honig graduated from Czech Technical University, Prague, Czech Republic, and has over 18 years experience at primary and national level laboratories. He is currently CEO of Measurements International, Europe (www.mintl.eu) and is Technical Specialist at Amtest-TM (www.amtest-tm.com).

Correction for the High Resistance Article.

The Auxiliary Resistor connecting two parts of split Guard at the OhmLabs resistors is not fixed at 100M Ohm value, but it equals to the nominal value of the standard resistor. Therefore they can be used with passive Guard source for any combination of resistance standards and create appropriate guard voltage.