# Agilent B2961A/B2962A Low Noise Power Source

## Programmable Output Resistance

## Using Constant Mode

Agilent Technologies

# Notices



## Manual Part Number

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# 1. Introduction

Ideal voltage source has zero-Ω output impedance and ideal current source has infinite output impedance. Generally, such ideal source is suitable for a device/module characterization. However in the real application environments, you cannot anticipate such ideal condition. You may be surprised by seeing your device/module behave strangely. And in a bad situation, you may stop working due to the voltage drop across the intolerable residual resistance, wire, output resistance of power supply, and so on.

The voltage drop can be given by a function of the current which varies according to the load resistance. So you can observe the affect of the voltage drop by emulating the voltage which will be actually applied to the load. Then, you have to calculate and adjust the voltage ($\mathrm{V_{Load}}$) to satisfy $\mathrm{V_{Load}} = \mathrm{V_0} - \mathrm{I_{Load}} \times \mathrm{R_{Residual}}$ ($\mathrm{V_0}$: output voltage at open, $\mathrm{I_{Load}}$: load current, $\mathrm{R_{Residual}}$: residual resistance).

Instead of above tasks, you may connect a real resistor to the instrument terminal externally. Then you have to prepare variety of resistors and replace the resistor manually to observe its dependency and change the resistance.

To avoid these troublesome tasks, you can use the Agilent B2961A/B2962A which provides the programmable output resistance function. The B2961A/B2962A supports two operation modes, constant and VI emulation, for this function. The constant mode lets the B2961A/B2962A channel work as a voltage source with built-in constant series resistor (Rs) or a current source with a built-in constant shunt resistor (Rsh). This mode can offer the negative series resistance that is used to compensate voltage drop same as when using the 4-wire connection even if the 4-wire connection cannot be made by some reasons. Also the VI emulation mode lets the channel work as a source with a built-in resistor which has a non-linear I-V characteristics. By using this function, DC I-V characteristics of device/module such as a battery can be emulated easily and effectively.

This document introduces the constant mode of the programmable output resistance function and the application examples by using the B2961A/B2962A. For the VI emulation mode, see another document *"Using VI Emulation Mode"*, publication number B2960-90042.

## 2. Constant Mode

Simplified block diagram of the B2961A/B2962A channel in the constant mode is shown in Figure 1. The channel works as a voltage source with built-in constant series resistor as shown in (a) or a current source with a built-in constant shunt resistor as shown in (b). They are electrically equivalent as Thevenin's theorem we learned in a basic electrical engineering class.

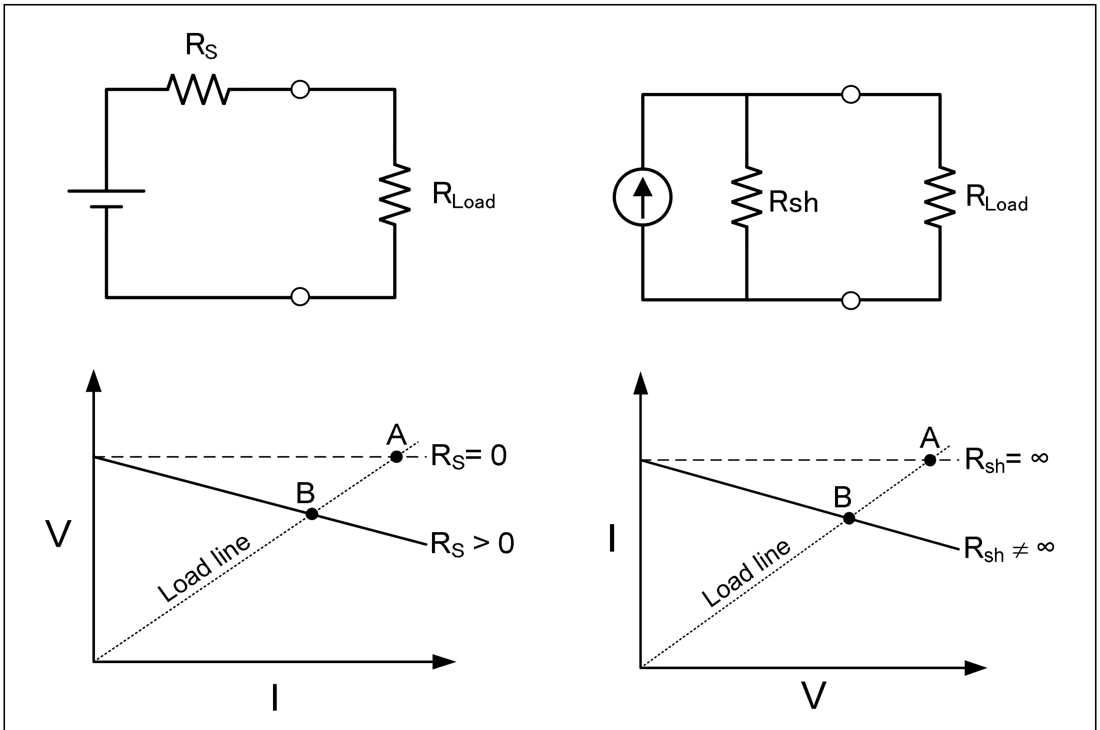



**Figure 1 Simplified block diagram and the output characteristics**

| |
|---|
| Agilent B2961A/B2962A setting parameter:<br>● Rs (series resistance) for the voltage source<br>● Rsh (shunt resistance) for the current source.<br>This parameter is set to the B2961A/B2962A front panel Output R. |

For the case (a), the channel emulates the situation like that the voltage source is connected to device/module ($R_{Load}$) via wire and the series resistor (Rs). This is not surprising situation in the real world. The graph shows the I-V characteristics at $R_{Load}$. X-axis is the load current and Y-axis is the voltage at $R_{Load}$. Dotted line is the load line. If the series resistance Rs is 0, the load voltage is constant regardless of the load resistance, and the operating point reaches the point A. However, if the series resistance is more than 0 (Rs > 0), the load voltage will be less than the setting value due to the voltage drop caused by Rs, and the operating point reaches the point B. This voltage drop will affect the operation of a device/module.

For the case (b), the channel emulates the situation that the current source is connected to $R_{Load}$ with leakage current that is proportional to the output voltage. The graph shows the I-V characteristics at $R_{Load}$. X-axis is the load voltage and Y-axis is the current. The load current will be less than the setting value due to the leakage current through Rsh. Finally the operating point reaches the point B instead of the point A.

Instead of installing the built-in constant Rs/Rsh actually, the B2961A/B2962A adjusts its channel output by monitoring the load current/voltage, and applies voltage/current as if the built-in resistor is installed. This operation is effective for the 4-wire (Kelvin) connection too, which eliminates the unwanted effect due to the residual resistance of connection cable and wire.

By using this function, you can specify your desired Rs/Rsh value and simulate the behavior of the device/module as if it is under the actual operating conditions. This function frees you from troublesome tasks such as calculating the output voltage, adjusting the channel output, and replacing the real resistor connected to the instrument terminal externally.

### Available Rs/Rsh values

For the voltage source operation of the B2961A/B2962A, a negative feedback loop is used to obtain accurate and stable output voltage. The resistance loop is added to the system as shown in Figure 2. For stable operation, obviously, the voltage feedback loop must be dominant in this system. In other words, the voltage feedback loop must be stronger than the resistance loop that is proportional to Rs. Thus the maximum Rs is determined by this requirement. Similarly the minimum Rsh requirement is determined in current source operation.

The strength of the resistance loop depends on the Rs value, the circuit characteristics, and the load attached to the system. To make it simple, we determine the maximum Rs and the minimum Rsh as a function of the load resistance, the load capacitance, and the current range as shown in Figure 3.

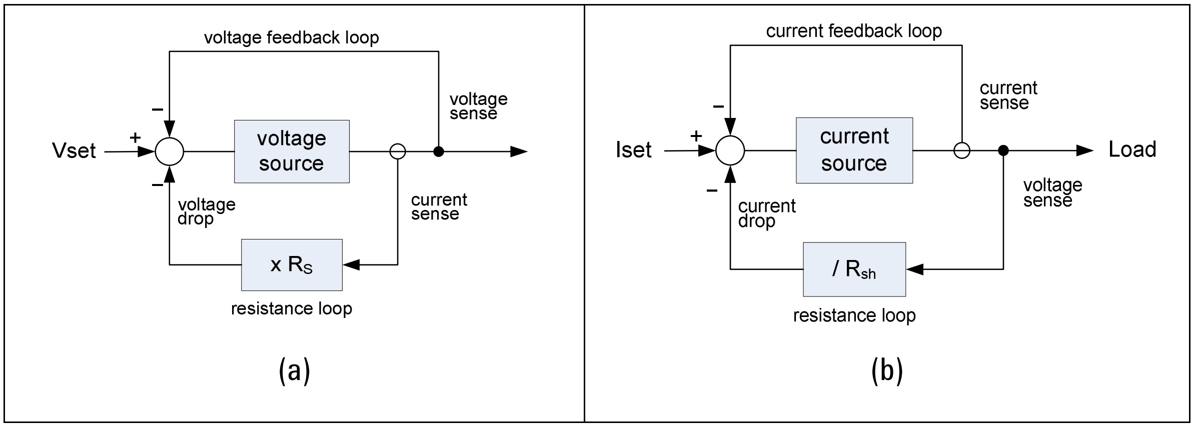



**Figure 2 Control loop**

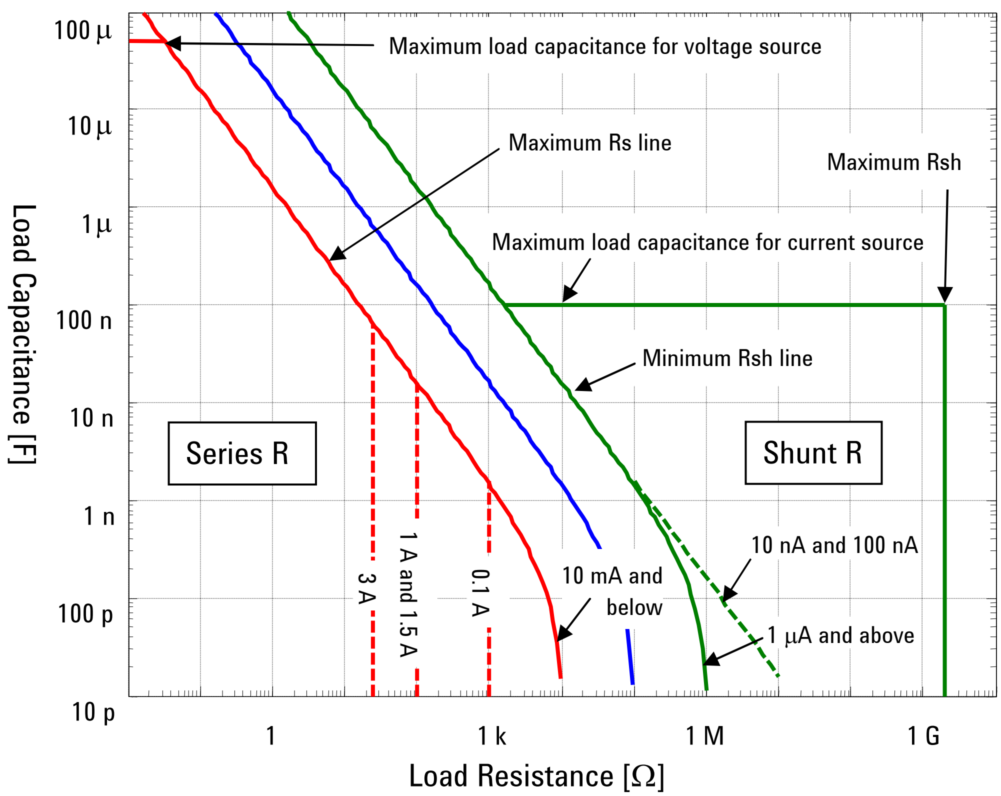



**Figure 3 Available Rs/Rsh values**

The minimum Rs is zero (negative number is discussed later) and the maximum Rs is the left-most line. And the minimum Rsh is the right-most line and the maximum Rsh is 2 GΩ. To use constant mode stably, Rs must be in the left region where the textbox Series R is located and Rsh must be in the right region where the textbox Shunt R is located.

50 µF line at the top of the Series R region is the maximum load capacitance for the voltage source mode. 100 nF line at the top of the Shunt R region is the maximum load capacitance for the current source mode. Dotted lines are dedicated limits for those specific current ranges. For example, the limit for the 1 A range is smaller than the limit for the 0.1 A range.

### To find the available Rs/Rsh values

Examples to find Rs are described below.

If the load resistance, load capacitance, and current range are 10 Ω, 10 nF, and 100 mA respectively, see the point A shown in Figure 4. This point is below the maximum Rs line. In this case, the maximum Rs will be the load resistance. So the available Rs values are 0 to 10 Ω.

If the load resistance, load capacitance, and current range are 20 MΩ, 200 pF, and 1 μA respectively, see the point B. This point is over the maximum Rs line. In this case, the values over the line are not allowed. So the maximum Rs value is approximately 4 kΩ which is a point on the line. You may notice that this condition is not suitable for the voltage source because the load resistance is much higher than the Rs value. The Rs value should be close to the load resistance to obtain the effect of the series resistor enough.

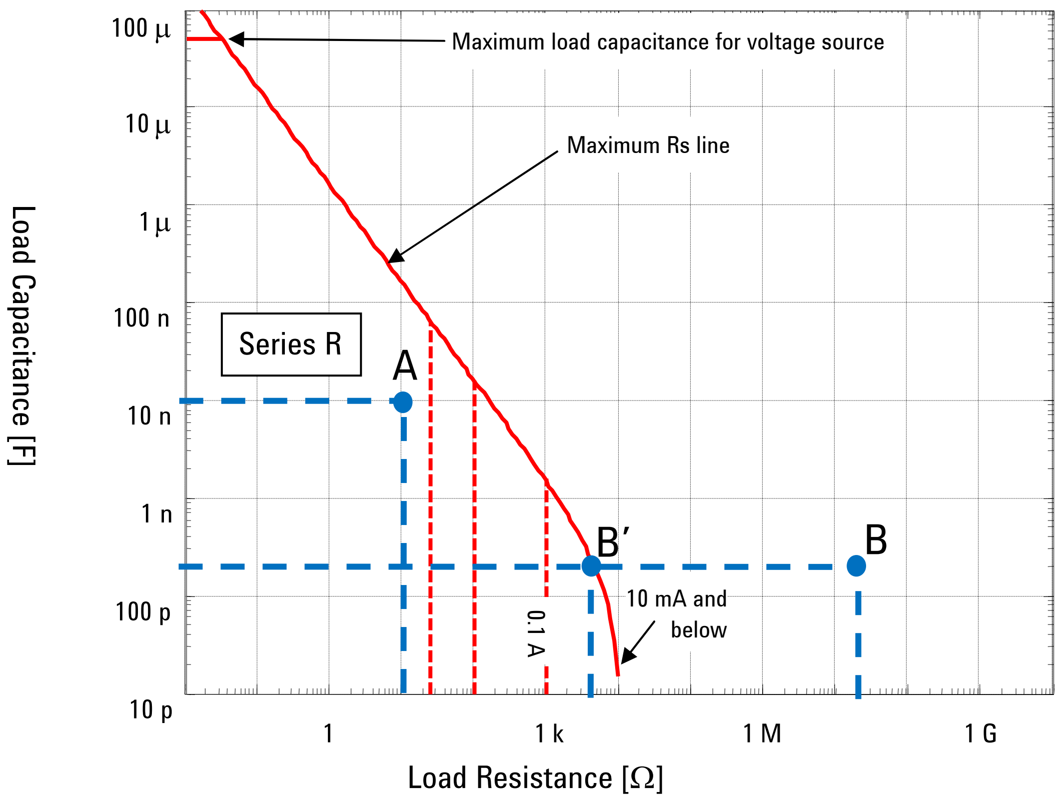



**Figure 4 Examples to find Rs**

Examples to find Rsh are described below.

If the load resistance, load capacitance, and current range are 100 MΩ, 10 nF, and 1 μA respectively, see the point C shown in Figure 5. This point is over the minimum Rsh line. In this case, the minimum Rsh will be the load resistance. So the available Rsh values are 100 MΩ to 2 GΩ.

If the load resistance, load capacitance, and current range are 10 Ω, 1 nF, and 100 mA respectively, see the point D. This point is below the minimum Rsh line. In this case, the values below the line are not allowed. So the minimum Rsh value is approximately 200 kΩ which is a point on the line. You may notice that this condition is not suitable for the current source because the load resistance is much lower than the Rsh value. The Rsh value should be close to the load resistance to obtain the effect of the shunt resistor enough.

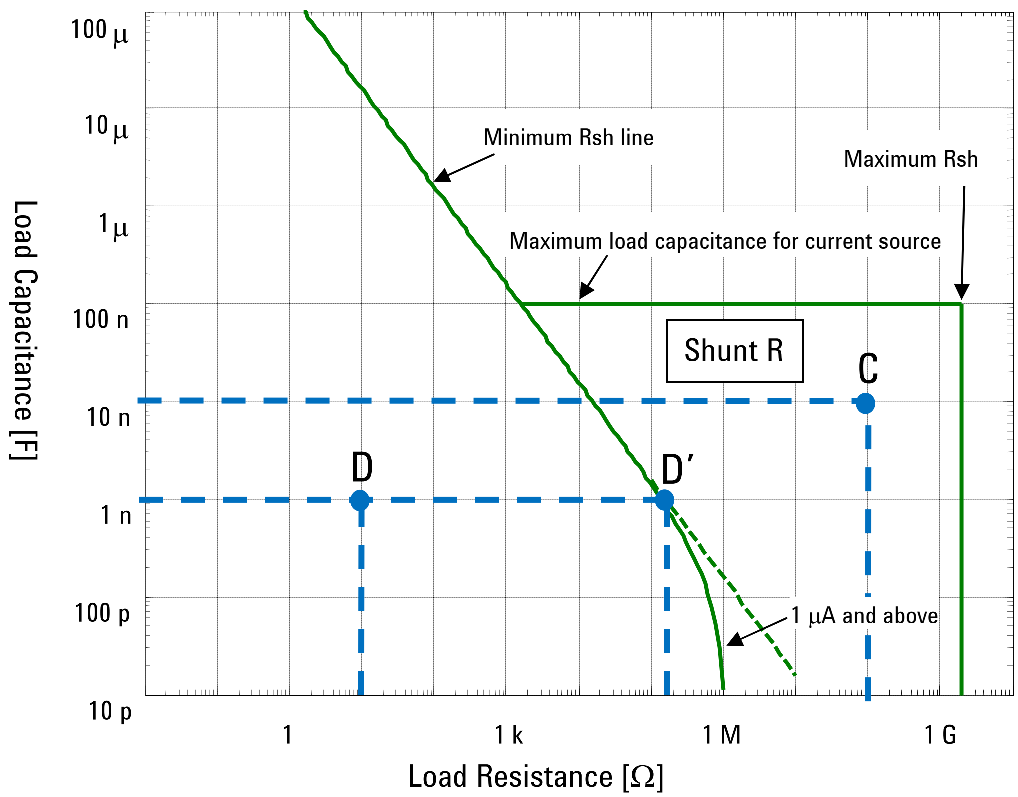



**Figure 5 Examples to find Rsh**

## Negative Rs

The series resistance Rs can be negative. The available negative values are 0 to –Rs-max/2. In this case, Rs-max means the maximum Rs value. For example, if the maximum Rs is 100 Ω, Rs can be -50 Ω to +100 Ω.

Be careful about the negative Rs may increase the output voltage. If $R_{Load}$ is 100 Ω and Rs is set to -50 Ω without having the actual residual resistance, the output voltage increases up to twice the setting voltage as shown below.

$$\frac{V_{out}}{V_{set}} = \frac{R_L}{R_L + R_S} = \frac{100}{100-50} = 2$$

For the shunt resistance Rsh, negative value is not allowed.

In summary, the available Rs and Rsh values are as follows. In this case, $R_L$ is a pure resistance load.

Series resistance Rs:

$-R_L/2 \le Rs \le R_L$

Rs < 25 Ω for 3 A range

Rs < 100 Ω for 1 A and 1.5 A ranges

Rs < 1 kΩ for 100 mA range

Rs < 10 kΩ for 10 mA range and below

Shunt resistance Rsh:

$R_L \le Rsh \le 2$ GΩ

10 MΩ ≤ Rsh for 10 nA and 100 nA ranges

1 MΩ ≤ Rsh for 1 μA range and above

## To expand the available Rs/Rsh values

Available Rs/Rsh values are limited by instability and noise of the measurement system. But, in many cases, the B2961A/B2962A can work beyond the available values described above although you may encounter the instability. Then, increase the time constant of the output filter. Generally, 100 μs or longer is recommended.

### Considering the Rs/Rsh setting errors

When the channel works as a voltage source, the series resistance Rs seen from the load is as follows.

$$R_s = -\frac{\Delta V_s}{\Delta I_m}$$

Where, $\Delta V_s$ is the change in output voltage and $\Delta I_m$ is the change in measurement current. When gain and offset error for Vs and Im are considered, Rs is as follows.

$$R_s \ with \ error = \frac{V_s(1 \pm E_{gain\_Vs}) \pm E_{offset\_Vs}}{I_m(1 \pm E_{gain\_Im}) \pm E_{offset\_Im}}$$

Where, $E_{gain\_xx}$ and $E_{offset\_xx}$ are gain error and offset error of voltage source or current measure.

As the measurement accuracy is 4 digits and the source accuracy is 6 digits, total error is dominated by the measurement accuracy. So the error of Rs is as follows.

$$Error = \frac{V_s}{I_m}\left(\left|E_{gain\_Im}\right| + \left|\frac{E_{offset\_Im}}{I_m}\right|\right) + \left|\frac{E_{offset\_Vs}}{I_m}\right|$$

Similarly, when the channel works as a current source, the shunt resistance Rsh seen from the load is as follows.

$$R_{sh} = -\frac{\Delta V_m}{\Delta I_s}$$

Where, $\Delta I_s$ is the change in output current and $\Delta V_m$ is the change in measurement voltage. When gain and offset error are considered, Rsh is as follows.

$$R_{sh} \ with \ error = \frac{V_m(1 \pm E_{gain\_Vm}) \pm E_{offset\_Vm}}{I_s(1 \pm E_{gain\_Is}) \pm E_{offset\_Is}}$$

And the error of Rsh is as follows.

$$Error = \frac{V_m}{I_s}\left(\left|E_{gain\_Vm}\right| + \left|\frac{E_{offset\_Is}}{I_s}\right|\right) + \left|\frac{E_{offset\_Vm}}{I_s}\right|$$

Following example calculates the error of Rs when Vs = 5 V at 20 V range and Im = 5 mA at 10 mA range. According to the specifications of the B2961A/B2962A, the gain and offset errors for these ranges are $E_{gain\_Im}$ = 0.02 %, $E_{offset\_Im}$ = 2.5 μA, and $E_{offset\_Vs}$ = 5 mV. So the error of Rs is calculated as follows.

Gain error = 0.02 % + 2.5 μA / 5 mA = 0.02 % + 0.05 % = 0.07 %

Offset error = $\left|\frac{E_{offset\_Vs}}{I_m}\right|$ = 5 mV / 5 mA = 1 Ω

$$Error \ of \ Rs = 0.0007 \times \frac{V_s}{I_m} + 1 \ \ \Omega$$

# 3. Application

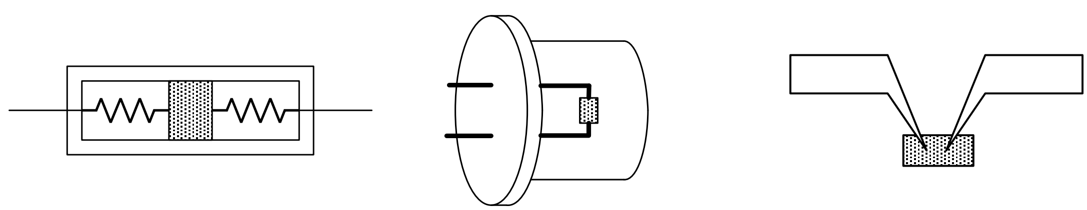
Agilent B2961A/B2962A Power Source can be a voltage source or a current source which enables wide range voltage/current output and advanced test and evaluation. And its programmable output resistance function is effective for several applications such as error compensation, source emulation, resistance emulation, and so on. This section introduces the following examples for using this function.

- To compensate voltage drop caused by residual resistance
- To emulate a battery with internal resistance

## To compensate voltage drop caused by residual resistance

### Introduction

The B2961A/B2962A supports 4-wire configuration which enables the Kelvin connection effective for minimizing error caused by the connection wire and for applying voltage accurately at the end of the load. However there are some cases you cannot use this feature, as shown in Figure 6 for example.



(a) Special structure (b) Fixture (c) Probe tip with no sense line

**Figure 6 Structures do not allow 4-wire connection**

(a) Load with the structure which does not allow the 4-wire connection
(b) Fixture which does not support the 4-wire connection
(c) Special probe tips which do not support the 4-wire connection

In such cases, you have to make the 2-wire configuration as shown in Figure 7. However, the 2-wire method cannot eliminate the effect of residual resistance across the connection wire. As a result, you cannot apply expected voltage or cannot tell how much voltage is applied to the load. The constant mode of the programmable output resistance function is effective and can solve the issue by using the 2-wire method.

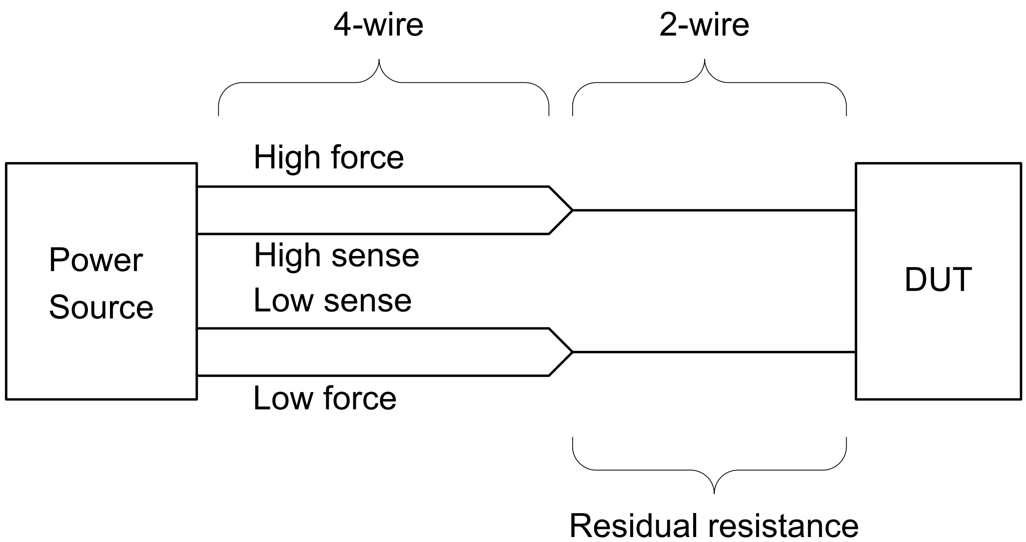



**Figure 7 4-wire connection and 2-wire connection**

### Solution

Simplified block diagram to solve the problem is shown in Figure 8. $R_{Load}$ is the load resistance and $R_{wire}$ is the residual resistance of the connection wire. And the left block consists of voltage source and series resistance Rs indicates the B2961A/B2962A channel. Then the negative value must be set to the Rs to eliminate the $R_{wire}$.

Example condition:

| | |
|---|---|
| $R_{Load}$ | 0.9969 Ω |
| $R_{wire}$ (residual resistance of wire) | 69.4 mΩ |
| Vout | 1.0 V |

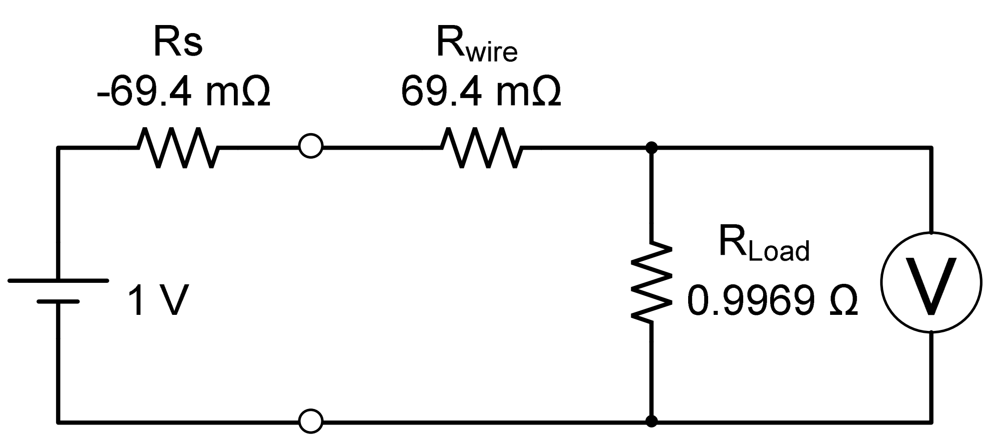



**Figure 8 Simplified block diagram**

**Result**

Measurement results are shown below. They are the results using the 2-wire connection (a), the 4-wire connection (b), and the 2-wire connection with the negative Rs (c).

(a) Result using the 2-wire connection

Vout = 1000.0 mV, $I_{measure}$ = 0.9376 A, $V_{measure}$ at $R_{Load}$ = 935.1 mV (-6.5 %)

(b) Result using the 4-wire connection

Vout = 1000.0 mV, $I_{measure}$ = 1.0031 A, $V_{measure}$ at $R_{Load}$ = 1000.35 mV (+0.04 %)

(c) Result using the 2-wire connection with the negative Rs (Rs = -69.4 mΩ)

Vout = 1069.6 mV, $I_{measure}$ = 1.0034 A, $V_{measure}$ at $R_{Load}$ = 1000.5 mV (+0.05 %)

Thus, the negative Rs can effectively cancel the residual resistance of the connection wire. Figure 9 shows the voltage characteristics at $R_{Load}$. X-axis is the expected output voltage. The upper line is the characteristics by using the 2-wire connection with the negative Rs. The lower line is the characteristics without the negative Rs. It is clearly seen that the voltage drop caused by the residual resistance is canceled by the hypothetical negative resistance.

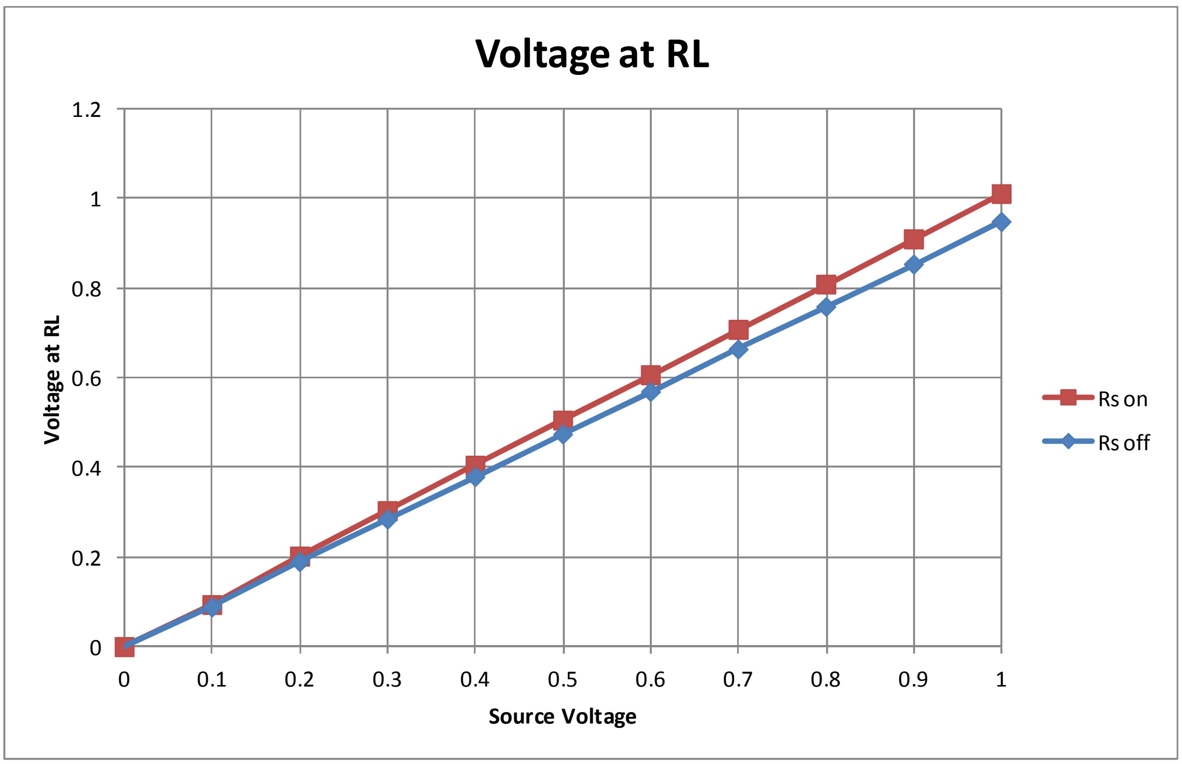



**Figure 9 Setting voltage vs measured voltage at $R_{Load}$**

Note that this solution is effective when the residual resistance is fixed and the voltage drop is linear for the current. Also see *"Negative Rs"* section in this document.

## To emulate a battery with internal resistance

### Introduction

Every battery has some internal resistance. For example, typical alkaline cylindrical batteries have internal resistance between 0.1 Ω and 0.3 Ω. This resistance causes not only voltage drop but also power loss. And generally, output characteristics of batteries are affected by the operating conditions such as temperature, number of charge/discharge cycles, and so on.

In case of designing a device, a module, or a circuit which internally uses a battery, it is wanted to evaluate the operation of it in various operating conditions. This means that the evaluation needs the real batteries under the various conditions. However it is difficult and is inefficient to prepare these batteries. So it is important to know or simulate the DC I-V characteristics of batteries in the several conditions, brand new or after 1000 times recharged, high or low ambient temperatures, and so on.

To solve this problem, the programmable output resistance function is effective. The B2961A/B2962A can emulate the output of several batteries by knowing their internal resistance which you can obtain from a battery data sheet.

Also the B2961A/B2962A can handle low current and high output resistance. This is suitable for emulating a battery used for energy harvesting application in which the device consumes very small power. The battery used there also supplies small power and its internal impedance is higher than normal battery (few hundred Ω or more).

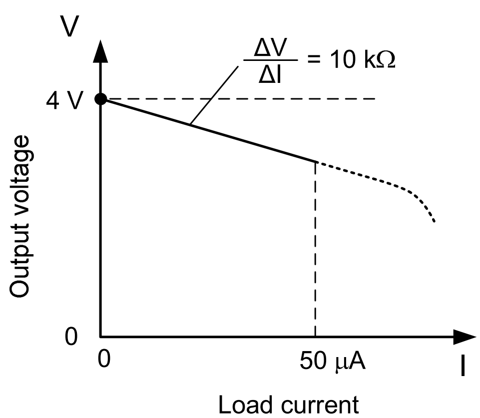



**Figure 10 Linear I-V characteristics of Vopen=4 V**

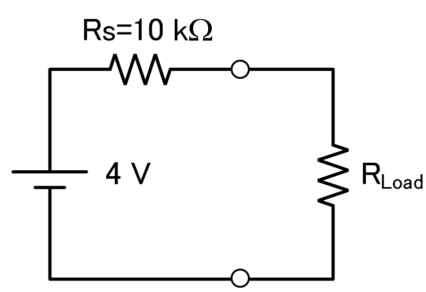



**Figure 11 Equivalent circuit to realize characteristics shown in Figure 10**

**Emulation example**

The following example is for the I-V characteristics emulation of a battery for energy harvesting. The settings of the B2961A/B2962A are shown below. The output filter is set to 100 μs to avoid oscillation caused by the high resistance loop gain. The output filter effectively reduces the loop gain.

B2961A/B2962A output settings:

| | |
|---|---|
| Vout | 4 V |
| Iout | 0 μA to 50 μA |
| Output R (Rs) | 10 kΩ (internal resistance of battery) |
| Output filter | 100 μs |

Figure 12 shows the I-V characteristics of the B2961A/B2962A channel output. This is the emulation result of the battery which has the 10 kΩ internal resistance. Output voltage at open condition (0 A) is 4 V and the voltage linearly decreases with the increase of the load current by the rate of 10 kV/A (10 kΩ).

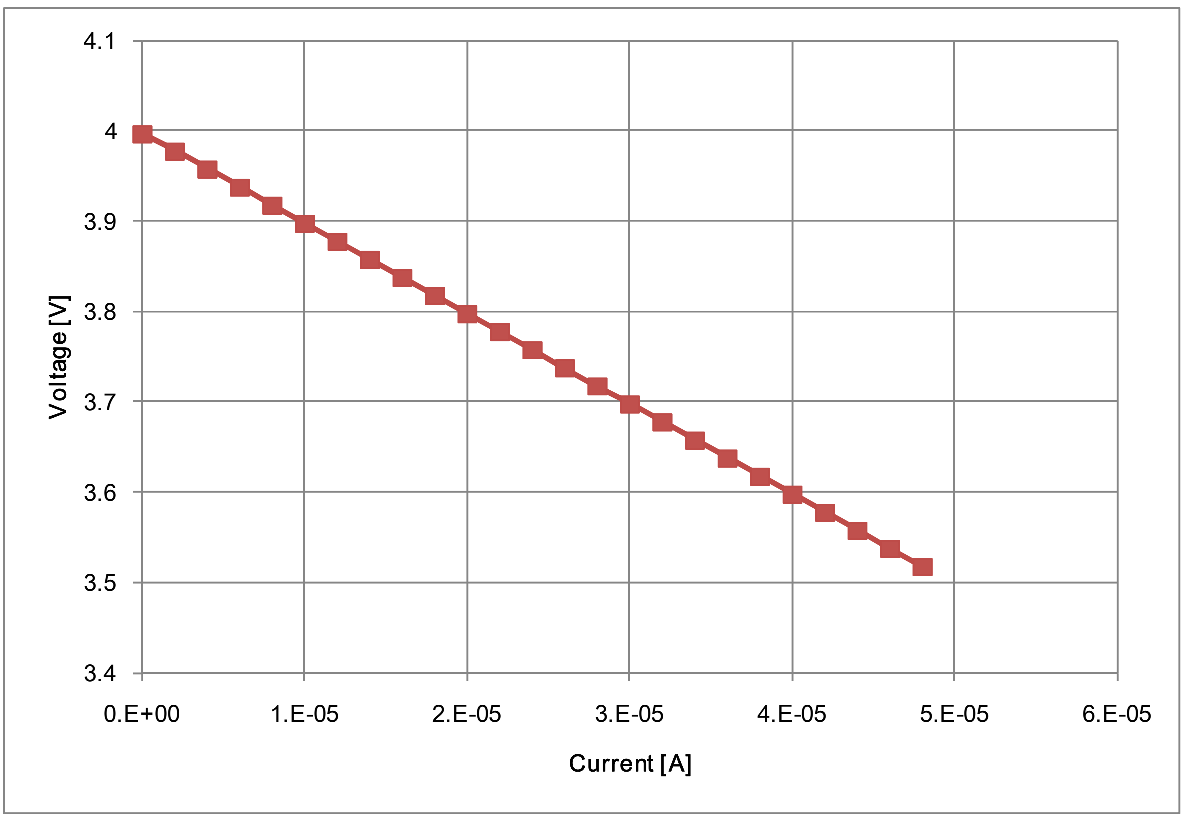



**Figure 12 B2961A/B2962A channel output, emulation result of a battery**