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Obtaining More Accurate Resistance Measurements Using the 6-Wire Ohms Measurement Technique

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Introduction

The explosive growth in the computer, telecommunications, and automotive electronics industries continues to drive efforts to minimize component size and speed high-volume production. This is placing similar demands on component manufacturers. In the resistive devices market segment, discrete resistors continue to maintain a strong position, but resistor networks are growing rapidly because they offer high functionality while conserving precious PC board space.

Manufacturers of resistors and resistor networks are being asked to increase their productivity, while maintaining guaranteed component accuracies. To meet these goals, resistance measurements must be performed in various stages of production as quickly as possible.

One of the most troublesome problems manufacturers encounter in electrical testing of resistors and resistor networks are the measurement errors caused by parallel resistance paths. Major sources of these errors include:

- Adjacent resistive elements in a network, and
- Contamination of the test probes and fixturing.

Either of these problems can lead to poorer product quality, lower yields, and ultimately, reduced manufacturer profitability. This paper offers an overview of these measurement problems and describes how the 6-wire ohms technique electrically eliminates these fundamental sources of error.

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Parallel Resistance Paths Caused by Adjacent Resistive Elements

This problem occurs most frequently for manufacturers of “dual terminator” networks used for SCSI terminator applications, high-frequency attenuators used in RF communications, and impedance-matching circuits. In these types of components, the resistive element under test is shunted by other resistive elements, creating a “delta” or “loop” configuration. With ordinary test methods, a significant part of the test current will flow through all the other elements, producing a lower resistance reading than the actual resistance value. In most cases, it is not possible or desirable to break the loop physically in order to measure the individual resistive elements.

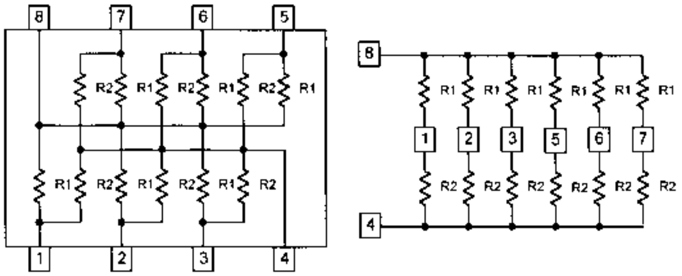

Figure 1: An 8-pin dual-terminator network and its electrical equivalent.

An 8-pin dual-terminator resistor network (***Figure 1***, left) will be used to illustrate this problem. Each resistor in this network is connected to a series resistor and to several series resistor loops in parallel. The electrical equivalent is a group of delta circuits (***Figure 1***, right.) Because of the effects of shunting resistances, the apparent value of adjacent resistors will be less than the resistance of each individual resistor element when using conventional measurement techniques.

Parallel Resistive Paths Caused by Contaminated Test Fixturing

This type of measurement problem is most common for manufacturers of high volume resistors and resistive devices that require precision tolerances. Typically, these resistive devices are assembled, labeled and tested using a high-speed handler. Over time, the lubricants used on the moving parts of the handler and other processing equipment become dispersed to many areas of the production floor, including the test fixturing. This contamination causes resistive paths to form across the resistor under test.

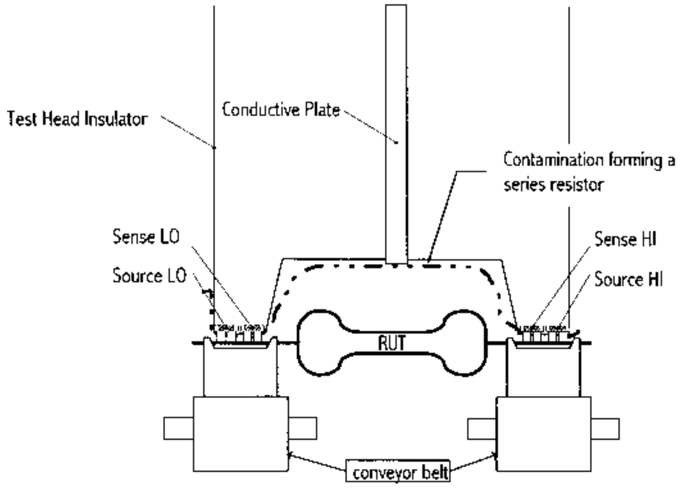

Figure 2: Axial resistor handler

Figure 2 illustrates this problem, using an axial resistor handler as an example. These types of handlers offer throughputs of more than 20,000 parts/hour.

Over time, the dispersed lubricants will cause a conductive film to build up across the two sides of the test heads probes, forming a bridge resistor. Eventually, the resistive value of this resistor in series could go as high as 100,000Ω. When measuring a 10,000Ω resistor, this would result in an additional error of about 9%.

One way to eliminate the problem is to clean the test fixture frequently on a regular schedule. However, frequent cleaning cycles may lead to excessive downtime and lower productivity. An alternative would be to use a guarded text fixture. Guarding is achieved by splitting the insulator between the LO and HI side of the probes of the test head and placing a conductive layer in between. This will electrically split the series resistor built by the contamination into two series resistors. The equivalent electrical model is equal to a three resistor delta configuration, similar to that shown in ***Figure 3***. Once this is done, the guarded ohm technique can be employed to eliminate electrically the error caused by the contamination. This permits the use of longer cleaning cycles and helps maintains the productivity of the test stand.

Applying the 6-Wire Ohms Technique to Solve Shunting Resistance Measurement Problems

The 6-wire ohms technique builds upon the industry-standard 4-wire ohms measurement technique, enhancing its performance in these applications by eliminating the

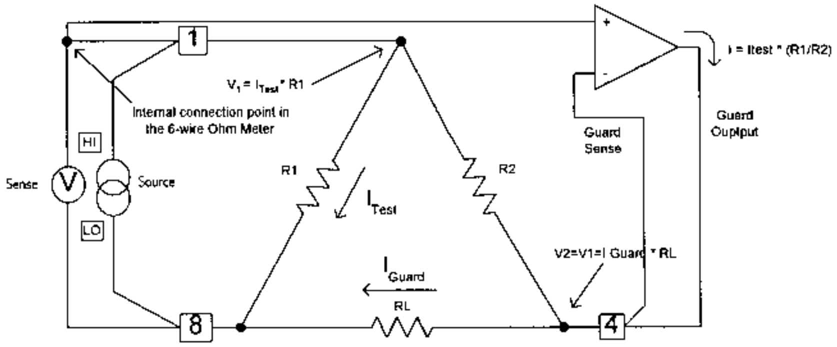

Figure 3: Equivalent circuit when measuring R1 of the dual-terminator shown in ***Figure 1***.

effects of any shunt resistance. Creating a 6-wire ohmmeter involves adding a low impedance guard buffer with sufficient drive current to a 4-wire ohmmeter.

As noted previously, both the cases described have a similar electrical equivalent, a circuit where three resistive elements are being connected in a triangular fashion. ***Figure 3*** shows the electrical equivalent circuit when measuring resistor element R1 of the resistor network device shown in ***Figure 1***. Related to the resistive path caused by contamination, R1 would be the resistor under test (RUT), while R2 and RL would be the resistive equivalent of the contaminating film in ***Figure 2***.

The solution to this measurement problem is to “guard out” the parallel resistance electrically by forcing the voltage on the middle point of the two bridging resistors (R2 and RL) to the same potential as Source HI. No more current will flow through the series-parallel loop. The 6-wire ohmmeter guard buffer accomplishes this by forcing current through RL.

From a technical perspective, the 6-wire ohmmeter guard buffer is a unity-gain amplifier (op-amp) with a shunt resistor across the input, which will hold the voltage between its inputs and therefore, across the resistor (R2 in ***Figure 3***), to nearly 0V. In the technical literature, this technique is sometimes also referred to as a “voltage follower” technique.

The level of current the Guard Output has to provide in order to guard out the series resistance built up in an automatic component handler’s test heads, e.g., for axial resistors (***Figure 2***) is fairly low, probably on the order of 0.5mA in the worst case. For networks with adjacent resistor loops, however, it might go as high as 50mA. At this current level, any lead resistance (the sum of cable, contact, and switch relay resistance) will cause a voltage drop, resulting in an additional error. To compensate for it, the Guard Sense terminal, which is essentially the inverting input of the amplifier, has to be connected to the same point as Guard Output.

To summarize, a 6-wire ohmmeter takes advantage of an operational amplifier technique, the unity-gain circuit. With the provision of sufficient drive current, electrical guarding attains isolation of the resistor element under test, allowing for more precise measurements.

Practical Aspects and Limits of Guard Buffer Circuitry

Traditionally, in electronics design, tradeoffs must be made between stability, speed, offset, and noise. Together, the sum of these tradeoffs determines the final accuracy of the instrument for a particular application. The guard buffer is no exception. The following discussion will deal with tradeoffs and errors the user must take into consideration when using the guarded ohms technique.

Guard Buffer Offset

An ideal operational amplifier will hold the voltage between the inputs to zero. However, with commercially-available op-amps, a small offset voltage always remains, which may range from a few microvolts to hundreds of microvolts. The small offset voltage generates a current through the resistor (R2 in ***Figure 3***) between Guard Output and Sense HI. This current subtracts from the sourced or measured current and produces an error. The error can be calculated as:

$\text{error} = [V_{\text{offset}} /(R \cdot I_{\text{test}})] \times 100\%$

R is the resistor between Guard Output and Sense HI (R2 in ***Figure 3***)

I_{test} is the measured or sourced current through the RUT

The formula shows that as R decreases, the error increases, whereas the error decreases as the test current increases. Two examples illustrating the use of this formula follow. One example calculates the additional error for a 180/390 dual terminator, while the other calculates the additional error contributed by the guard buffer for a 2MΩ axial resistor.

Example 1

The resistor under test is 390Ω, R = 180Ω and the test current 1mA. Assuming a 20µV offset voltage, the error = 0.011%.

Example 2

The resistance due to contamination is assumed to be 100kΩ and a test current is 10µA. Assuming a 20µV offset voltage, the error = 0.002%.

The above calculations show that the contributing error is directly proportional to the offset error of the guard buffer and inversely proportional to the shunt resistor between Guard Output and Sense HI. With the error in Example 1, a part with a specified tolerance as tight as 0.1% can be tested with good accuracy, while in Example 2, a part with 0.01% is still testable with sufficient accuracy. This assumes that the measure circuit does not contribute significantly to the error. Note: *Always* consider the guard error contribution to the total system error.

Noise and stability

Any circuitry added to a measurement system will invariably add some noise. This is especially significant in applications where high measurement rates (A/D integration rates lower than the line cycle frequency) are important, because additional circuitry will contribute to some degree to the measurement uncertainty.

When designing a guard buffer circuit, a bipolar op-amp would be a desirable choice in order to minimize the noise. However, in a test system environment, the problem is that cable lengths of six feet or more are common. Under this circumstance, bipolar amplifiers tend to oscillate, which would cause an equivalent DC component, which, in turn, will cause a significant error. To avoid this problem, a chopper-stabilized amplifier should be used for additional system stability, even though it will contribute additional noise.

System noise is especially a problem in applications where higher repeatability is required. Modern 6-wire ohmmeters allow users to adjust the measurement speed in multiples of the line cycle, and also offer digital filtering. These features make it possible for users to find the right measurement tradeoffs for applications where higher repeatability is critical.

Input bias current and common mode rejection

The 6-wire ohmmeter must have a fairly high input impedance (e.g., $>10^{10}\Omega$) in order to provide good 4-wire resistance performance, particularly in applications where significant lead resistance is expected. The non-inverting input of the guard buffer is connected to the Sense HI line and, therefore, adds to the input impedance. For this reason, an op-amp with an input impedance of $>10^{11}\Omega$ should be chosen.

In applications where precision measurements are required, the common mode rejection ratio (CMRR) of the amplifier becomes critical. In the case of the guard buffer circuit, a common mode voltage error will add to the guard buffer offset voltage, which will increase the total error. Assuming a 80dB CMRR and a 2V signal level, the additional voltage error would be 200µV. With 100dB CMRR, the voltage error would be 20µV. Therefore, it's desirable to choose an op-amp with a CMRR greater than 100dB.

Guard output current

Operational amplifiers that can be used for designing a guard buffer typically have no more than 2mA output drive capacity. In general, this is enough to guard out any resistance due to contamination on a component test head.

In fact, this technique is widely used in low current applications such as leakage measurements.

Electrometers and current sources usually provide a terminal for the xl buffer with drive currents up to 2mA. Even some precision multimeters offer a Guard Output. Guard Sense usually is not available on these meters. (See Ref. 1 for information on a test configuration and instrument that makes all of these connections available.)

Nevertheless, to provide a production test solution for parts like the dual terminator network in ***Figure 1***, the drive current provided must be significantly higher. The load resistor between Guard Output and Source LO can go as low as 20Ω. Given that relatively high voltage noise levels are inherent in a factory floor environment, it is desirable to adjust the source signals at the highest possible level. The voltage across the load resistor is the same as that across the RUT. Assuming a voltage of 0.5V and a 20Ω load resistor, the guard buffer has to deliver a 25mA guard current. To obtain this level of current, a booster stage must be added to the guard buffer. This booster stage is essentially a transistor stage, designed to increase the level of the guard drive to about 50mA .

Protection and overloading

In essence, the guard buffer is an amplifier with a booster stage, thus creating a voltage source with a remote sense line. In additional to preventing oscillation, it is good practice to protect the guard buffer against overloading, electrostatic shock, and fly-back voltages.

It is not uncommon for measure leads to get shorted or for a programming mistake to close a switch at the scanning mainframe, which produces a short, especially during the design phase of a measurement system. Electrostatic loads and voltage peaks are very common on a production floor, especially when long cables and switching systems are involved.

To protect the guard buffer against shorts due to these problems, a series resistor and a fuse (preferably a thermal fuse) can be used. Peak voltage can be covered with protection diodes. The inverting input of the amplifier can be protected with a high value series resistor.

Connection points of the guard buffer

Once the guard buffer is designed, it must be tied into the rest of the circuitry to create the 6-wire ohmmeter. ***Figure 3*** illustrates the connections that must be made. The non-inverting input of the amplifier connects to the Sense HI lead, which is virtually current free. Connecting it to the Source HI Output would cause errors due to the voltage drop in printed circuit traces or elsewhere. The guard buffer ground reference connects to Source LO Output to provide the current return path for the amplifier. It does not connect to Sense LO, because the sense lines have to be held at zero amps.

Limits on guarded ohms measurements

At certain resistor ratios, there are some limitations on the use of the 6-wire ohms technique. Essentially, the theories of operational amplifier design apply, but there are two general limits. One limit is caused by the value of the R_{shunt} resistor between Guard Output and Sense HI and the other by the ratio of the load resistor (R_{load}) between Guard Output and Source LO and the RUT.

When R_{shunt} approaches very low values, two things happen. First, the current caused by the offset voltage causes a high error. Second, positive feedback may occur. This positive feedback means that noise will be amplified and back-coupled into the circuit, causing an additional error. Also, additional settling time will be required. This is particularly true if the ohmmeter uses a constant current measurement method.

When the ratio between RUT and R_{load} becomes very high (e.g., 1000:1), the guard current drive capacity provided by a single booster stage might not be sufficient to drive enough current through R_{load}. It is possible to furnish a second booster stage in order to provide more current capacity for the guard buffer, but the component can only tolerate a limited amount of power. If the power becomes too high, the RUT will overheat and be damaged.

Special Considerations for Production Testing

In general, two resistance measurement techniques can be used: constant current or constant voltage. Modern resistance measurement instruments like digital multimeters use the constant current method, while the constant voltage method usually is used in meters capable of measuring resistances of $10^8\Omega$ and higher. The following provides a brief description of both the techniques and shows how the constant voltage method increases production throughput, while the constant current method allows achieving maximum accuracy.

The constant current method

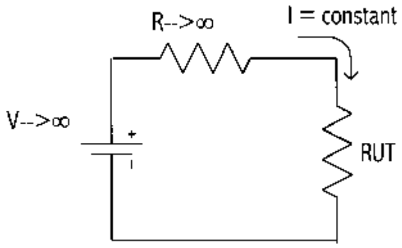

Figure 4: Equivalent current source circuit

The constant current method allows measuring resistances from fractions of an ohm to values as high as 1GΩ. In principle, a constant current source is a fixed level voltage source with a resistor of a high resistive value in series. An ideal current source has infinitely high output impedance.

In a typical DMM, the voltage is usually derived from the precision reference that the meter needs for the analog-to-digital conversion. The value of the series resistor can be determined very accurately and stored as a calibration constant. Given that a typical DMM is supplied with five to seven ranges, this consequently offers a very precise method to measure resistance. Digital multimeters with better than 0.005% basic resistance accuracy are available.

The constant voltage method

The constant voltage method is traditionally used in very high resistance measurements. A variable voltage source up to 1000V is combined with a feedback ammeter to perform the measurement. An ideal voltage source has infinitely low output impedance. A feedback ammeter has virtually zero voltage burden across it.

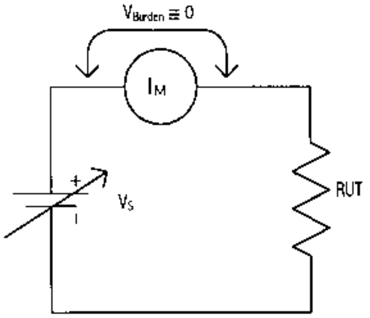

Figure 5: Ideal voltage source with ideal ampere meter

However, it is possible and desirable to apply this method for measuring resistances of less than 100Ω. The lowest resistance range where this method is applicable is determined by the quality of the voltage source. Every voltage source has certain offsets. These offsets are temperature-dependent and usually stay constant in between subsequent measurements.

Assuming a voltage source with an offset of 600µV and a RUT of 10Ω, an error current of 60µA would flow. Unless the current meter allows suppressing this error current, this would equal a 0.06% error with a 1V test voltage. A suppression option can significantly improve the accuracy.

How to choose between the methods

It may not be obvious why one would choose to use the constant voltage technique rather than the traditional constant current technique. However, the demands of high-throughput production testing may add other considerations. In general, the issue can be divided into two categories: 1) applications with precision requirements and/or medium measure speed, and 2) applications with medium or low accuracy requirements but very high measurement speed.

In production test applications like testing precision wire-wound axial resistors or precision metal film resistors, the constant current technique is the best method, because it is possible using commercially-available high-performance digital multimeters. These DMMs offer base accuracies of better than 0.01% at measurement speeds of 40 readings/second.

In applications like testing high volume dual terminator resistor networks, a 6-wire ohmmeter that uses the constant voltage technique is best. In this type of application, the measurement system is coupled with a switching system in a matrix configuration. The throughput is very critical—the time spent in testing adds an expense that is directly proportional to the cost of the part. With modern 6-wire ohmmeters, throughput times of less than 4ms per network element can be achieved, while maintaining an absolute accuracy of 0.1% and a repeatability of better than 0.01%.

How the constant voltage method improves throughput

The constant voltage method offers significant throughput improvements over the constant current method by minimizing source and system settling times. The result is faster measurement cycles and, therefore, a higher parts per second ratio. In addition, sourcing voltage decreases the system's noise susceptibility at high reading rates.

To explore the details of how the constant voltage technique works, let's first discuss the influence of settling time, then the noise issues involved:

Reduced settling time. In any measurement system, certain delay times are inherent. The sum of the external cabling, switching systems, and common mode capacitance, which forms a parallel capacitance across the Source HI and Source LO outputs, also increases the required settling time. The capacitive value of this "apparent" capacitor might go as high as 5nF.

With the constant current method, the capacitor needs to be charged first, because it will appear initially as a virtual short. It takes roughly seven times the time constant (RC) for the signal to settle to 0.1% of its final value. For example, assuming a 100kΩ resistor under test, a 10µA test current, and a 5nF apparent parallel capacitor, it would take about 3.5ms for the signal to settle ($t_{0.1} \approx 7 \cdot \tau$; $\tau = R \cdot C$; $V_{Final} = 1V$).

The guard buffer will follow the voltage apparent on the Sense HI but will also contribute additional settling time. With low R_{shunt} values, the guard will back-couple phase and level shifted voltage noise. Finally, at fast measurement rates, this will cause an additional error.

One solution would be to add another guard to the system, which would drive the Sense and Source HI shield. In a switching application with multiple elements, it would add significantly to the cost of the system. The better solution is to use the constant voltage method.

In sharp contrast to the constant current method, the settling time of a system using the constant voltage method is dependent on the slew rate of the voltage source. With slew rates on the order of 0.08V/µs, in principle, it would take 12.5µs to reach a 1V source value. In practice, the time is slightly longer.

Noise. In the constant current method, a source with a very high theoretical output impedance is attempting to force a constant current through a resistance by varying the voltage across it in response to an error signal (noise). The guard buffer is attempting to control a voltage on the other end of R_{shunt} without regard to current flow through it. In situations where the RUT, R_{shunt}, and R_{load} become small in value ($R_{shunt} < 100\Omega$, $V_{guard}/R_{load} > 10mA$, and RUT < 500Ω), measurement noise will increase noticeably at sub-line frequency integration rates. The noise generated is a combination of periodic and random noise elements.

By comparison, a constant voltage source with a low impedance output will clamp the voltage to the programmed value. The guard buffer follows to the same value minus its offset voltage. By choosing a source voltage well above the noise floor, the energy of the error signal will not, in general, be sufficient to contribute significantly to the current flowing though the RUT. Therefore, the constant voltage method will result in more accurate resistance measurements.

Practical Aspects of Building a Test System

The following section provides a practical overview on building a test system, particularly the wiring involved. In order to cover a wide resistance range, 4-wire connections are used. This section will focus on axial or chip resistors and resistor networks.

Axial or chip resistors

Making the correct connections to the handler test head is crucial to successful measurements using the guarded technique for single-resistor elements. The constant current method is used to ensure higher accuracy. Unlike measurements on resistor networks, no switching is involved in testing axial resistors, so only a single cable is needed. The best way to make the connection is to use a 7-conductor cable, one of which is a outer shield. The other six connectors are two sets of twisted pairs, with each pair surrounded by its own shield. The connections to the 6-wire ohmmeter are made in pairs of HIs and LOs. It is always desirable to pair wires with nearly the same potential, to minimize loading and leakage effects.

The shield around the Sense HI and Source HI pair is connected to the Guard Output. Guard Sense can be connected to Guard Output at the meter, because minimal current is flowing. The shield of the Sense LO and Source LO pair is connected to earth ground. The outer shield is also connected to earth ground at the same point. To avoid forming ground loops, do not connect the other end of the cable to the earth ground of the device handler.

A common mode voltage and a common mode capacitance exists between Source LO and earth ground. In areas like a manufacturing floor, where the earth ground changes potential at fairly high peaks, this can induce error signals. It is important to note that Source LO should also be connected to earth ground as shown in ***Figure 6*** to avoid additional errors.

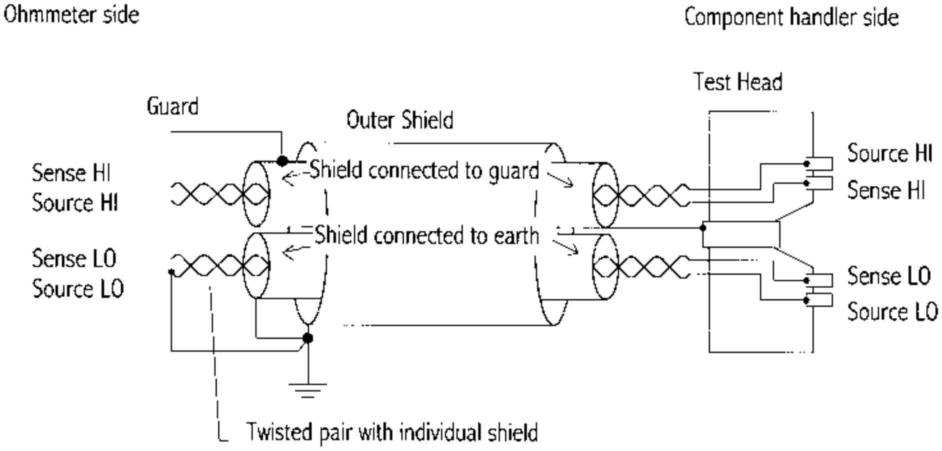

Figure 6: Proper connection scheme for axial or single chip resistors

By connecting the guard to the shield around the HI pair, capacitive coupling and leakage between LO and earth are effectively avoided, thereby providing faster and more accurate measurements. Guard is also routed to the conductive plate of the test head or to the guard ring around the test probes.

Resistor network devices

Resistor network devices contain multiple resistive elements that must be tested. In general, this involves the use of switching hardware, so the connection scheme is not as straightforward as that illustrated in ***Figure 6***. Depending on the device and the application, large switching matrixes may be required. The following example for a 8-pin dual terminator device offers a glimpse of some of the connection issues involved.

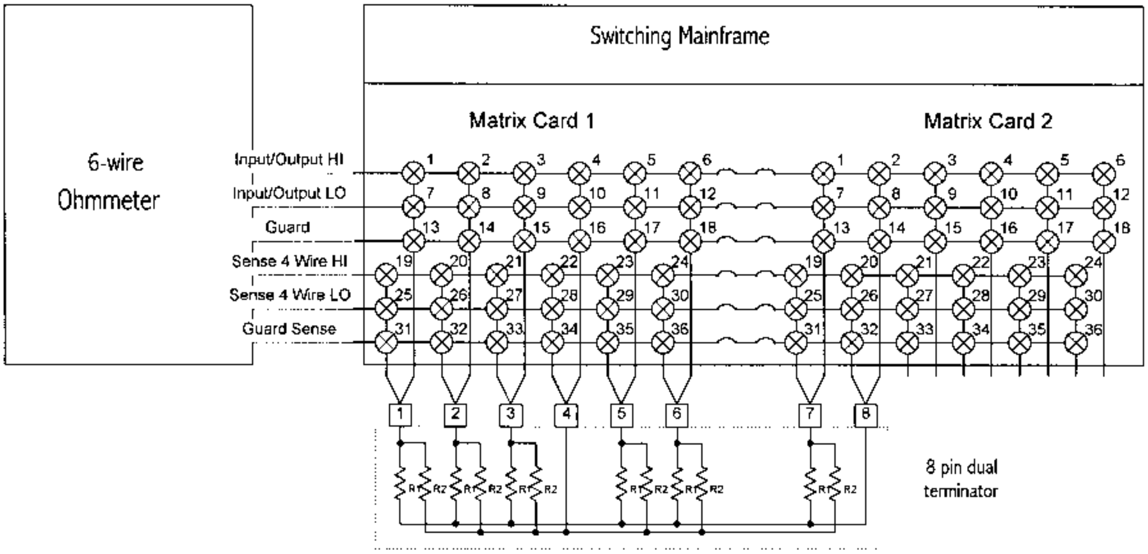

Figure 7: 6-wire Ohmmeter combined with a Switching Solution

To test the dual terminator device shown in ***Figure 1***, the switching scheme must be able to connect three pairs of connections to each of the device pins. Source HI and Sense HI, Source LO and Sense LO, as well as Guard Output and Guard Sense must be switched to the individual device pins. ***Figure 7*** shows a solution that could handle an 8-pin dual terminator device as well as a wide variety of other devices.

In this configuration, the guard can not be used to shield the HI pairs. To provide proper shielding, choose a multiple-conductor cable with a good quality shield around it, like that shown in ***Figure 8***. Through the use of the constant voltage method, parallel capacitance will not slow down the measurement. However, if resistances higher than 1MΩ must be tested to very tight tolerances, use the wiring scheme shown in ***Figure 6*** instead.

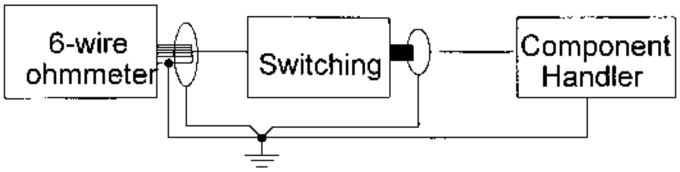

Figure 8: Shielding scheme for resistor network applications

Practical System Speeds and Accuracy Considerations

This discussion will conclude with a quick overview of system speed and how it will ultimately affect the parts per hour throughput.

Single resistor elements

In situations where high volume precision parts are being tested and contamination may be causing error, the guarded measurement technique enables the ohmmeter to achieve its base accuracy. High performance ohmmeters, essentially precision digital multimeters, make it possible to attain high reading rates without sacrificing the meter's base accuracy substantially. The following table shows the correlation between the meter's measurement speed and throughput, assuming the system uses an automated component handler capable of handling 50,000 devices per hour.

Measurement speed in ms	Base Accuracy	Devices/hour
25	0.0025%	37,113
8	0.005%	45,000
5	0.035%	46,753

Resistor network devices

Resistor network devices require a combined switching and measurement solution, so the overall throughput achievable is very dependent on both of these factors. The following table provides an overview of different test solutions. The base accuracy obtained is 0.1% and the repeatability is better than 0.01%.

# of Elements/ Network	Measure and Binning (sec)	Data Transfer/ Handler (sec)	Total Time per Network (sec)	# of Networks/ Hour
8	0.004	0.1	0.132	27,273
8	0.012	0.1	0.196	18,367
8	0.020	0.1	0.260	13,846

Conclusion

The 6-wire ohms technique builds upon the industry-standard 4-wire ohms technique by adding a low impedance guard buffer to eliminate the effects of any shunt resistance causes by parallel resistance paths of the device under test and fixturing.

Integrating the guard buffer into a 4-wire ohms measurement instrument creates a "6-wire ohmmeter" and makes it possible to perform a variety of resistance measurements faster and more accurately than in the past.

In addition, allowing precise control of the current source and/or voltage source when measuring ohms enables the user to compensate for induced errors such as noise, system capacitance, lead resistance, and offsets. The Vsource ohms method is especially useful for minimizing settling times and, thus, increasing system throughput.

These two measurement considerations are especially critical in the production of resistor networks and precision resistors, and should be considered when choosing a measurement instrument.

References for Further Reading

1. "Configuring a Resistor Network Production Test System with the Model 2400 Digital SourceMeter™," Keithley Instruments, Inc., Cleveland, OH, Application Note No. 802, Aug. 1996.
2. Model 2400 Digital SourceMeter User's Manual, Keithley Instruments, Inc., Cleveland, OH, Jan. 1996.
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