

Electronic Load

EL1002
(Operation Manual)

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1 Electronic load EL1002

Zahner products are carefully manufactured, calibrated and tested to ensure our high-quality standard. Packing of the electronic load EL1002 and accessories is done with great care to avoid damage during transport. Upon receipt of the Zahner shipment, please check the device and accessories to make sure they are intact. If a product is damaged during shipment, please immediately contact your Zahner's service partner.

1.1 Packing List

- EL1002
- EPC42 cable
- Sense cable (Lemosa plug to blue & green twisted cables)
- USB cable
- Power cord
- USB Stick:
 - Calibration report
 - Calibration data
 - This manual (pdf)
- Zahner Analysis license key
- This manual

2 Caution

Please read the [risk assessment document](#) before operating the potentiostat.

Prevent the inputs of the potentiostat from electrostatic discharge (ESD)! ESD may damage the potentiostat. ESD-related damages are not covered by the warranty of the potentiostat. The user must make sure to discharge themselves from any electrical charge before touching the potentiostat (**TIP:** use grounded ESD-matts).

Zahner's potentiostats require a warm-up time of 30 minutes for optimum performance.

Do not leave the active objects such as batteries or fuel cells connected to the power outputs of the potentiostat when the potentiostat is switched off! This may damage the potentiostat.

To drive high currents with an EL1002, the customer must use a cable set recommended for high current applications and fasten it to the terminals with suitable cable lugs.

Pay attention to the cable connection schemes and strictly follow the guidelines of this manual. A connection scheme with reversed polarity may damage your device.

During operation, the potential directly on the positive (+) terminal of the EL1002 should be at least 1 V higher than the negative (–) terminal.

Always turn ON the EL1002 after turning on the external load or the external power supply (if any is connected).

No current should flow through the EL1002 immediately after turning on the EL1002.

No current should flow through the EL1002 immediately after selecting the EL1002 in Thales software until the startup calibration is finished.

Always turn OFF the EL1002 prior to turning OFF the external load or the external power supply (if any is connected).

Properly fasten the EPC42 cable with the EL1002 using screws. Accidental unplugging of the EPC42 cable during operation may damage your device.

When working with high currents, remove all metallic jewelry/watches which can possibly create short circuits.

Don't touch the electrical connections during operation.

Never expose potentials higher than 100 V to the EL1002.

The maximum current through the positive (+) terminal of EL1002 must never exceed 200 A.

The maximum current through the shunt/current measurement unit of the EL1002 must never exceed 680 A.

The current cables from EL1002 to the test object must be as short and thick as possible.

During EL1002 start up and calibration, do not sink external DC current.

3 Introduction

Zahner's electronic load EL1002 can be used as an extension to the ZENNIUM series potentiostat or in a stand-alone configuration. In the following sections, both scenarios are discussed.

3.1 Modular concept – extension to ZENNIUM series potentiostat

3.1.1 EL1002 electronic load

Dynamic measurements (e.g. impedance spectroscopy) on electrochemical objects is a topic of high interest in the field of electrochemistry. Modern EIS instruments cover a broad frequency range from μHz to MHz and can handle impedances ranging from $\mu\Omega$ to $\text{G}\Omega$. However, the maximum applied current is mostly limited to a few amperes. For many applications in the field of batteries and fuel cells, measurements at high currents are desired. For the ZENNIUM series potentiostats, the current range can be significantly extended using Zahner's electronic load EL1002.

The EL1002 is a single quadrant potentiostat (**it can sink but cannot source current**) and is designed to be used as an extension of the ZENNIUM potentiostat to investigate high power electrochemical systems. The highly dynamic EL1002 load is optimized for galvanostatic EIS measurements up to 100 kHz on energy storage and conversion devices such as proton-exchange membrane (PEM) and solid oxide (SO) fuel cells.

The EL1002 allows for power dissipation of up to 1 kW in terms of voltages up to 100 V and currents up to 200 A. In combination with a third-party instrument (electronic loads or sources), measurements at higher currents (up to 680 A) can be carried out. Moreover, the EL1002 setup can be combined in different ways with power supplies to allow for measurements on electrolyzers and large format batteries.

Equipping our ZENNIUM potentiostat with our parallel measurement channel cards ([PAD4](#)), the EL1002 and an optional power supply upgrades the whole system as an optimal system for all kinds of stack measurements on batteries, fuel cells and electrolyzers. For the connection of the EL1002 with the ZENNIUM potentiostat, an [EPC42 interface card](#) is also used.

3.1.2 EPC42 controller card

An EPC42 card has 4 connection ports by which up to 4 external devices (PP2X2, XPOT2, EL1002) can be connected. Up to four EPC42 cards can be installed in a ZENNIUM series potentiostat. Therefore, a total of up to 16 external devices (PP2X2, XPOT2, EL1002) can be connected to a ZENNIUM series potentiostat with four EPC42 cards.

Each port of the EPC42 card provides analogue and digital interfaces for the communication between the electronic load and the ZENNIUM potentiostat. The analogue part of the port feeds the electronic load with a signal which dictates DC voltage as well as AC amplitude at a resolution of 16 bit. The current and voltage signals measured by the electronic load are forwarded via the digital part of the port to the ZENNIUM, where they are processed in the same way as the signals from the internal cards. This means the signals are quantized with up to 24 bits. The EPC42 card provides a bandwidth of 250 kHz.

A bi-directional serial communication line allows to digitally control the external potentiostat functions and measuring ranges.

Multiple external power potentiostats or loads can be simultaneously connected to a ZENNIUM series potentiostat but can only be operated sequentially. Simultaneously controlling multiple external device in the modular mode is not possible.

Never plug or unplug the D-SUB connector at the backside of the EL1002 while the ZENNIUM is switched on. Otherwise, the devices and the object may be damaged. It is recommended to fasten the D-SUB connector with the screws to prevent accidental unplugging.

3.2 Stand-alone mode

Zahner's power potentiostats or electronic loads (PP2X2, XPOT2, EL1002) can also be operated in stand-alone mode, for which a Windows 10/11 or Linux computer is necessary. For software updates, Windows 10/11 is required and the use of a virtual machine is not permitted. The application of a USB hub for connecting the device is not recommended.

The PP2X2/XPOT2/EL1002 potentiostat can also be controlled with other third-party software (e.g., Python). This allows for the integration in already established experimental setups. The potentiostats provide serial interfaces via the USB serial port which can be used to communicate with the potentiostat via the SCPI protocol.

In the future, it is planned that the ethernet interface will be activated via a free software update.

Zahner has prepared a GitHub library for controlling the PP2X2/XPOT2/EL1002 potentiostats with Python via SCPI:

https://github.com/Zahner-elektrik/zahner_potentiostat

And a GitHub repository with examples using the library:

<https://github.com/Zahner-elektrik/Zahner-Remote-Python>

The API documentation can be found at:

https://doc.zahner.de/zahner_potentiostat

Only DC measurements can be carried out in the stand-alone mode.

4 Operation basics

The EL1002 electronic load is a one quadrant potentiostat. This means that it can sink (but cannot source) current in a fixed, given polarity. Hence, when the EL1002 is connected to a battery, it can only discharge the battery, while charging is not possible without a third-party source.

Typical applications of the EL1002 are discharging experiments at (rechargeable) batteries and fuel cells. The EL1002 can be operated in both potentiostatic and galvanostatic modes, controlled by the software. For low impedance objects such as batteries and fuel cells, the galvanostatic mode is highly recommended. The EL1002 is optimized for galvanostatic impedance measurements.

4.1 Signals & connections



Fig. 1: EL1002 front panel



Fig. 2: EL1002 back panel

4.1.1 Conductor rails

The EL1002 copper rails feature M10 screw threads for proper mounting of the cables. The screws should be tightened with a maximum torque of 47 Nm, corresponding to the torque of screws with a strength class of 8.8. The screws must be driven through the entire copper rail (15 mm thread depth in the copper). It is recommended to use screws with a strength class of 8.8 and a length exceeding 15 mm, depending on the thickness of the cable lug.

EL1002 has three terminals at the backside of the device labeled as positive (+), negative (-) and external positive (EXT+) terminals. The EL1002 only allows current (I) flow into one direction from the + to the - terminal. This means that a device under test (DUT) e.g., a battery may only be connected to the EL1002 in one polarity. Always connect the negative (-) pole i.e., anode of a battery with the - terminal of the EL1002 and the positive (+) pole i.e., cathode of a battery with the + terminal. If the DUT is connected to the EL1002 using wrong polarity, the polarity error LED will light up. However, when the EL1002 is combined with an external power supply via the EXT+ terminal (see chapter 6), then the current (i) may flow into both directions between the EXT+ and - terminals.

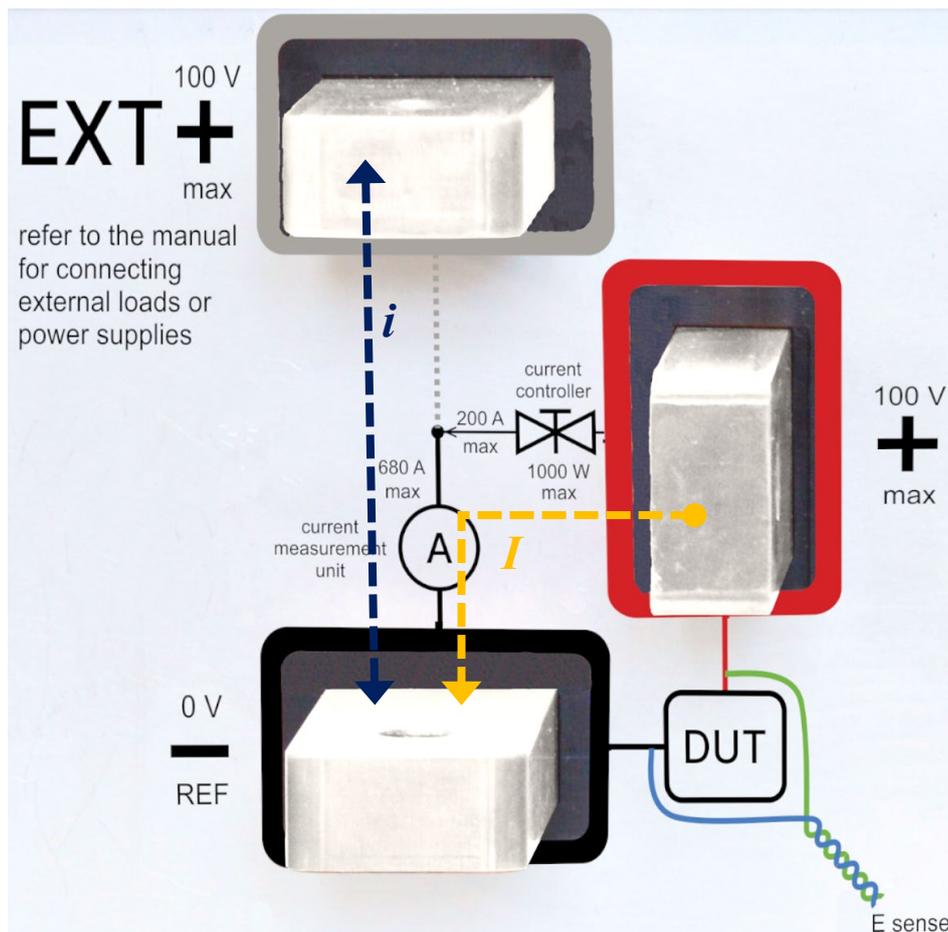


Fig. 3: EL1002 connection scheme

For simplification, we will distinguish the current between the + and - terminals of EL1002 with I and current between EXT+ and - terminals of EL1002 with i .

The current I is limited to +200 A (unidirectional, single quadrant, sink).

The current i is limited to ± 680 A (bidirectional).

4.1.2 Safety interlock

The output stage of the EL1002 can be switched off by a **potential-free** relay contact by opening the interlock contact. The cable should be as short as possible and twisted to avoid interferences. The connection from the copper rails EXT+ to - is not interrupted when the interlock is opened.

The EL1002 and the software do not recognize whether the interlock is open or closed.

The interlock only interrupts the gate voltage (control voltage) of the power transistors of the current controller. No relay or anything comparable is opened. If the power transistors are faulty and short-circuited, they cannot be interrupted.

Carefully read the [risk assessment document](#) for the operation of the EL1002.

4.1.3 Signal LEDs & buzzer

The EL1002 is equipped with various signal and warning LEDs on the front panel as well as a buzzer.

The status LED lights up green when the CPU of the EL1002 is running and the device is ready for use. When the CPU is busy with a task or command, the status LED lights up orange. The active LED lights up green when the power supply of the device is switched on. When the output stage (current controller) of the EL1002 is switched on, the LED lights up orange.

The polarity error indicating wrong connection between EL1002 and an active object is only shown by a LED as warning signal. All other errors such as over-current or over-voltage, power or temperature limits are displayed by LEDs' lighting up above certain threshold values and additional buzzers beeping above a second set of threshold values.

The warning threshold at which the LEDs start to light up is set at about 95% of the maximum allowed limits, whereas the buzzer sets in when the limit is exceeded.

4.2 Operation steps

1. Turn **ON** external power supply/load (if it is planned to be used).
2. Turn **ON** the ZENNIUM device as well as the EL1002 and allow for 30 minutes of warm-up time.
3. Start the Thales software.
4. Select the EL1002 device in the **Test Sampling Window**. This will initiate a calibration procedure of EL1002. At this time, no current should flow between EXT+ and - terminals under any circumstances.
5. Select the desired potential range and reference electrode.
6. Connect the sense cables to the DUT with correct polarity – connect the blue sense cable to the negative terminal and the green sense cable to the positive terminal of the DUT.
7. The displayed potentials in the **Test Sampling Window** must be **negative**.
8. The potential difference between the positive and negative terminal of EL1002 must not exceed the selected voltage range of 4 V or 100 V, respectively (absolute limit: 100 V)
9. Connect the power cables to the DUT (as well as to an external power supply or load/sink, if necessary) according to the preferred configuration.
10. Connect the PAD4 sensing cables (if required) and activate the data acquisition from PAD4 cards in the Thales software.
11. Select the potentiostatic or galvanostatic mode and turn **ON** (for low Ohmic DUT the galvanostatic mode is recommended).
12. Perform the experiment.
13. Turn **OFF** the potentiostat/galvanostat.
14. Shut down the Thales software.
15. Turn **OFF** the EL1002 and ZENNIUM.
16. Turn **OFF** the external power supply/load.
17. Remove all the cables (sense and power cables).

If the external power supply is required to supply the DUT, skip the last two steps.

▲□ Do not sink external DC current during EL1002 start up and calibration. No current is allowed to flow through the current measuring device, otherwise it will be calibrated as an offset.

5 Thales software

The EL1002 requires Thales version 5.8.3 or later.

All external potentiostats or the EL1002 are directly controlled by the Thales software. In Thales, each device has a unique device number which is identical to the EPC42 port number to which the external potentiostat or EL1002 is connected, if no RMUX card is installed. For example, if a device is connected to EPC port 3, then in Thales the device is addressed as “device number 3”. Device number 0 is reserved for the internal main potentiostat of the ZENNIUM series potentiostat.

If a RMUX4 or RMUX16 (relay multiplexer) card is installed in a ZENNIUM series potentiostat, then the first 4 or 16 device numbers (per RMUX card) are assigned to the RMUX channels, respectively. Hence, if one RMUX16 card is installed, the device numbers 1-16 are assigned to the RMUX16 channels. Similarly, if 2 RMUX16 cards are installed, the device numbers 1-32 are assigned to the RMUX16 channels.

To select a potentiostat in the Thales software, follow these steps:

1. Start the Thales software in the classic mode.
2. Click on the “EIS” icon.
3. Click on “Control potentiostat”.
4. Click on the “DEVICE” button in “Test sampling & control potentiostat” window.

By clicking on the “DEVICE” button, an input box opens where the user can type in the device number. After confirming, the device is selected and the type of device is displayed.



Fig. 4: Selecting an external potentiostat in the test sampling window. DEVICE 1: EL1002 indicates that the EL1002 is connected to the port 1 of the EPC42 card.

If no device is connected to the selected EPC42 port, an error message is displayed and the Thales software automatically switches to the internal potentiostat.

If the selected device is connected, the Thales software automatically starts the start-up calibration routine of the external potentiostats upon selection.

Thales outputs an error message if no calibration data is found for the device and a question mark (?) is displayed after the calibration button on the GUI.

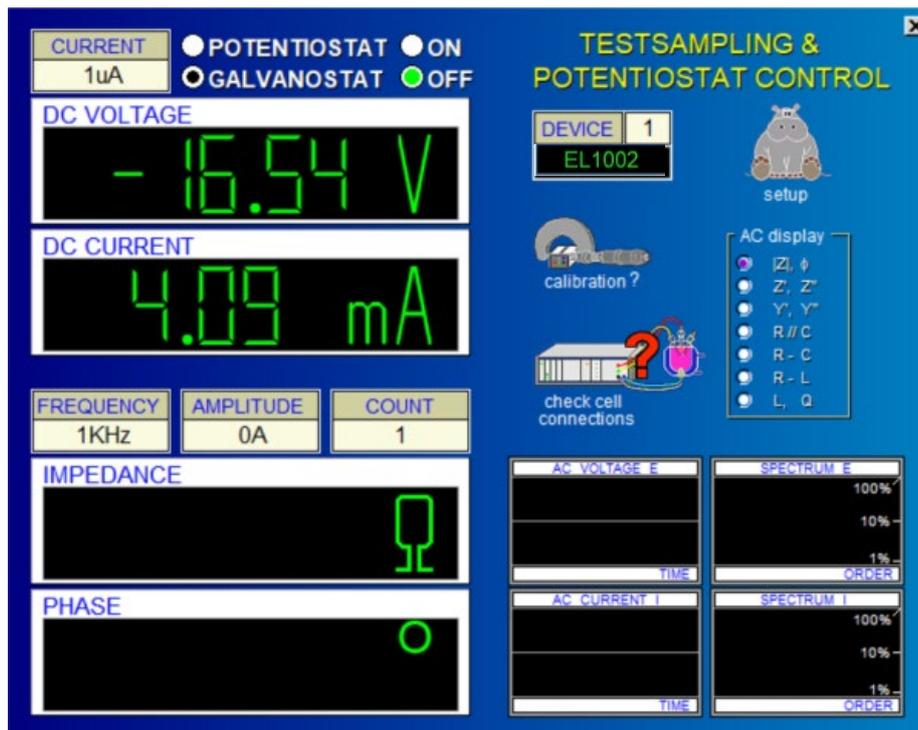


Fig. 5: Test sampling page

Connect the blue sense cable to the negative (-) terminal and the green sense cable to the positive (+) terminal of the DUT. This will lead to correct polarity display and a **negative potential** in the DC VOLTAGE window.

When the mouse cursor hovers above a button or input box and the item is highlighted, the current and voltage displays are **not** updated.

In "check cell connections" one can set the desired potential range (4 V / 100 V) and may choose a reference electrode. For convenience, the EL1000 connection scheme with the third-party DC load is shown in Fig. 6 (same for EL1002).

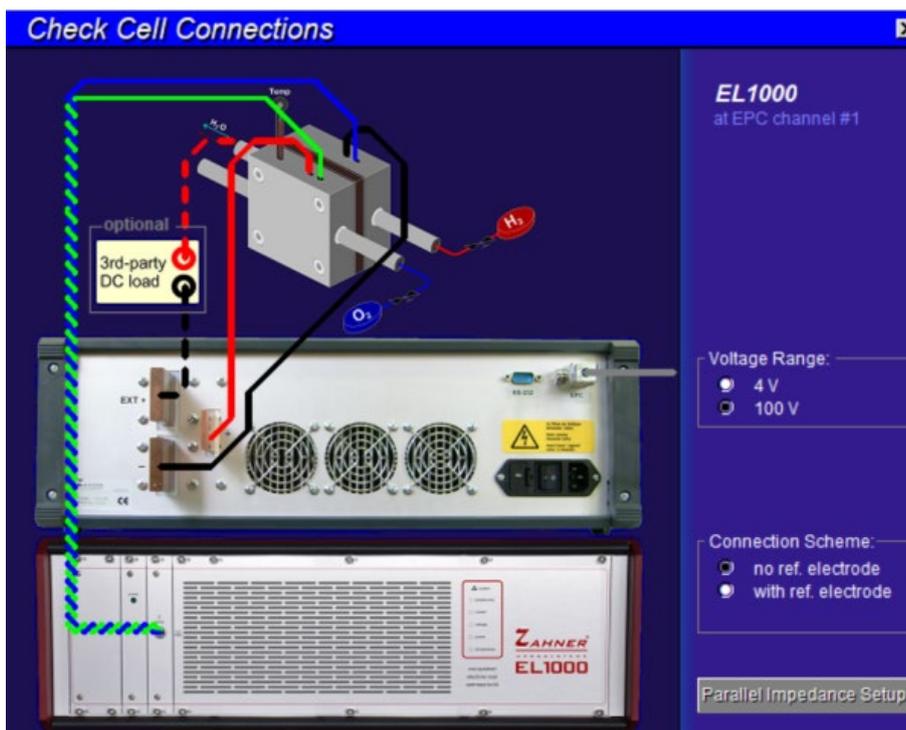


Fig. 6: Check Cell Connections page

After choosing the desired voltage range and the reference electrode settings, one may connect the sense cables from the EL1002 to the DUT. Thereafter, connect the power cables used for the desired EL1002 arrangement, making sure the correct polarity. Please note that by connecting the power cables, the potential **must not change considerably** (connect power cables as shown for your preferred arrangement in the manual below). If the voltage changes when the DUT is connected to a switched-off EL1002, there is probably a fault in the circuit.

When the DUT is connected correctly, the **voltage is negative** and the **current** flowing into the EL1002 is **positive**.

When changing the device number, the now unselected external potentiostat or EL1002 will hold its DC conditions such as DC potential or current and its on/off status until the settings are changed again.

Voltage and current outputs of the unselected external potentiostat are **not measured** and are **not monitored** for defined voltage/current limits.

Only the selected external potentiostat is internally connected to the FRA of the ZENNIUM series potentiostat. Therefore, only the active external potentiostat can output an AC signal for EIS.

6 Cell connection fundamentals

All Zahner’s potentiostats follow the same 4-electrode cell connection scheme, which is also referred to as 4-terminal sensing or Kelvin connection. This includes connections to the working electrode (copper rail denoted with –), counter electrode (copper rail denoted with +), working electrode sense (WES), and reference electrode (RE). These connections are specified by their color code, with WES: blue and RE: green, while the copper rails are labelled on the rear panel. To minimize interference due to stray- and mutual inductance, the power cables (current-carrying cables) should be twisted around each other to the longest-possible length, and moreover, the green and blue sense cables should also be twisted. For simplification, twisting is not depicted in the schematic below.

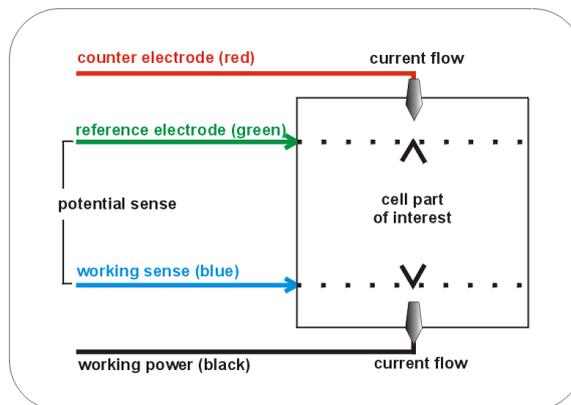


Fig. 7: 4-electrode connection scheme. The current is conducted through the black (WE) and red (CE) wires. The voltage is measured between the green (RE) and blue (WES) wires.

For high current flow, the 4-electrode connection scheme is highly recommended to minimize the error margin in the measurement, especially when using the EL1002.

6.1 Contact resistance

Fig. 8 shows a typical electrical wire connection between the potentiostat and the test object. The resistance of the wire can be divided into two parts, being the wire resistance and the contact resistance.

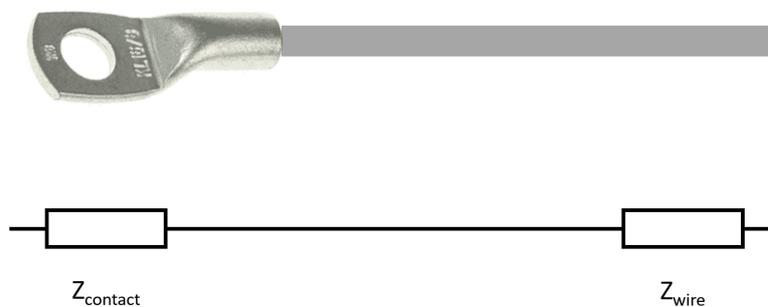


Fig. 8: Typical electrical wire used to contact potentiostat with a test object. Resistance of the electrical wire is divided into two different parts. 1) contact resistance Z_{contact} and 2) wire resistance Z_{wire} .

6.2 Four-electrode cell connection scheme

The advantage of a 4-electrode connection scheme is illustrated in Fig. 9. A pouch cell is connected to the ZENNIUM potentiostat using a 4-electrode connection scheme. With the WES and RE being directly connected to the pouch-cell, the contact resistance for the WE and CE can be ignored as they don't affect the voltage drop between WES and RE, which cannot be realized in a 2-electrode connection.

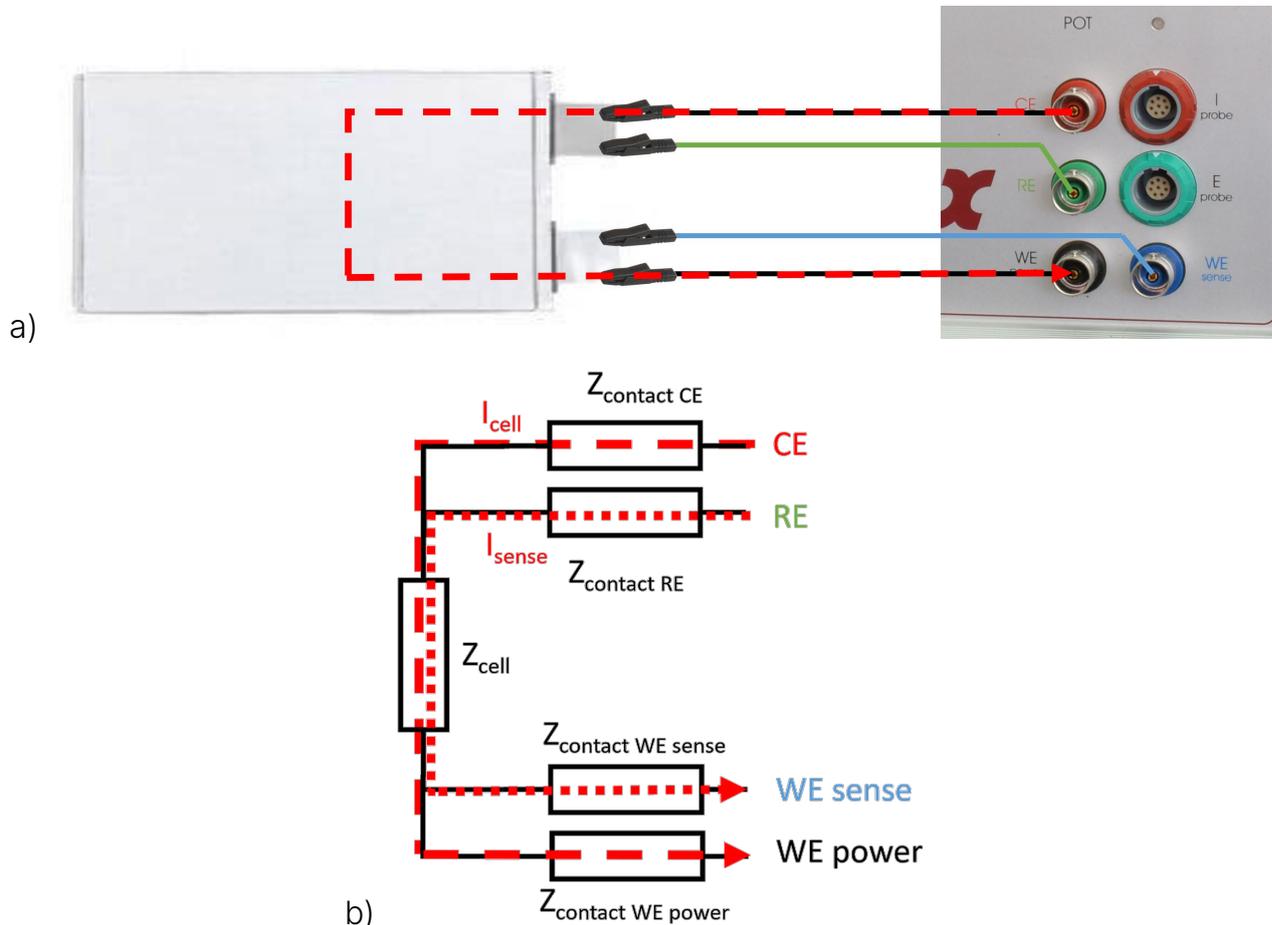


Fig. 9: (a) 4-electrode connection scheme for a 2-electrode pouch cell. For optimum measurement results, the WE and CE as well as the RE and WES cables must be **twisted** around each other as separate pairs (not displayed in the image). (b) Electrical equivalent circuit of the cell connection displayed in (a).

In this chapter, images from the ZENNIUM potentiostat are used for the sake of simplicity and to explain the two and four electrode connection scheme. When working with EL1002, the BNC connectors of the ZENNIUM potentiostat shall be left unconnected and should not be connected to the test object.

The voltage across the pouch-cell can be calculated using the following equation. The intrinsic cell voltage is neglected in this consideration.

$$U_{Ref} = Z_{cell} * (I_{cell} + I_{sense}) + Z_{contact-RE} * I_{sense} + Z_{contact-WES} * I_{sense} \quad (1)$$

Due to the high input-impedance of the potentiostat (many orders of magnitude higher than Z_{cell}), the input current I_{sense} flowing into the sense inputs is close to zero.

$$I_{sense} \sim \frac{1}{R_{IN}} \approx \frac{1}{\infty} \approx 0 \quad (2)$$

With $I_{sense} = 0$, equation 1 can be simplified to

$$U_{Ref} = Z_{cell} * I_{cell} \quad (3)$$

$$Z_{cell} = \frac{U_{Ref}}{I_{cell}} \quad (4)$$

Using the 4-electrode connection scheme, the contact resistances do not influence the measured cell impedance, as long as the cell impedance is much smaller than the object impedance.

6.3 Two-electrode cell connection scheme

Fig. 10 shows a 2-electrode cell connection scheme for measurements on a pouch cells. The WE and the WES cables are clamped together and connected to one electrode. Similarly, the RE and the CE cables are clamped together and connected to the other electrode.

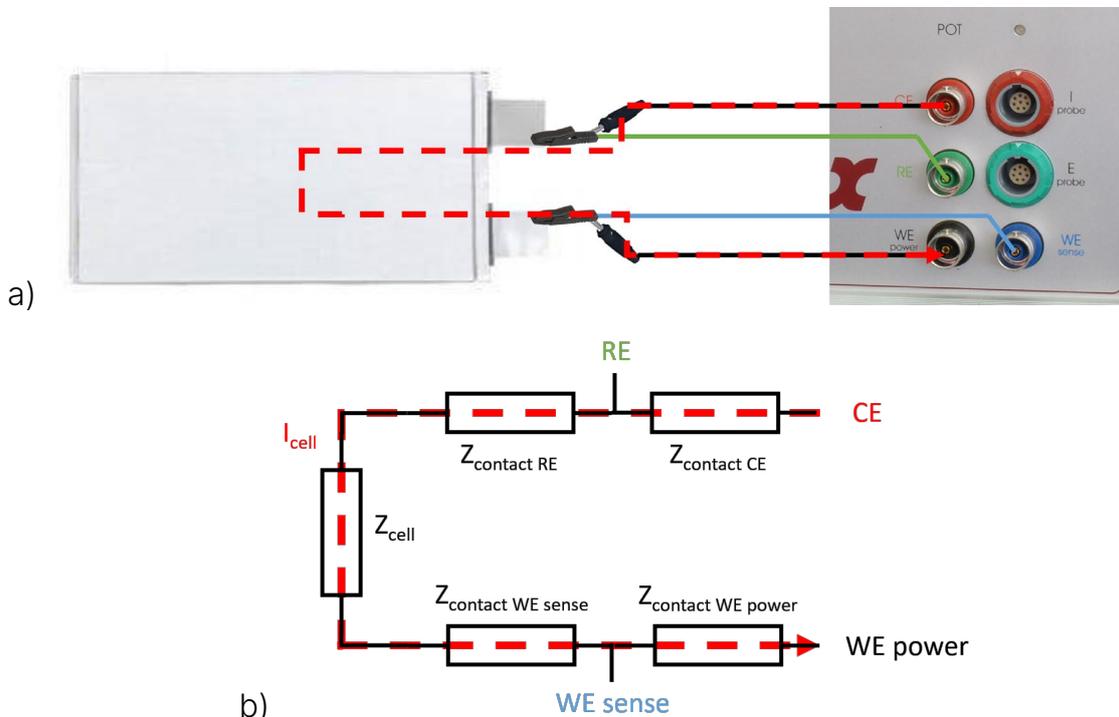


Fig. 10: a) Illustration of a 2-electrode connection scheme for a 2-electrode pouch cell. (b) Electrical equivalent circuit of the cell connection displayed in (a).

Here, the voltage can be calculated using the equation below, again neglecting the intrinsic cell voltage:

$$U_{Ref} = (Z_{cell} + Z_{contact-RE} + Z_{contact-WES}) * (I_{cell} + I_{sense}) \quad (5)$$

The currents (I_{cell} and I_{sense}) are flowing through the pouch cell and the WES- and the RE contacts. Neglecting the small sense current (I_{sense}) flowing into the input of the potentiostat, eq. 5 can be simplified:

$$U_{Ref} = (Z_{cell} + Z_{contact-RE} + Z_{contact-WES}) * I_{cell} \quad (6)$$

Eq. 6 shows that the calculated voltage of the pouch cell includes the voltage drop occurring at the RE and WES contacts.

6.4 Parasitic inductances

For low impedance objects and applications with high current amplitudes in the >1 A current range, particular attention must be paid to the measurement setup and wiring, since the parasitic resistances and inductances of the cabling can become as large as the impedance of the object under test.

As an example, a commercially available 70 mm² copper wire with 1 m length and cable lugs for the connections is examined, which could be used to connect the EL1002 to the object. Two of these wires are attached to each other by cable ties to minimize the mutual inductance. Theoretically, twisting the cables around each other is the most preferable configuration as the magnetic fields are mutually compensated (canceled out), most effectively. However, it is difficult to twist the wires with a wire cross section of 70 mm². Fig. 11 shows the pair of wires to be analyzed.



Fig. 11: Pair of wires which is analyzed.

These cables are screwed together with a cable lug at one end to determine the inductance and resistance of the cable without a connected DUT. Afterwards, an impedance spectrum is measured which is fitted by a resistance and an inductance.

Fig. 12 shows two impedance spectra in the bode representation. The phase is plotted in red and the magnitude of the impedance in blue. The solid lines shows the measurement result of the 70 mm² and 1 m long wire pair described above. The dashed lines are the measurement result of a similar wire pair with 2 m length.

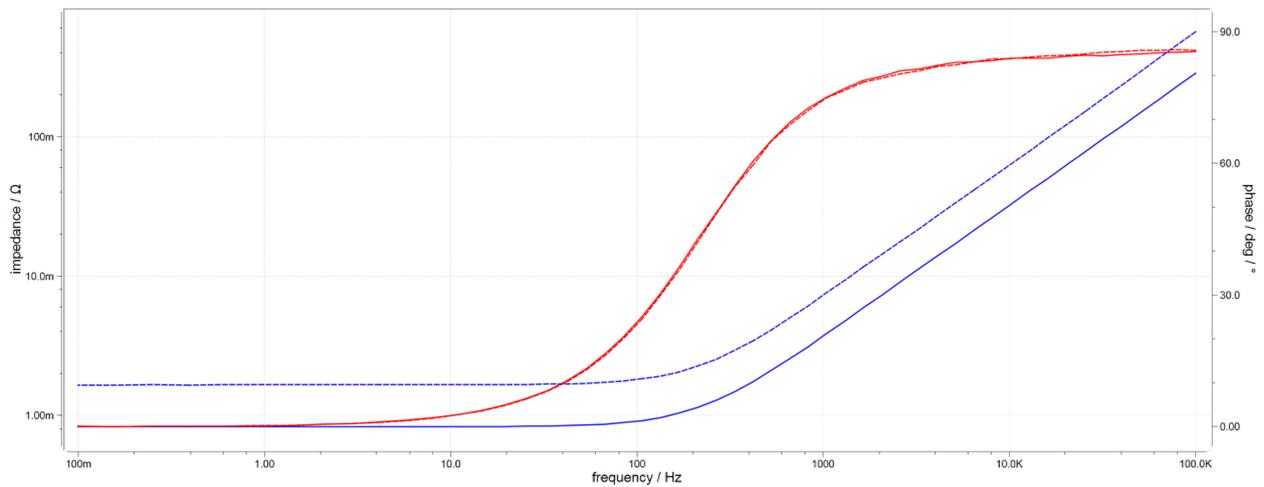


Fig. 12: Impedance spectra of 1 m (solid lines) and 2 m (dashed lines) connected wire pairs (70 mm²) in Bode representation.

The fitting results for the 1 m wire pair read as 828 μΩ resistance and 529 nH inductance. The real impedance is even higher than the result of the fit, because the parasitic wire inductance is not an ideal inductance due to the [skin effect](#) and the [proximity effect](#). The fitting results for the 2 m cable pair amount to 1.65 mΩ and 1.03 μH, which is about twice the resistance and inductance compared to the 1 m cable. This measurement was performed to demonstrate that the parasitic elements are directly proportional to the cable length. Therefore, the 2 m wire pair will not be considered further in the following.

The 1 m wire pair can be treated as a series connection of 828 μΩ and 529 nH. This must be carefully considered especially in impedance measurements due to the voltage drop at the cable impedance. The latter splits up between the two wires when the test object is connected between both cables. This setup is shown in Fig. 13:

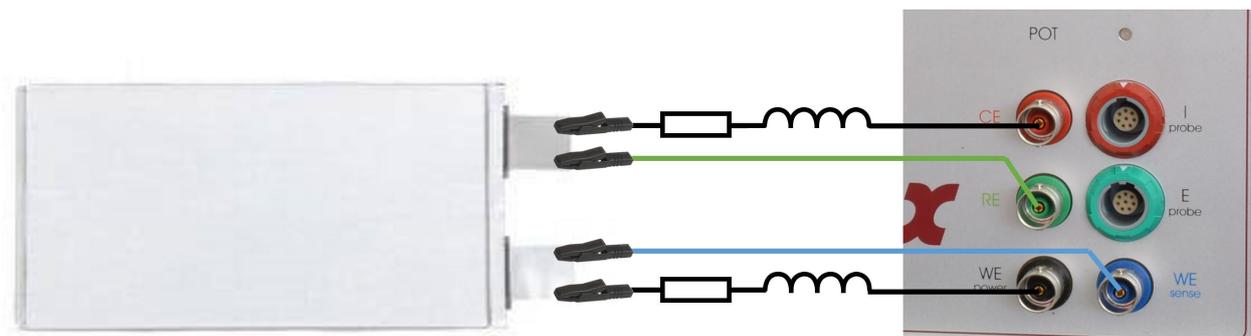


Fig. 13: 4-electrode connection scheme considering the parasitic elements resistance and inductance within the current-carrying wires.

The following table shows the theoretical cable impedance and the peak voltage amplitude that would drop across the cable at 10 A_{AC} peak current amplitude for different frequencies, using the 1 m cable pair:

Frequency	Impedance	Peak Voltage Amplitude @ 10 A _{AC}
100 Hz	892 $\mu\Omega$	8.92 mV
1 kHz	3.43 m Ω	34.3 mV
10 kHz	33.2 m Ω	332 mV
50 kHz	166 m Ω	1.66 V
100 kHz	332 m Ω	3.32 V

Consider a battery with a typical voltage of about 3 V, it can easily be seen that measurements above 100 kHz become very difficult as the compliance voltage necessary for a sufficient amplitude becomes too low. The EL1002 also requires a voltage drop of 1 V between its + and – terminals for proper functioning. This means that the maximum affordable voltage drop in this case is 2 V. This further restricts the upper frequency limit for impedance measurement on the 3 V battery to somewhat between 50 kHz and 100 kHz. At higher frequencies, the voltage drop in the cables will consume most of the compliance voltage, leaving less than 1 V between the EL1002's + and – terminals. If the voltage falls below 1 V, the control loop of the EL1002 will not work properly, causing collapsed amplitude and/or distorted excitation signal (current or voltage). In such cases, an external power supply is required which can compensate for the voltage drop (further info in section 7.4).

The voltage drop problem also exists when using four-quadrant potentiostats like ZENNIUM series potentiostat or PP2X2, however, these have a high output (compliance) voltage range, such as the 28 V of the ZENNIUM PRO potentiostat. This makes the object voltage less relevant as the voltage drop across the wire can be compensated. Electronic loads or one-quadrant potentiostats such as the EL1002 do not have a voltage output that could compensate for voltage drops.

In summary it should be noted that the cabling is essential for high current applications. The cable should be as short as possible with a high cross section. The inductance of the setup should be kept as small as possible by using cables that are brought together as close as possible, in the best-case coaxial cables or densely twisted cable pairs.

7 Connection configurations

The following chapter describes the different connection schemes of the EL1002 for measurement setups with and without external source or load.

The EL1002 must only be connected to or disconnected from the ZENNIUM system if both the ZENNIUM and the EL1002 are switched off.

It is important to know that EL potentiostats SINK current from the DUT and therefore the cell cables must be as short and thick as possible to minimize the resistive losses. In the case of very long cables, the measurements may be faulty and it may even look as if the EL1002 is defective.

It is also important to connect the DUT to the EL1002 with the correct polarity. For the case of wrong connections, the EL1002 has a protection circuit which will indicate a polarity error. To avoid polarity error issue, we recommend connecting the sense cables before connecting the power cables as described in chapter 4.

For the sake of convenience and simplicity, we will distinguish the current between the + and – terminals of the EL1002 denoted as I from the current between the EXT+ and – terminals of the EL1002 denoted as i .

7.1 Applications for the EL1002 without external devices

7.1.1 Full cell configuration (standard Kelvin scheme)

This configuration is used with DUTs like (rechargeable) batteries and fuel cells if a complete cell is to be investigated. First, the sense cables are attached to the DUT with the correct polarity and then the power cables are connected. Since EL1002 is a one-quadrant potentiostat, it cannot work as a source but only as an electronic load. Hence, it is recommended to use as short and thick cables as possible to minimize the resistive losses during operation.

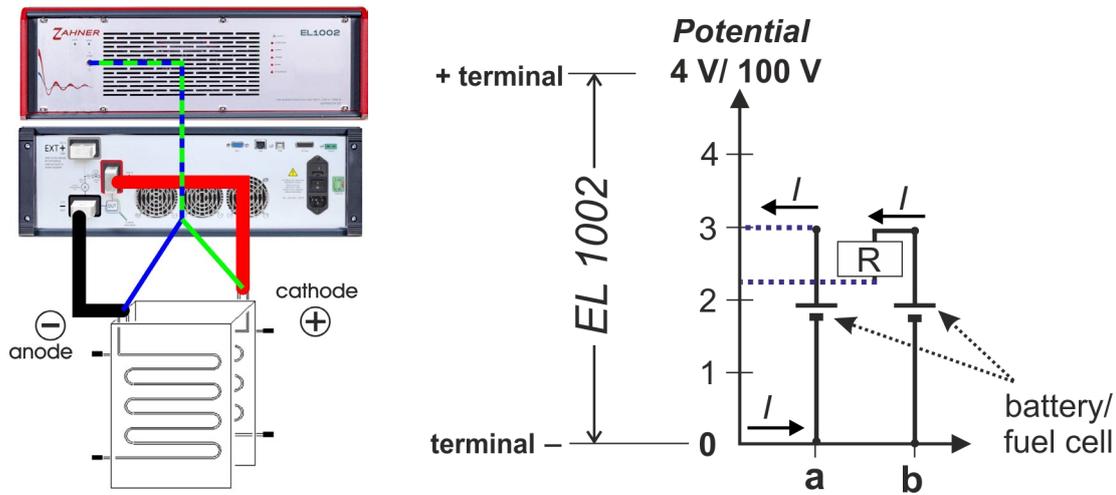


Fig. 14: One-quadrant representation showing a battery or fuel cell connected to the EL1002.

The graph in Fig. 14 shows the one-quadrant representation of the EL1002 connection with a DUT (i.e., 3 V battery or fuel cell stack). In this graph, the X-axis represents the - terminal of the EL1002 and Y-axis represents the voltage difference between the - and + terminals of EL1002 (with a maximum potential limit of 100 V). In part a), the anode (negative electrode) of the DUT is connected to the - terminal (X-axis) of EL1002, while the cathode (positive electrode) is connected to the + terminal of EL1002 (connected to the Y-axis via the blue dashed line). In this configuration, the potential is positive but will be displayed as a negative value in the Thales software.

In this representation, the current flows counter-clockwise (i.e., current > 0). The EL1002 measures the potential with the sense cables and will always display the correct voltage of the DUT, here -3 V. However, the potential between the terminals of the EL1002 will be less than 3 V. This decrease (Fig. 14, b) is caused by the voltage drop ($U_{\text{drop}} = R \cdot I$) within the system, which depends on the current flowing through the system. If the current is high then the voltage drop will also be high. When sinking high currents from low potential cells (such as for large area fuelcell), the potential at the + terminal of EL1002 may become less than 1 V. In such conditions, the EL1002 will not work properly. Hence, when controlling current keep in mind that high currents will increase the voltage drop and pay attention to the voltage drop between the - and + terminals of EL1002.

A PAD4 card provides 4 additional channels for parallel impedance measurements on a stack. These channels allow for a simultaneous investigation of several different parts of the DUT. With a ZENNIUM X, up to 4 PAD4 cards can be installed which allows for up to 17 parallel impedance measurements on a stack. A possible application of such a setup is the simultaneous investigation of 17 cells in a battery or a fuel cell stack as shown in Fig. 15. The sensor cables (green and blue) of the PAD4 card must be twisted around each other in analogy to the main channel to minimize artifacts.

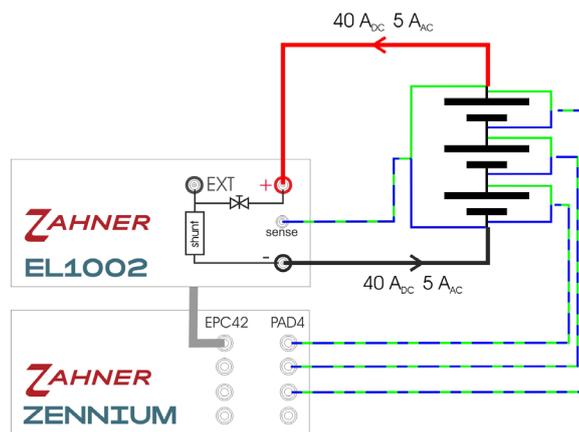


Fig. 15: EL1002 with PAD4

Power dissipation (Fig. 15):

- DUT: Battery of 9 V potential at 40 A_{DC} and 5 A_{AC} amplitude for EIS
- EL1002 part of the DC current: 40 A
- EL1002 AC amplitude: 5 A
- EL1002 power dissipation: 9 V * 45 A = 405 W (<1000 W)
- The power dissipation in EL1002 is limited to 1000 W.

The voltage used to calculate the power dissipation is the one that drops across the current controller in Fig. 3, i.e., the voltage between the + terminal and EXT+ or – terminal, respectively.

If we assume, no voltage drop in the cables then the voltage of test object will be the same as the voltage drop across the current controller. In case of voltage drop in the cables, the actual power dissipation will be lower than what will be calculated using the test object voltage.

Since voltage drop in cable varies from setup to setup hence, for simplicity, we will calculate the power dissipation using the voltage of test object.

The current used to calculate power dissipation is the current that flows through the current controller, which does not necessarily have to be the same current that flows through the current measuring unit if external sources or sinks are used.

7.1.2 Half-cell configuration – Cathode

This configuration is used with DUTs such as (rechargeable) batteries and fuel cells if only the cathodic part of the cell is to be investigated.

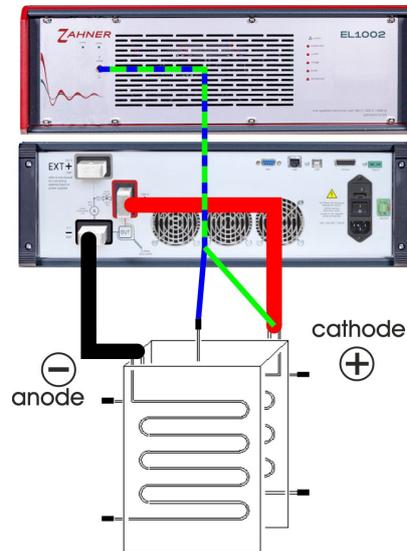


Fig. 16: Half-cell configuration - Cathode

In this case, the sense cables are only connected to the cathode and not to the complete cell.

7.1.3 Half-cell configuration – Anode

This configuration is used with DUTs such as (rechargeable) batteries and fuel cells if only the anodic part of the cell is to be investigated.

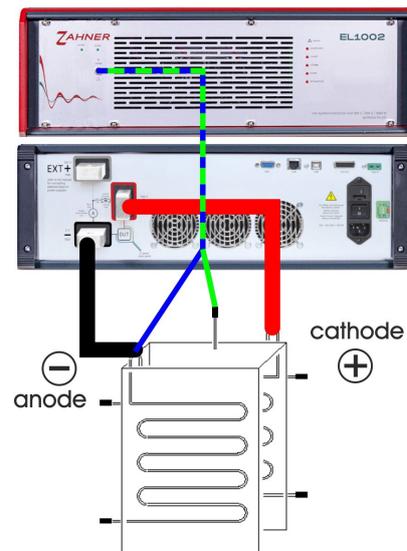


Fig. 17: Half-cell configuration - Anode

In this case, the sense cables are only connected to the anode and not to the complete cell.

7.1.4 Partial cell configuration

This configuration can be used if a certain part of a battery or fuel cell stack is to be investigated.

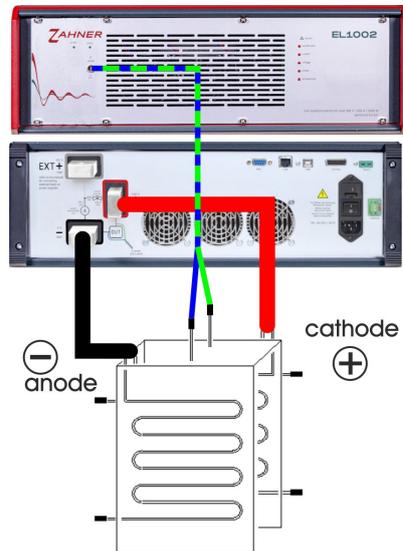


Fig. 18: Partial cell configuration

7.2 General notes for applications with external supply or load

▲□ During the startup and calibration of the EL1002, do not sink external DC current. No current is allowed to flow through the EL1002 otherwise, it will be calibrated as an offset.

The total current must **NOT EXCEED 680 A** (thereby, max. 200 A through the EL1002 current regulator).

There are two current loops and both currents flow through the EL1002 current measurement unit:

- 1) From EL1002 to DUT (I Fig. 3)
- 2) From EL1002 EXT+ to third-party load to DUT (i Fig. 3)

Make sure to switch ON the external device before switching ON the EL1002.

Make sure to switch OFF the EL1002 before switching OFF the external device.

The maximum power dissipation of the EL1002 must not exceed 1000 W.

It is recommended to test different DC currents of the EL1002, because depending on the setup the ratio of DC to AC current may affect the bandwidth of the EIS measurement or may cause interference with harmonics. A good starting value for the DC current of the external source is $I_{DC\ EL1002} = 3 * I_{AC\ EL1002}$ for measurements at the open circuit voltage/potential (OCV/OCP) of a DUT.

Note the operation steps for the devices in chapter 4.2

To give a brief note on nomenclature, a source or supply outputs constant current or constant voltage. A sink or load consumes constant voltage or constant current. To optimize the setup and to avoid artifacts in the measurement, it is important to consider whether constant current or constant voltage is given out of the external device.

In **constant voltage** operation of the external device, a low-inductive connection of the external device close to the [ideal 0 zero-Ohm internal resistance](#) is important. On the other hand, [ideal constant current](#) sources or sinks have an infinitely large internal impedance. However, this is not achievable in reality due to the control loops and the electrical construction, among other things. A high connection inductance of the device setting the DC operating point at constant current therefore has a positive effect, because the connection inductance increases the impedance of the source in the high-frequency range. This brings the real behavior closer to the ideal behavior.

To avoid errors with this more advanced setup involving an external source or sink, it is a good idea to automate the measurement process. To control the EL1002 and a power supply with Python, we provide an [example on GitHub](#).

7.3 Applications with an additional DC load

The measured current (sum of both currents sunk by the EL1002 as well as the external load) must be positive $I \geq 0$.

The external load must operate in **constant current** mode.

The current flow cannot be switched off by the EL1002 in this configuration, as it is also dependent on the external device, which is controlled separately.

7.3.1 DUT connected to the EL1002 with an additional DC load through EXT+

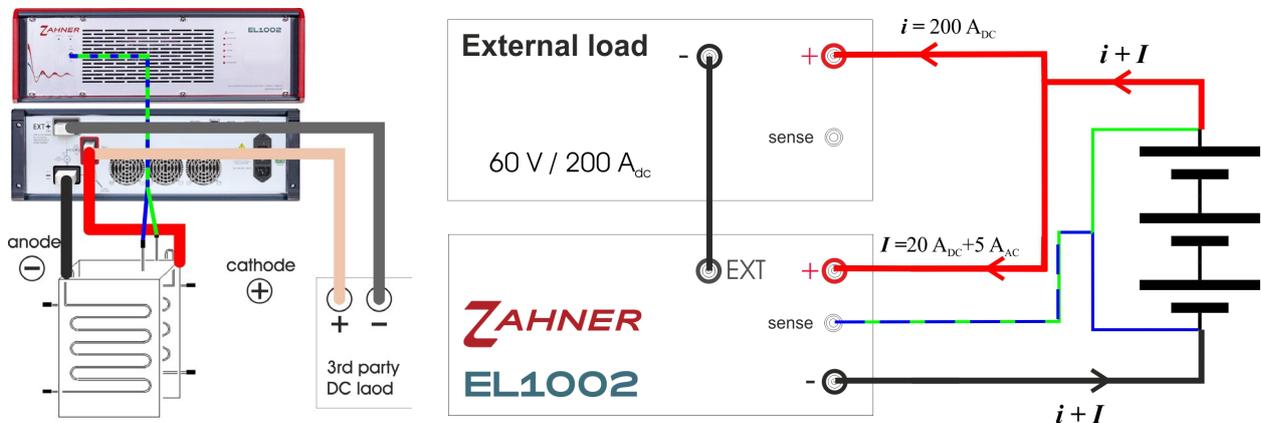


Fig. 19: EL1002 with additional DC load using EXT terminal

The image on left shows the correct cable connection scheme whereas the schematic on right emphasis on different current loops for a better understanding.

Power dissipation (Fig. 19):

DUT: Battery of 9 V potential at 220 A_{DC} and additional EIS with 5 A_{AC} amplitude

EL1002 part of the DC current: 20 A

EL1002 AC amplitude: 5 A

EL1002 power dissipation: 9 V * 25 A = 225 W (<1000 W)

External load part of the DC current: 220 A – 20 A = 200 A

The power dissipation in EL1002 is limited to 1000 W.

EIS settings in the control potentiostat menu: Galvanostatic mode, DC CURRENT 220 A, Amplitude 5 A. 200 A of the external load must be adjusted separately and directly at the external load. With these parameters, the EL1002 automatically adjusts the current flow through its + terminal so that a total of 220 A of current flows. The total current can only be greater than the current through the sink.

It is recommended to test different DC currents with the EL1002 because the ratio of DC to AC current may affect the bandwidth of the EIS measurement or cause interference with harmonics, depending on the setup. A good starting value for the DC current of the external source is $I_{DC\ EL1002} = 3 \cdot I_{AC\ EL1002}$ for measurements at the open circuit voltage/potential of a DUT.

Here, PAD4 cards can also be used to investigate the individual cells of a battery or a fuel cell stack. The potential range of PAD4 cards is fixed at ± 4 V with a compliance voltage of ± 100 V. Higher input voltage ranges can be achieved by special sense cables (± 5 V, ± 10 V, ± 12 V, ± 20 V, ± 24 V). However, the resolution of the impedance spectra measured by PAD4 channels will decrease with increasing potential range.

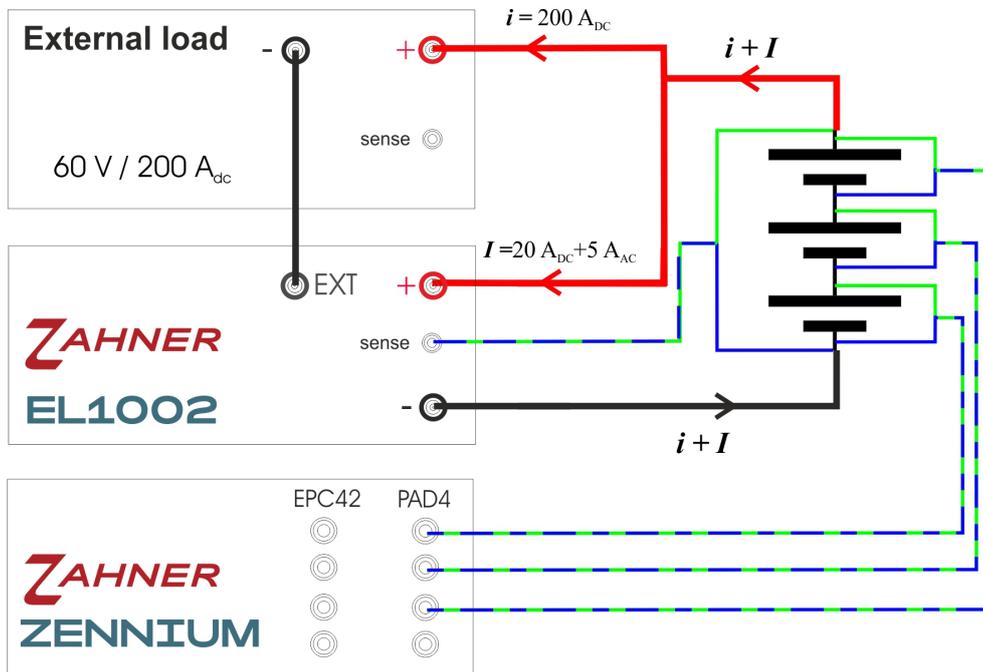


Fig. 20: EL1002 with EXT connection and PAD4

7.3.2 DUT connected to the EL1002 with a parallel DC load

To sink more current from the DUT than possible through the EXT+ extension of the EL1002 (current > 680 A), an external load can be connected in parallel to the DUT and EL1002 as shown below. This allows independent control of the EL1002 and the external load connected to the DUT.

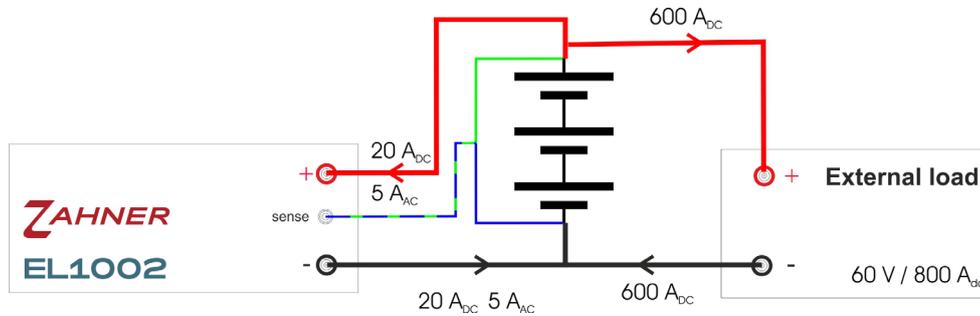


Fig. 21: EL1002 and an external electric load connected in parallel to a test object

Power dissipation (Fig. 21):

- DUT: Battery of 9 V potential
- EL1002 part of the DC current: 20 A
- EL1002 AC amplitude: 5 A
- EL1002 power dissipation: $9 \text{ V} * 25 \text{ A} = 225 \text{ W}$ (<1000 W)
- The power dissipation in EL1002 is limited to 1000 W.

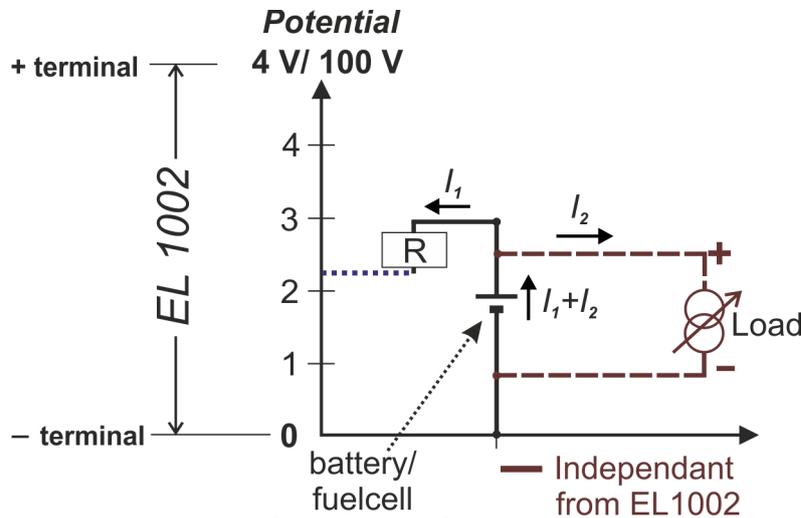


Fig. 22: One-quadrant representation of a battery or fuel cell connected to the EL1002 and a parallel external load.

Fig. 22 illustrates the two independent current loops for the parallel connection of the EL1002 and an external load with the DUT in the one-quadrant representation. Here, the current flowing through and controlled by the external load (I_2) does not flow through the EL1002 and the current limitations valid for the EL1002 do not apply to I_2 . In this configuration, the EXT + terminal of the EL1002 is not in use. The resistance (R) in Fig. 22 represents the voltage drop in the EL1002 current loop during operation.

Thales only measures and displays the current through the EL1002. In impedance measurements, the external load is also seen as a parallel object to the DUT. This makes the impedance spectrum recorded in this configuration, prone to artifacts.

In this setup, the parallel connection between the DUT and the external load is measured. However, since the DUT usually has a much lower impedance than the load, the load only has a minimal effect on the measurement. With increasing connection inductance of the load, the total impedance of the load becomes even higher, leading to a further decreased influence of the load on the high-frequency measurements.

7.4 Applications with an additional power supply in series

This configuration may be used if the voltage drop on the cabling is too high to reach the high-current test conditions. In addition, it allows experiments on passive objects, batteries under charging conditions & electrolysis cells etc.

The external power supply must operate in **constant voltage** mode.

In this application, the voltage source must be connected as low inductively as possible to avoid artifacts.

7.4.1 Electrolysis / charging batteries

For charging batteries or electrolysis, an EL1002 is connected in series with a DUT (i.e., an inversed battery) and an external power supply.

Charging batteries:

This configuration is used for experiments on batteries under charging conditions.

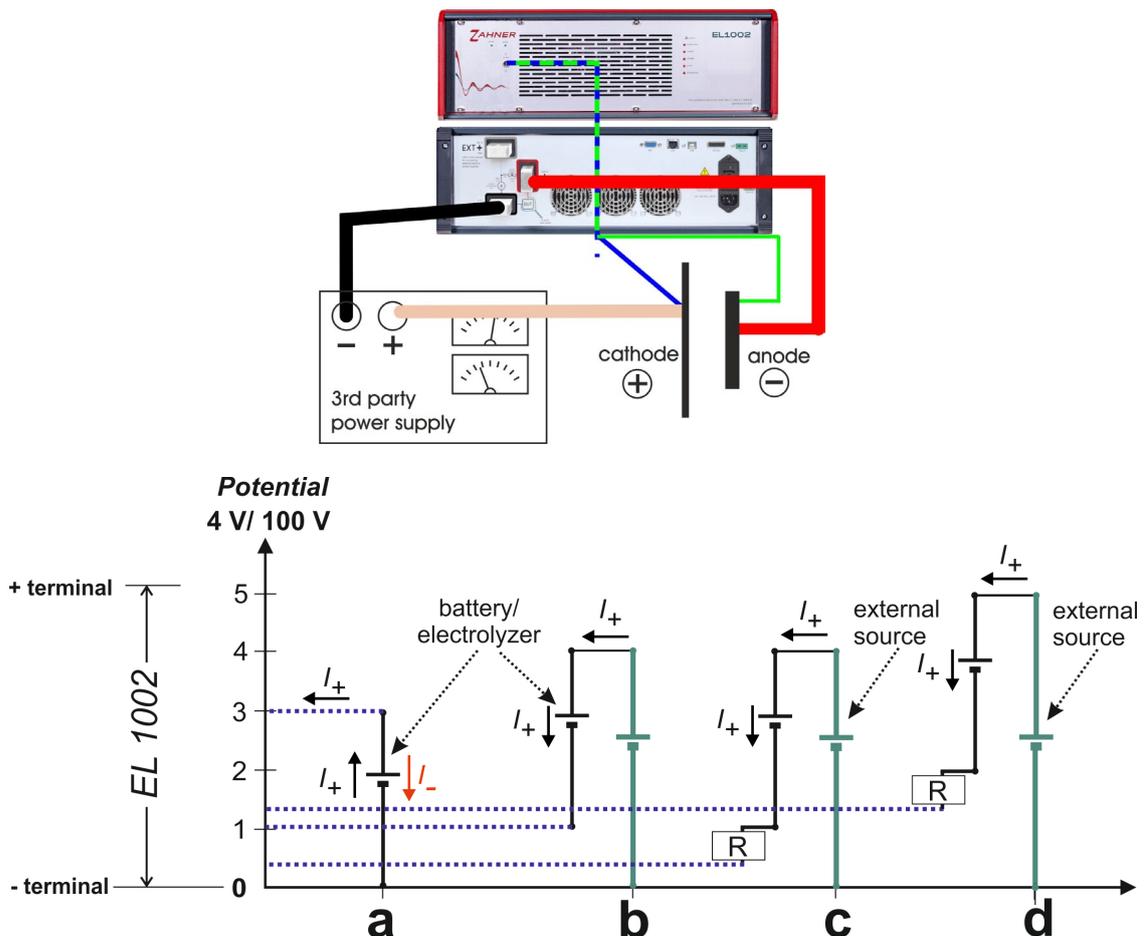


Fig. 23: Cable connection scheme for serial connection scheme and one-quadrant representation of an EL1002 in series with a battery and an external power supply.

The graph in Fig. 23 follows the same scheme as described in Fig. 14. The EL1002 allows current flow in one direction (counter-clockwise, Fig. 23a), which is represented as I_+ . When the EL1002 as load is connected to a battery, the battery is discharged. For charging the battery, a reversed current (I_-) must flow through the battery which is not possible with only the EL1002. Hence, to charge a battery using an EL1002, an external source is required as shown in Fig. 23b. This external source applies a potential against the battery and forces a change in the current direction in the battery which leads to charging. It should be noted that the potential of the external source should be higher than the battery's internal potential. Fig. 23c indicates the same situation as described in Fig. 23b, but under consideration of the voltage drop in the system. The blue line at the y-intercept shows the potential output between the + and – terminals of EL1002. Here the potential difference between the + and – terminals of the EL1002 is lower than 1 V. A simple schematic in Fig. 23c is also shown below to clearly indicate the connection scheme of the (reversed) battery to the EL1002 and the external source.

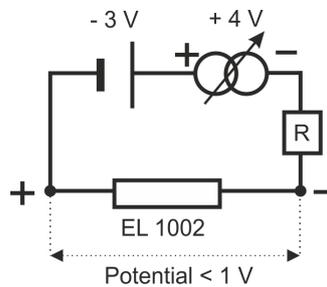


Fig. 24: EL1002 in series connection with a battery and an external power supply in reversed connections.

Usually, a cathode (positive terminal) of a battery is connected to the + terminal of the EL1002 during discharge. However, during charging (Fig. 24 & Fig. 23 b,c,d), the anode (negative terminal) of the battery is connected to the + terminal of the EL1002. Therefore, this is also referred to as the reversed connection of a battery to the EL1002.

Fig. 24 shows the same connection scheme as shown in Fig. 23c. Here, the EL1002 will read a potential of less than 1 V between its + and – terminals. The potential applied by the external power source should be increased up to a certain extent so that the total potential across the + and – terminals of EL1002 becomes higher than 1 V after compensating for both the opposing battery potential as well as the voltage drop (R). This scenario is shown in 23d.

The potential will be indicated as positive in the EL1002, because the battery connection is now reversed with regard to the sense cables.

The measured current must be positive ($I \geq 0$).

Electrolysis:

This configuration is used to allow for impedance experiments during the electrolysis of fuel cells. Electrolysis of the fuel cell utilizes the same cell connection scheme as for charging of batteries.

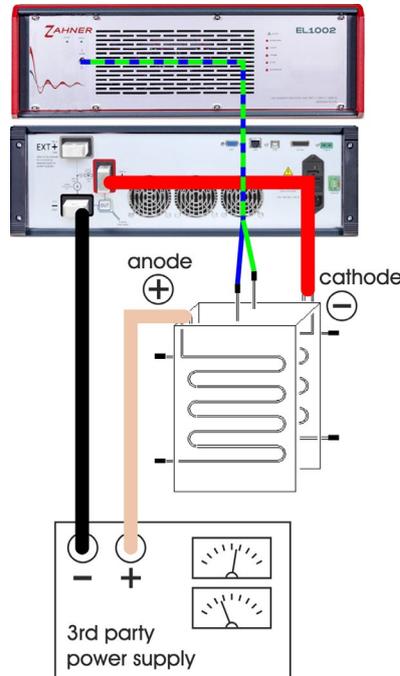


Fig. 25: EL1002 with serial supply

The potential will be indicated as positive in the EL1002 (because the connection is reversed with regard to the sense cables)

The measured current must be positive ($I \geq 0$).

7.4.2 Compensation for voltage drop (zero-volt option)

During regular operation of fuel cells, the typical current flowing through the cells is usually very high (a few hundred amperes). At such high currents, the potential drop ($U_{drop} = R \cdot I$) is also significant. Fuel cells typically have a potential of around 1 V. Such low potential is usually consumed by the voltage drop in cables at high currents. If a current value is set in the galvanostatic mode of the EL1002 at which the voltage drop exceeds the fuel cell potential, the current value will not build up.

Fig. 26 shows the voltage drop across the resistance (R) of the system. There are some additional resistances within the EL1002 leading to further voltage drops. The Fig. 26a illustrates this two-step voltage drop at very high currents. Since in this case the voltage drop is larger than the potential of the fuel cell, the set current cannot be achieved by the EL1002. To compensate for the voltage drop at high currents, a small additional potential is provided by the external power supply to the fuel cell

(Fig. 26b). This keeps the output potential between the + and – terminals of EL1002 positive ($> 1\text{ V}$), and allows for high current experiments.

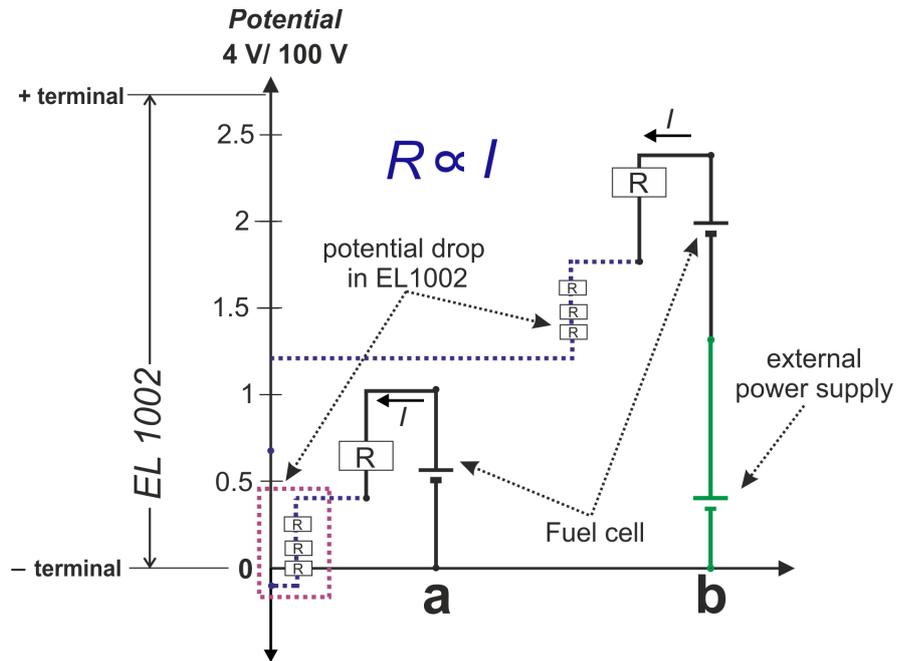


Fig. 26: Compensation of the voltage drop in a system using an external power supply.

In contrast to the arrangement in 7.4.1, the DUT is not reversed in the zero-volt option.

The potential will be indicated as negative in the EL1002. The measured current must be positive ($I \geq 0$).

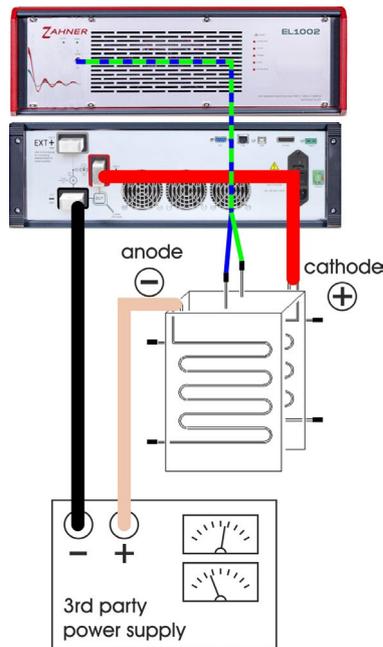


Fig. 27: EL1002 with serial supply as Zero-Volt Option

7.5 Applications with an additional power supply in parallel using the EXT+ terminal

This configuration allows for the following electrochemical experiments:

- Charging batteries
- State of charge (SoC)
- Discharging batteries
- Fuel cell and electrolysis cell operation

In this configuration, the charging, discharging or SOC operations can be controlled directly by Thales software without altering the hardware settings.

The external power supply must operate in **constant current** mode.

Charging: current through DUT is NEGATIVE

SoC: current through DUT is ZERO

Discharging: current through DUT is POSITIVE

The current flow cannot be switched off by the EL1002 in this configuration, as it is also dependent on the external device which is controlled separately.

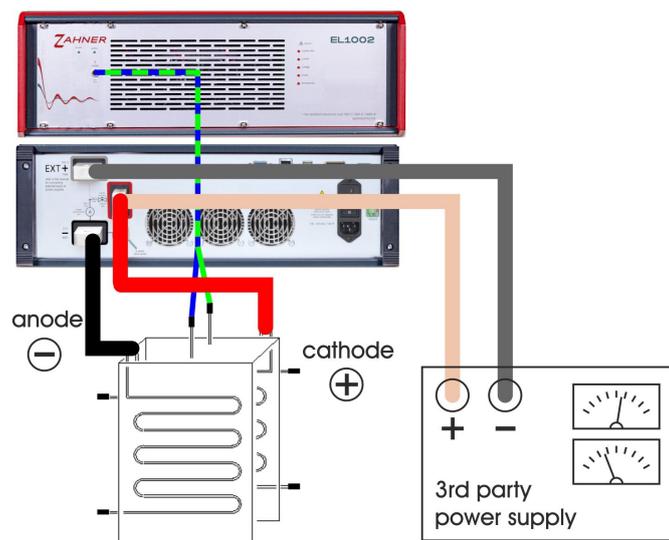


Fig. 28: Cable connection scheme of EL1002 with additional DC supply using EXT+ terminal.

Follow the cable connection scheme shown in Fig. 28 to connect the power supply in parallel to the EL1002.

It is recommended to use as short and thick cables as possible between the EL1002 and the DUT. Also, twist the cables around each other as much as possible to minimize mutual induction.

It is recommended to use long and untwisted cables between the EL1002 and the power supply. See chapter 7.2 ideal current source.

7.5.1 Charging

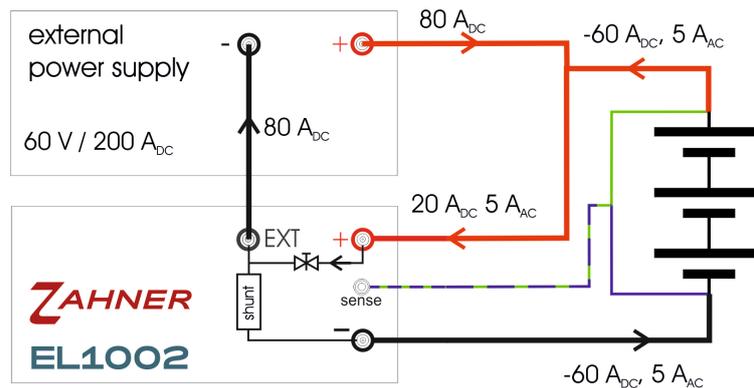


Fig. 29: Current flow scheme in the system during charging.

Power dissipation (Fig. 29):

DUT: Battery of 9 V potential

Charging current to DUT: 60 A

EL1002 part of the DC current: 20 A

EL1002 AC amplitude: 5 A

EL1002 power dissipation: $9 \text{ V} * 25 \text{ A} = 225 \text{ W} (<1000 \text{ W})$

The power dissipation in EL1002 is limited to 1000 W. The voltage used to calculate the power dissipation is the one that drops across the current controller in Fig. 3, i.e., the voltage between the + terminal and EXT+ or – terminal, respectively.

If we assume, no voltage drop in the cables then the voltage of test object will be the same as the voltage drop across the current controller. In case of voltage drop in the cables, the actual power dissipation will be lower than what will be calculated using the test object voltage. Since voltage drop in cable varies from setup to setup hence, for simplicity, we will calculate the power dissipation using the voltage of test object.

The current used to calculate power dissipation is the current that flows through the current controller, which does not necessarily have to be the same current that flows through the current measuring unit if external sources or sinks are used.

In Fig. 29, the schematic diagram shows the current scheme during the charging of a DUT (i.e., a battery). Here, the power supply is outputting $80 A_{DC}$, out of which a charging current of $60 A_{DC}$ is flowing through the DUT. User can define the charging current directly in Thales software with the DC CURRENT. Since the charging current sign is negative so DC CURRENT in Thales software will be $-60 A$.

The rest $20 A_{DC}$ ($80 A_{DC} - 60 A_{DC}$) is flowing to the + terminal of EL1002 where it will be used as buffer current for the EIS operation and then eventually sinked. The DC current in EL1002 must be higher than the AC amplitude for the EIS. The AC current between the + and – terminals of the EL1002 is only allowed in one direction (from + to –) and is therefore flowing in reversed direction with respect to the charging current.

In the above-provided scheme, the EL1002 is connected in parallel to the external power supply and when the EL1002 (galvanostatic mode in the Thales window) is turned off, all the current provided by the external power supply flows through and charges the DUT. Hence by turning of the EL1002, this scheme can also be used for charging batteries or for electrolysis and removing the EL1002 from the setup is not required.

The DC current flowing to the + terminal of the EL1002 must be higher than the EIS amplitude (A_{AC}), as the EL1002 only allows current flow in one direction. If the DC current is less than the EIS amplitude then a complete sine excitation by the EL1002 is not possible.

It is recommended to test different DC currents of the EL1002, because the ratio of DC to AC current may affect the bandwidth of the EIS measurement or cause interference with harmonics, depending on the power supply. A good starting value for the DC current of the external source is $I_{DC Source} = 3 * I_{AC EL1002}$ for measurements at the OCV/OCP of a DUT.

7.5.2 Discharging

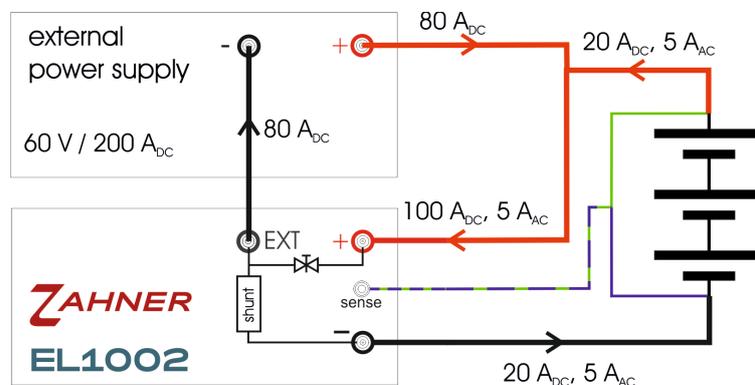


Fig. 30: Current flow scheme in the system during discharging.

Power dissipation (Fig. 30):

DUT: Battery of 9 V potential
 Current from external power supply: 80 A_{DC}
 Discharging current from DUT: 20 A_{DC}
 EL1002 part of the DC current: 100 A
 EL1002 AC amplitude: 5 A
 EL1002 power dissipation: 9 V * 105 A = 945 W (<1000 W)
 The power dissipation in EL1002 is limited to 1000 W.

Fig. 30 shows the current scheme during the discharging of a DUT (i.e., a battery) with electrical connections among the external power supply, EL1002 and DUT. Here, the current is read as a positive value in the Thales window, translating to a discharging current of 20 A_{DC}. The schematic diagram shows that both the 80 A_{DC} (used in section 7.5.1 for charging) from the external power supply as well as the 20 A_{DC} from the battery flow towards the + terminal of the EL1002. Here, the discharging current and the AC current from the external source flow into the same direction, opposite to the current flow in the charging setup. The 100 A_{DC} current flowing to the + terminal of the EL1002 will be used as buffer current for the EIS and will eventually be sinked in EL1002. Here, if the EL1002 is turned off, the power supply will start charging the DUT at a charging current of 80 A.

7.5.3 State of charge (SoC)

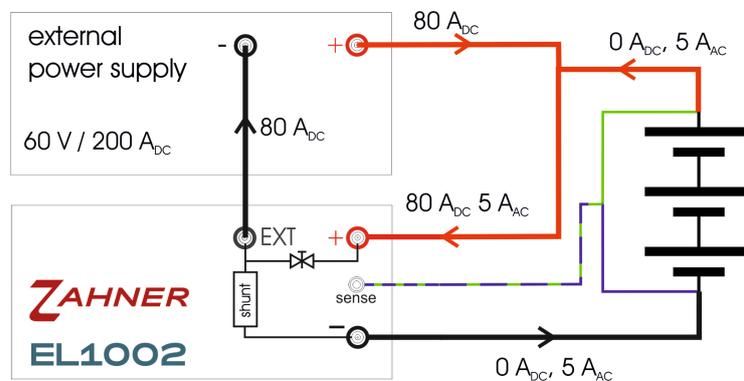


Fig. 311: Current flow scheme in the system at SoC.

Power dissipation (Fig. 31):

DUT: Battery of 9 V potential
 Current from external power supply: 80 A_{DC}
 Current from DUT: 0 A_{DC}
 EL1002 part of the DC current: 80 A
 EL1002 AC amplitude: 5 A
 EL1002 power dissipation: 9 V * 85 A = 765 W (<1000 W)
 The power dissipation in EL1002 is limited to 1000 W.

Fig. 31 illustrates the current scheme during the state of charge (SoC) measurement of a DUT (i.e., a battery) with electrical connections among the external power supply, EL1002 and DUT. In SoC, the DC current through the DUT is zero, which is

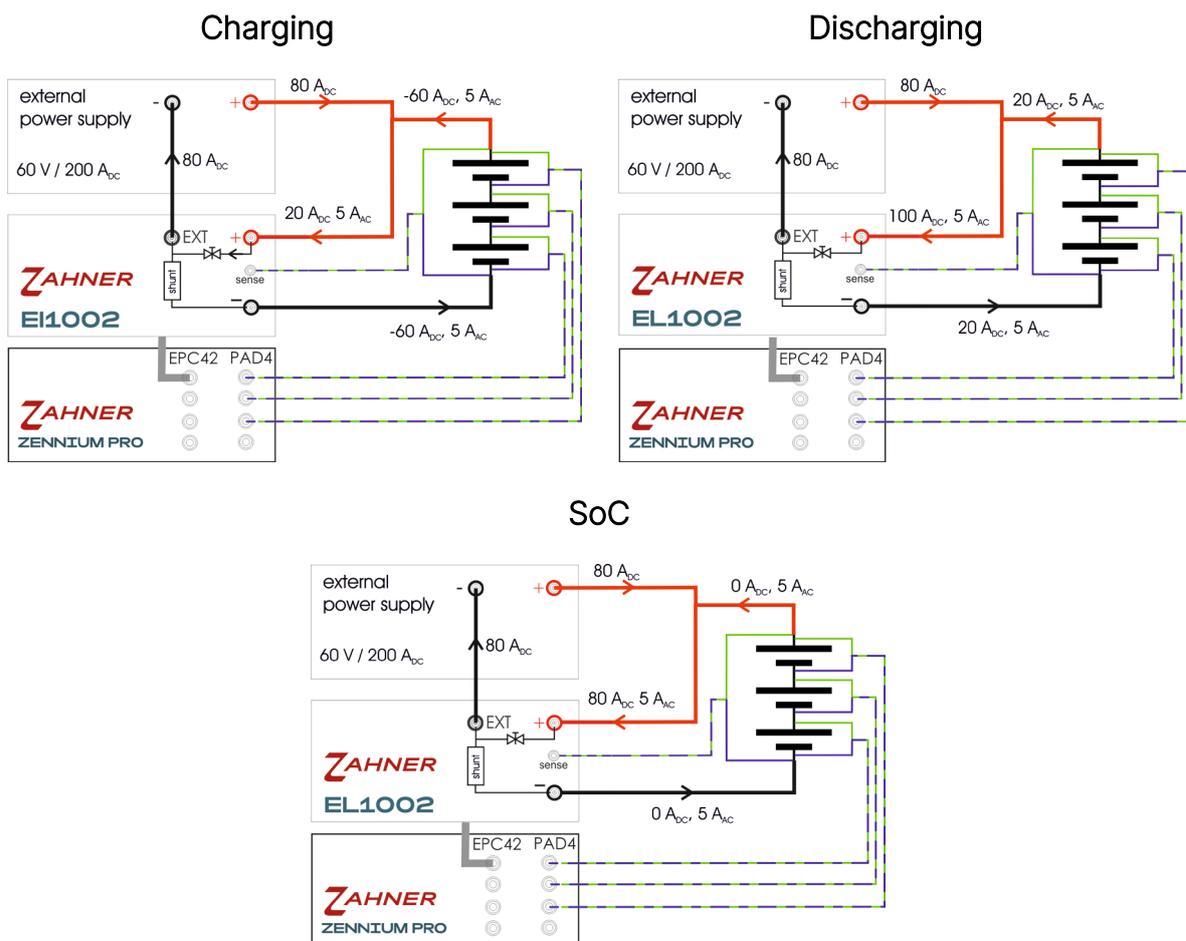
set in the Thales Window. Here, the current provided by the external power supply completely flows through + terminal of EL1002 where it is sunk and used as buffer current for the EIS excitation. DC current provided by the external power supply should be higher than the AC amplitude used for EIS excitation.

Here, if the EL1002 is turned off, the power supply will start charging the DUT at a charging current of $80 A_{DC}$.

In all three configurations of section 7.5 (charging, discharging and SOC) everything is kept the same and only the DC CURRENT in Thales software is changed which leads to switching between different operation modes.

7.5.4 Summary parallel power supply with PAD4

The PAD4 card can in this setup also be used to analyze individual parts of the DUT. The schematics below illustrate the connection schemes using the PAD4 card within charging, discharging and SoC scenarios.



8 Specifications

The following section lists the specifications of the EL1002.

8.1 Ranges and tolerances

Voltage Ranges						
Voltage Range		Range Standalone [V]		Range Thales [V]		Tolerance
Index	Factor	min	max	min	max	
0	1.0	-5.0	5.0	-4.0	4.0	$\pm 500 \mu\text{V} \pm 0.1\%$ of reading
1	0.4	-100	100	-100	100	$\pm 12.5 \text{ mV} \pm 0.1\%$ of reading
Current Ranges						
Shunt		Range Standalone [A]		Range Thales [A]		Tolerance
Index	Resistance [Ω]	min	max	min	max	
0	5m	680	-680	680	-680	$\pm 680 \text{ mA} \pm 0.1\%$ of reading
1	50m	60	-60	60	-60	$\pm 68 \text{ mA} \pm 0.1\%$ of reading

8.2 General specifications

Potentiostatic Modes	Potentiostatic, Galvanostatic, Pseudo-Galvanostatic, Off
Cell Connection	2-, 3-, 4-Terminal Sensing
Ground Reference	Floating
Maximum Measurable Voltage	±100 V
Maximum Measurable Current	±680 A (with 3 rd party power supply/sink)
Maximum Sink Current	200 A
Output Power	0 W
Power Dissipation	1000 W
Input Impedance	100 kΩ
Equivalent Input Noise	< 10 μV _{rms}
Memory	64 GB
Interface	USB, Ethernet ²
Additional IOs	5 ²
Additional Analog Outputs	1 ²
Additional Analog Inputs	4 ²
Temperature Sensor Interface	Type K ²
Ambient Temperature	10 °C – 25 °C
Maximum Humidity	60 %
Dimensions (H x W x D) in mm	160 x 470 x 485
Weight	21.5 kg
Zahner-Lab / SCPI³	
ADC Resolution	24 bits
Voltage Input Resolution	0.596 μV
Current Input Resolution	11.9 μA
DAC Resolution	18 bits
Voltage Output Resolution	38.14 μV
Current Output Resolution	763 μA
Thales XT³	
ADC Resolution	24 bits
Voltage Input Resolution	0.596 μV
Current Input Resolution	11.9 μA
DAC Resolution	16 bits
Voltage Output Resolution	250 μV
Current Output Resolution	2.44 mA
Impedance Frequency Range	10 μHz – 100 kHz
Impedance Range	1 μΩ - 100 Ω ¹

¹Impedances below 10 mΩ must be measured galvanostatically. EL1002 is optimized for galvanostatic operation on objects below 1 Ω. The device is not intended for Ohmic inductive objects.

²Hardware feature will be unlocked in the future by a free software update.

³The specifications for the resolution are given for the smallest current and voltage range.

8.3 Safe operation conditions

The maximum power dissipation (sink) of the EL1002 is **1000 W**. Fig. 3 is important for determining the power dissipation, which can be simply calculated by the formula $P = U * I$. It is important to always use the correct voltage and current that applies for the specific setup.

The voltage used to calculate the power dissipation is the one that drops across the current controller in Fig. 3, i.e., the voltage between the terminal + and EXT+ or -, respectively.

EXT+ and - are only connected via the current measuring unit, the electrical resistance is negligible for the voltage calculation.

The current used to calculate power is the current that flows through the current controller, which does not necessarily have to be the same current that flows through the current measuring unit if external sources or sinks are used.

If you have connected an external source, as described in section 7.5, the EL1002 can display 0 A, although the output stage consumes the entire current of the source - this must then be considered in the calculation of the power dissipation.