WHITE
PAPER

New Instruments Can Lock Out Lock-ins

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Sensitive Measurement Needs

Researchers today must measure material and device characteristics that involve very small currents and voltages. Examples include the measurement of resistance and I-V characteristics of nanowires, nanotubes, semiconductors, metals, superconductors, and insulating materials. In many of these applications, the applied power must be kept low in order to avoid heating the device under test (DUT), because (1) many DUTs are very small and their temperature can be raised significantly by small amounts of applied power, and (2) many DUTs are being tested at temperatures near absolute zero, where even a milli-degree of heating is not acceptable. Even if applied power is not an issue, the measured voltage or current may be quite small due to extremely low or high resistance.

Measurement Techniques and Error Sources

The key to making accurate low power measurements is minimizing the noise. In many low power measurements, a common technique is to use a lock-in amplifier to apply a low level AC current to the DUT and measure its voltage response. An alternative is to use a DC current reversal technique. In either case, a number of error sources must be considered and controlled.

Johnson noise places a fundamental limit on resistance measurements. In any resistance, thermal energy produces the motion of charged particles. This charge movement results in Johnson noise. It has a white noise spectrum

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A Greater Measure of Confidence

and is determined by the temperature, resistance, and frequency bandwidth values. The formula for the voltage noise generated is:

$$V_{Johnson}\ (rms) = \sqrt{4kTRB},$$

where: k = Boltzmann's constant (1.38×10^{-23} J/K)

T = absolute temperature in K

R = DUT resistance in Ω

B = noise bandwidth (measurement bandwidth) in Hz

Johnson noise may be reduced by:
- reducing the bandwidth – digital filtering (averaging readings) or analog filtering
- reducing the temperature of the device
- reducing the source resistance

External noise sources are interferences created by motors, computer screens, or other electrical equipment. They can be controlled by shielding and filtering or by removing or turning off the noise source. Because these noise sources are often at the power line frequency, it is common practice to avoid test frequencies that are exact multiples or fractions of 60Hz (or 50Hz) when making lock-in measurements. With the DC reversal technique, the same result is achieved by integrating each measurement for an integer number of power line cycles.

Thermoelectric voltages are generated when different parts of a circuit are at different temperatures and when conductors made of dissimilar metals are joined together. Reducing thermoelectric voltages can be accomplished by keeping all connections at the same temperature and using crimped copper-to-copper connections wherever possible. Given that it is rarely possible to use copper everywhere in the circuit (DUTs are rarely copper themselves), a measurement technique such as the lock-in technique or the DC reversal method is required to eliminate noise from thermal effects.

Test lead resistance may also create an additive error in the resistance being measured. To prevent lead resistance from affecting measurement accuracy, the four-wire (Kelvin) measurement configuration should be used.

1/f noise is a term used to describe any noise that has increasing magnitude at lower frequencies. Noise with this characteristic can be seen in components, test circuits, and instruments. It can be caused by environmental factors, such as temperature or humidity, or by chemical processes within components, which are often given the label "aging," "burn-in," or "drift." 1/f noise can be observed as a current, voltage, temperature, or resistance fluctuation.

For the discussion here, we will focus on the 1/f voltage noise in a measurement system. Material characteristics of a DUT or a test circuit component greatly influence this type of noise. For example, carbon composite resistors typically exhibit a resistance noise of 0.01% to 0.3% that has a 1/f characteristic. The noise value for metal film and wirewound resistors is about one-tenth that of composite resistors. Semiconductors fall somewhere in between these two material types.

Measurement Systems

In sensitive I-V and resistance measurements, there are two parts to the instrumentation: the current source and the voltage measurement instrument. For lock-in amplifier measurements, the researcher traditionally constructed the current source, because precision AC current sources simply were not available. For the DC reversal method, a reversible DC current source is used, and the DUT response is measured with a nanovoltmeter. The DC sources and nanovoltmeters now available offer significant advantages over lock-in amplifiers in reducing the impact of error sources and reduce the time required to achieve a low noise measurement.

Lock-in Amplifier Method – Lock-in amplifiers can measure small AC signals, some down to a few nanovolts. With this type of instrument, accurate measurements can be made even when noise sources are higher than the signal of interest. The lock-in amplifier uses a technique called "phase sensitive detection" to single out the signal at a specific test frequency. Noise signals at other frequencies are largely ignored. Because the lock-in amplifier only measures AC signals at or near the test frequency, the effects of thermoelectric voltages (both DC and AC) are also reduced.

Figure 1 is a simplified block diagram of a lock-in amplifier setup to measure the voltage of a DUT at low power. Current is forced through the DUT by applying a sinusoidal voltage ($A \sin[2\pi \cdot f_o \cdot t]$) across the series combination of R_{REF} and the DUT. Usually, R_{REF} is chosen to be much larger than the DUT resistance, thereby creating an approximate current source driving the DUT. The amplified voltage from the DUT is multiplied by both a sine and a cosine wave with the same frequency and phase as the applied source and then put through a low pass filter. This multiplication and filtering can be done with analog circuits, but today, they are more commonly performed digitally within the lock-in after the DUT's response signal is digitized. The outputs of the low pass filters are the real (in phase) and imaginary (out of phase) content of the voltage at the frequency f_o. Resistance values (DUT) must be calculated separately by the researcher based on the assumed current and measured voltage levels.
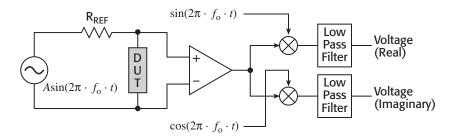
Figure 1. Simplified block diagram of a lock-in amplifier measurement setup.

Researchers using lock-in amplifiers often choose to operate the instrument at a relatively low frequency, i.e., less than 50Hz. A low frequency is chosen for many reasons. These include (1) getting far enough below the frequency roll-off of the DUT and interconnects for an accurate measurement, (2) avoiding noise at the power line frequency, and (3) getting below the frequency cutoff of in-line electromagnetic interference (EMI) filters added to keep environmental noise from reaching the DUT.

DC Reversal Measurement Method – An alternative to lock-in amplifiers uses DC polarity reversals in the applied current signal to nullify noise. This is a well-established technique for removing offsets and low frequency noise. As shown in **Figure 2**, one simply applies a current to the DUT and measures the DUT voltage, then reverses the current and re-measures the voltage. The difference of the two measurements divided by two is the voltage response of the DUT to the applied current level. Repeating the process and using averaging reduces the noise bandwidth and therefore the noise. These are called "Delta" measurements by some researchers.
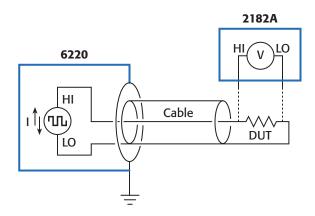

Figure 2. DC reversal measurement circuit using a four-wire lead arrangement.

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In the past, this was a manual technique with most instruments, which limited the reversal speed to less than 1Hz. Modern instruments now allow the technique to be automated and the reversal speed increased. The reversal speed sets the frequency that dominates the noise. Higher reversal speed removes low frequency noise and thermal drift better because these noise sources have lower power at higher frequencies.
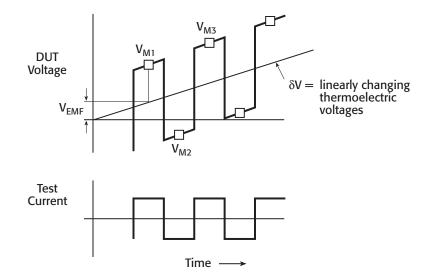

Figure 3. Test signals and thermoelectric error voltages during DC reversal (Delta) measurements.

Basically, the Delta method consists of alternating the current source polarity and using a moving average of three voltage readings to calculate resistance (***Figure 3***). The three measurements are:

$$V_{M1} = V_{DUT} + V_{EMF}$$

$$V_{M2} = -V_{DUT} + V_{EMF} + \delta V$$

$$V_{M3} = V_{DUT} + V_{EMF} + 2\delta V,$$

where V_{M1}, V_{M2} and V_{M3} are voltage measurements

   V_{DUT} = the voltage drop of the DUT due to the applied current

   V_{EMF} = the constant thermoelectric voltage offset at the time V_{M1} is taken

   δV = linearly changing thermoelectric voltage

Cancellation of both the thermoelectric voltage offset (V_{EMF}) and the thermoelectric voltage change (δV) term is possible through a mathematical computation using the three voltage measurements. First, take one-half the difference of the first two voltage measurements and call this V_A:

$$V_A = \frac{V_{M1} - V_{M2}}{2} = \frac{(V_{DUT} + V_{EMF}) - (-V_{DUT} + V_{EMF} + \delta V)}{2} = V_{DUT} - \frac{\delta V}{2}$$

Likewise, take one-half the difference of the second (V_{M2}) and third (V_{M3}) voltage measurements and call this term V_B:

$$V_B = \frac{V_{M3} - V_{M2}}{2} = \frac{(V_{DUT} + V_{EMF} + 2\delta V) - (-V_{DUT} + V_{EMF} + \delta V)}{2} = V_{DUT} + \frac{\delta V}{2}$$

Each of these results has eliminated the constant offset, V_{EMF}, but still has errors from the drift term, δV. The average of V_A and V_B, however, is simply V_{DUT}.

$$V_{final} = \frac{V_A + V_B}{2} = \frac{(V_1 - 2V_2 + V_3)}{4} = V_{DUT}$$

Successive readings can then be averaged to reduce the measurement bandwidth to reach desired noise levels.

Upon examination, the preceeding mathematics is really the multiplication of a string of V_M readings by a sequence of weightings +1, –1, +1, etc. It is exactly analogous to the way a lock-in amplifier multiplies its acquired signals by the sine functions, which are used as the stimulus. The commercially available instruments described in the box at the end of this white paper automate this entire procedure. Resistance values are calculated and displayed by the instrumentation.

Same Technique, Better Measurement Hardware – As we've seen, the lock-in amplifier method and DC reversal method are both AC measurements. In both methods, DC noise and the noise at higher frequencies are rejected. However, the nanovoltmeter/current source combination provides superior measurement capability over the entire range of device resistances, as explained in the following paragraphs.

Lock-in Limitations with Low Resistance DUTs

A typical low resistance measurement application is shown in *Figure 4*. Instrument voltage noise is generally the dominant error in low resistance measurements, but below a certain level of device resistance, common mode noise becomes a problem.
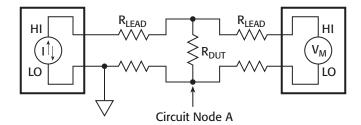
Figure 4. Block diagram of a typical low resistance measurement.

The four lead resistances shown in ***Figure 4*** vary from 0.1Ω to 100Ω, depending on the experiment. They are important to note, because with low resistance devices, even the impedance of copper connection wires can become large compared to the DUT resistance. Further, in the case of many low impedance experiments carried out at low temperatures, there are often RF filters (e.g., Pi filters) in each of the four device connection leads, typically having 100Ω of resistance.

Regardless of the instruments used to carry out the AC measurements, the test current flows through the source connection leads and develops a voltage drop from the circuit ground to the connection to the DUT, denoted as node A. Thus, the voltage at circuit node A moves up and down, with an amplitude of $I_{TEST} \times R_{LEAD}$ volts, while the $V_{MEASURE}$ input is trying to detect a much smaller AC voltage of $I_{TEST} \times R_{DUT}$.

With the connections in this type of measurement circuit, common mode rejection ratio (CMRR) becomes an issue. CMRR specifies how well an instrument can reject variations in the measurement LO potential. Lock-in amplifiers typically claim a CMRR of 100dB (a factor of 10^5 rejection). However, in actual practice, this is more like 85–90dB. By comparison, the nanovoltmeter described in the box at the end of this white paper has a CMRR spec of 140dB. When the Model 6220 and Model 2182A described, are used together in a Delta Mode (current reversal) setup, their CMRR is better than 200dB.

To understand the impact of CMRR, consider the example described previously. With only 100dB rejection, the measurement of V_{DUT} (which should be $I_{TEST} \times R_{DUT}$) is in fact $I_{TEST} \times R_{DUT} \pm I_{TEST} \times R_{LEAD}/10^5$. Thus, there is a 1% error when R_{LEAD} is $10^3 \times R_{DUT}$. With 100Ω lead resistance, it is impossible to make a measurement within 1% error bounds when R_{DUT} is less than 0.1Ω. On the other hand, the Model 6220/2182A instrument combination, with its CMRR of greater than 200dB, measures resistances as low as $1\mu\Omega$ within 1% error bounds, even with 100Ω of lead resistance.

It is also worth noting that in the case of the lock-in amplifier, the current source shown in *Figure 4* would really be a homemade source constructed from the V_{OUTPUT} and a hand-selected (and thoroughly characterized) resistor (R) as *Figure 5* shows. Every time a different test current is desired, a new resistor must be characterized, inserted in the circuit, temperature stabilized, and shielded. Even with this effort, it does not deliver constant current, but instead varies as the DUT resistance varies. With a stable current source like the Model 6220, the current is far more predictable and does not require manually adjusted circuitry to control its magnitude.
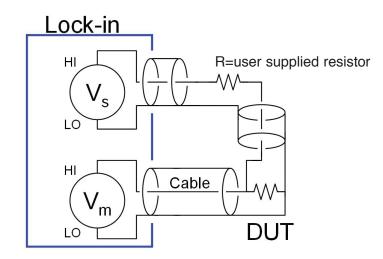

Figure 5. Making a "current source" from a lock-in amplifier

Lock-in Limitations with High Resistance DUTs

Values of DUT resistance greater than $10k\Omega$ present challenges of current noise and input loading errors. Current noise becomes visible as a measured voltage noise that scales with the DUT resistance. In both the lock-in amplifier and the DC reversal systems, current noise comes from the measurement circuit and creates additional AC and DC voltage as it flows through the DUT and/or lead resistance.

For both types of systems, noise values can be of a similar magnitude (50pA DC with $80fA/\sqrt{Hz}$ noise for the Model 6220/2182A, and ~50pA DC with $180fA/\sqrt{Hz}$ noise for a lock-in like the SRS 830). While the 50pA DC does not interfere with the AC measurements, it does add power to the DUT and must be counted in the total power applied to the DUT by the measurement system. This presents a much smaller problem for the DC reversal measurement system, because the programmable current source can easily be made to add a DC component

A G r e a t e r M e a s u r e o f C o n f i d e n c e

to the sourced current to cancel out the DC current emanating from the nanovoltmeter. The lock-in does not have this capability.

The second limitation in measuring higher DUT resistances is the input impedance of the voltage measuring circuit, which causes loading errors. For example, if the lock-in with its 10MΩ input impedance is used to measure a 10MΩ DUT, half of the current intended for the DUT will instead flow through the instrument input, and the measured voltage will be in error by 50%. Even with careful subtraction schemes, it is not practical to measure any device greater than 1MΩ with 1% accuracy.

By contrast, the Model 2182A Nanovoltmeter has 1000 times higher input impedance, so it can measure up to 1GΩ with 1% accuracy. (Subtracting the loading effect of the 10GΩ only requires knowing the input resistance to 10% accuracy, which is readily measured by performing the DC reversal measurement using an open circuit as the "DUT.") Moreover, because the Keithley Model 6220 current source provides a guard amplifier, the Model 2182A can measure the guard voltage instead of the DUT voltage directly (*Figure 6*). This reduces the current noise transmitted to the DUT down to the noise of the current source (below 20fA/√Hz). This configuration reduces the loading error, noise, and power in situations where the lead resistance is negligible and a two-wire connection to the DUT is acceptable.
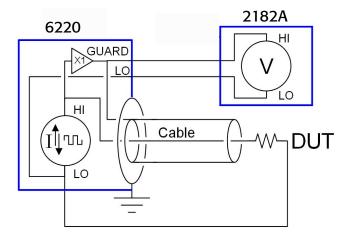

Figure 6. Guard buffer circuit in a two-wire, DC reversal measurement.

Midrange Resistance Measurements

Traditionally, lock-in amplifiers have been used for measurements in the range of 100mΩ to 1MΩ due to the significant limitations outside this range. Even when R_{DUT} falls in this range, using the DC reversal method with newer instruments may provide an advantage. For example,

a lock-in amplifier has two times (or higher) more white noise than a modern DC reversal system, and its 1/f voltage noise is ten times higher. (See *Figure 7*.) For example, when working at 13Hz (a typical frequency in lock-in measurements), the DC reversal system has 7.2 times lower voltage noise than the lock-in. This leads to 50 times less required power.
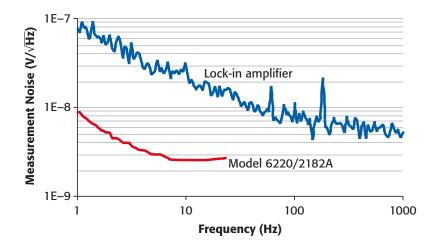

Figure 7. Noise comparison of SRS 830 lock-in amplifier and DC reversal measurements with Keithley Models 6220 and 2182A.

Noise Power and Measurement Time

To put noise error into perspective, consider measurements with a desired signal-to-noise ratio of 100. *Figure 8* shows the applied measurement power required on DUTs of various resistances in order to achieve a voltage response equal to 100 times the measurement system's RMS noise for a one-half second measurement. The curves shown are for measurement setups using a lock-in amplifier system and a DC reversal system. For the lock-in amplifier, it illustrates the relatively small range of measurable resistances and the need for greater applied power to overcome the higher noise levels. The noise of the DUT is shown separately because it is dependent on temperature. However, the Johnson noise power for room temperature resistances is represented by the lower horizontal dashed line in *Figure 8*.
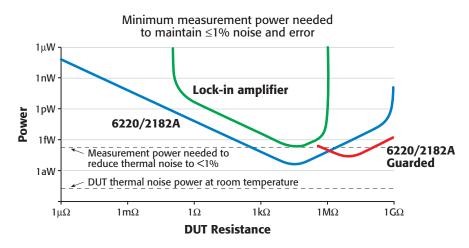
Figure 8. DUT power required for typical measurements with different instruments.

It can be shown that noise power ($V_{Johnson}^2/R$) in the DUT measurement is a function of temperature and is not dependent on its resistance. Measuring a DUT with 1% RMS noise requires a signal voltage 100 times the noise voltage, thus a signal power 100^2 or 10,000 times the noise power, as shown by the upper dashed line in *Figure 8*. (See the box at the end of this white paper for a description of the instruments used to collect the data.)

Depending on which is greater, the system noise or the DUT noise should be used to determine the applied power required, which should be as low as possible. Increasing the measurement time decreases the required power by the same factor as the increase in time. For example, if time is increased by a factor of four (to two seconds in this case), then the required power decreases by a factor of four. For the current source and nanovoltmeter combination, *Figure 8* shows that the system noise is less than the Johnson noise of room temperature DUTs between 500Ω and 100MΩ. Physics presents the only measurement limitation, and low temperature measurements will benefit from the full capability of this system to make measurements with even lower power.

Instrument Noise Comparisons

All electronic circuits generate both white noise and 1/f noise. The noise of low frequency measurements are often dominated by the latter. The lock-in amplifier's front end is usually the dominant source of 1/f noise. The DC reversal method has similar issues. Therefore, comparing the noise performance of a lock-in amplifier with an instrument using the DC reversal method comes down to comparing the noise performance of their front-end circuitry. Furthermore, the DUT resistance value must be considered when making these comparisons.

It is common for manufacturers to specify their white noise performance, but less common to be given a 1/f noise specification. To make a valid comparison, like the one in *Figure 7*, the noise level should be determined as measurements are made. Another important consideration is whether to use the system voltage noise or current noise. *Figure 9* shows a model of a measurement system with V_n being the voltage noise of the system, I_n being the current noise, and I_S being the source current.
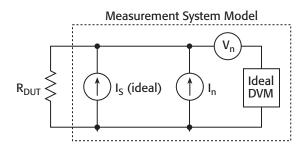

Figure 9. Idealized measurement circuit with current and voltage noise sources, I_n and V_n.

A signal-to-noise ratio of one (one possible measurement objective) is achieved when the power forced on the DUT equals the noise power of the system. This is expressed by:

$$P_{DUT} = I^2{}_S \cdot R_{DUT} = \frac{V^2{}_n}{R_{DUT}} + I^2{}_n \cdot R_{DUT}$$

This equation describes the V-shaped curves in *Figure 8*. Voltage noise dominates when the DUT resistance is low, and current noise dominates when the DUT resistance is high. The required power is minimum when R_{DUT} equals V_n / I_n. Ultimately, the real measure of instrument quality becomes how little power can be imposed on the DUT and still get a good measurement. Nevertheless, it is important to remember that very low and very high values or R_{DUT} impose different types of instrument limitations on these measurements compared to midrange values.

Summary

Lock-in amplifiers are useful for many measurement applications. Still, their common mode rejection ratio and low input impedance limits low power resistance measurements to a range of about 100mΩ to 1MΩ. Typically, they are employed with user constructed current sources, which are difficult to control with variable loads, resulting in poor source accuracy. Results are obtained as current and voltage readings, requiring the researcher to calculate resistance.

With modern instruments like the Keithley Model 6220 Current Source and Model 2182A Nanovoltmeter, the DC reversal method requires less power while providing excellent low-noise results. This combination is optimal for low frequencies (0.1–24Hz), allowing measurements to be made much faster than with a lock-in amplifier. At resistances less than 100mΩ, they have much better rejection of lead resistances, and at resistances greater than 1MΩ, they have much higher input impedance and less associated loading error.

New Instruments Improve Critical Resistance Measurements

Today, precision AC and DC current sources are available that eliminate the need for user- constructed instruments. These newer instruments provide significant advantages. For example, the Keithley Model 6220 DC Current Source has features that make its operation much easier than using a "homemade" source. Moreover, it offers guarded source connections, which provide a way around the problems associated with the low input impedance of a measurement circuit.

Together with the Model 2182A Nanovoltmeter, the Keithley Model 6220 DC current source provides excellent accuracy in the DC reversal method for measurements from 10nΩ to 1GΩ. The Model 2182A and Model 6220 are designed specifically to work together in Delta Mode. The two instruments are connected by a communication path that synchronizes them and allows current reversal frequencies up to 24Hz. Working as a system, they effectively cancel thermoelectric offsets that drift over time and avoid errors associated with common mode rejection problems. The latter are prevalent in low impedance measurements. With high DUT resistances, the Model 2182A's 10GΩ input impedance avoids loading errors. Resistance values are read directly from the Model 6220 display; separate calculations are not required. The measurement noise level for the system is about $3\text{nV}/\sqrt{\text{Hz}}$ at 5Hz and higher frequencies.

Another option is the Model 6221 AC and DC Current source. With all of the features of the Model 6220, it adds pulse I-V capability with the Model 2182A for measurements of pulses as short as 50μs, AC current and arbitrary waveform capability up to 100kHz, and an Ethernet communications bus.

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