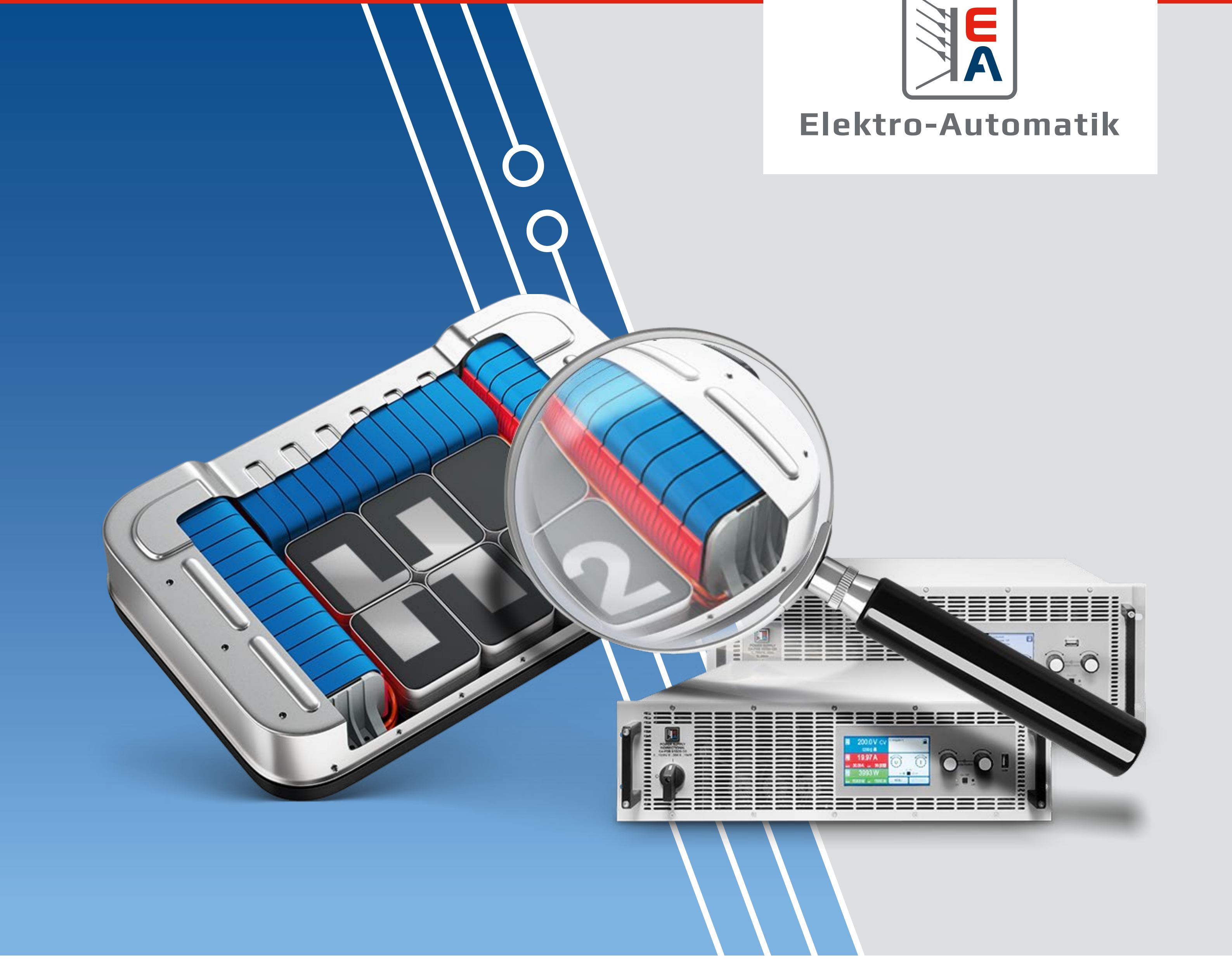
Elektro-Automatik



EFFICIENTLY AND EASILY TEST FUEL CELLS

Supporting advances in climate-neutral energy

simplified

cost-effective

sustainable

Testing Fuel Cell Stacks

Fuel cells use hydrogen as fuel which combines with oxygen to produce electricity. The byproducts of the electricity process are heat and water. With zero emission of greenhouse gas, carbon dioxide, use of fuel cell power sources contribute to the needed reduction of carbon dioxide in the environment. Figure 1 shows how a fuel cell operates. Hydrogen and oxygen form ions via oxidation at an anode and reduction at a cathode. The chemical energy of the reactions converts to electrical energy as electrons can flow from anode to cathode through an external load and protons flow from anode to cathode through the electrolyte. The end products are water and heat and not carbon dioxide. The fuel cell illustrated is a proton exchange membrane (PEM) fuel cell.

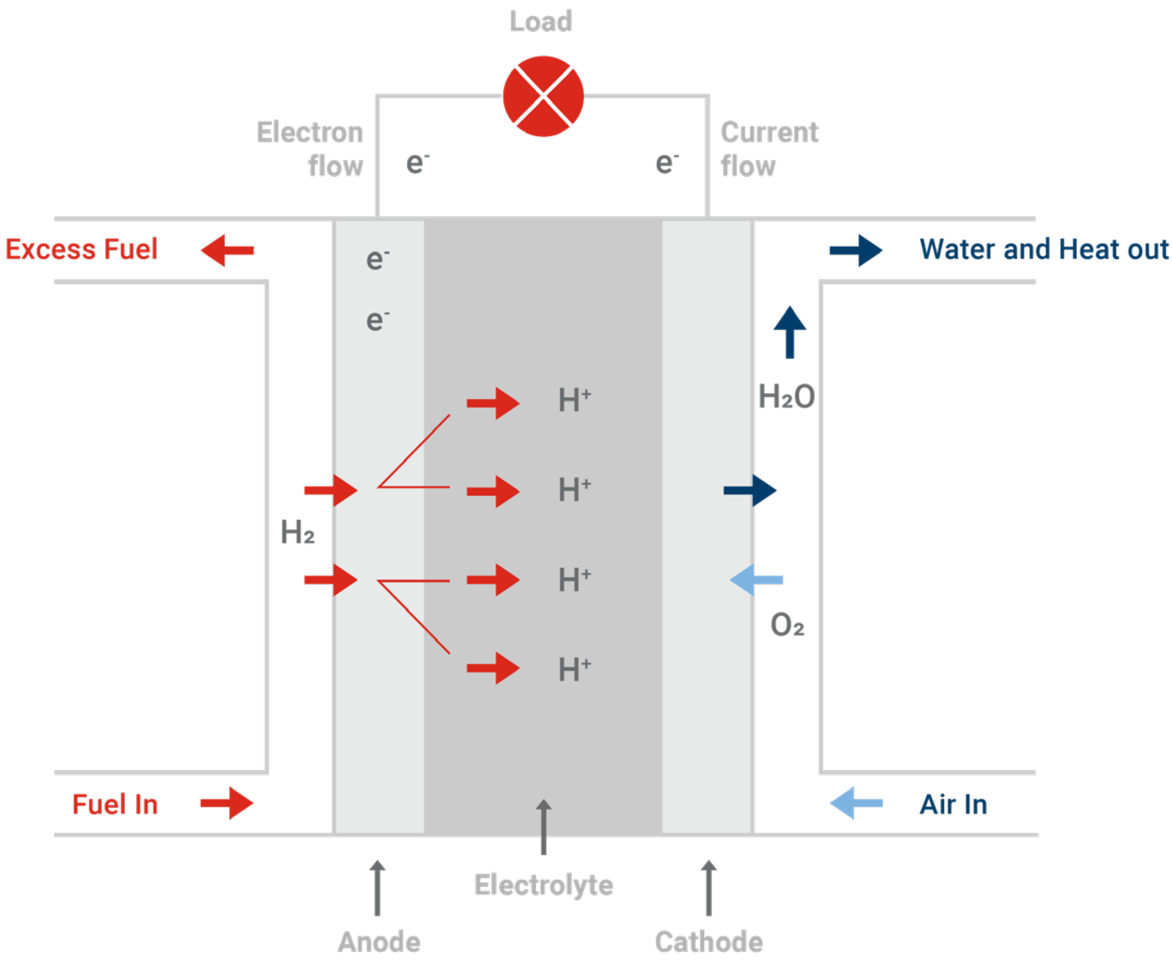


Figure 1
Basic functional diagram of a proton exchange membrane fuel cell

Fuel cells* have found applications in material handling vehicles, delivery vehicles, long-haul trucks, and use as backup power systems. Government initiatives, economic incentives, and new applications are resulting in a market growth rate exceeding 30%.

An individual fuel cell generates under 2 V of output, so practical fuel cells are assemblies or stacks of multiple cells. Fuel cells can output up to 125 kW for vehicles; and, the largest fuel cells, used for backup power, can have a capacity of 1.5 MW and operate at 900 V. As fuel cell technology is improved, manufacturers will be designing fuel cell stacks with higher power and higher voltage ratings.

With such high power capacity, testing fuel cell stacks is essential to ensure that they have a minimum specified efficiency, are safe, and have the required operating life. EA Elektro-Automatik electronic loads and bidirectional power supplies have high input and output capacity to test fuel cell stacks. Electronic loads are available in models with a 30 kW capacity and voltage output of 2000 V. Current capacity can be 1000 A. Up to 64 loads can be paralleled to enable testing fuel cells with power levels up to 1.92 MW. The same power handling and parallel instrument capacity exists in the bidirectional power supplies for either sourcing or sinking power.

Measuring fuel cell resistance using an AC perturbation technique

Figure 2 shows a simplified circuit model for a fuel cell. The most important parameter of a fuel cell is its resistive component. The electrolyte resistance is the main contributor to the total resistance of the fuel cell. The polarization resistance models the reaction equivalent resistance, and the double layer capacitance models the anode-electrolyte-cathode interfaces. The lower the total resistance of the fuel cell is, the lower is its power loss and its efficiency is higher. With power generation of kW to MW, an excessively high total resistance can prevent a fuel cell stack from outputting its maximum rated power.

The difficulty with measuring the resistance of the fuel cell is due to fact that the cell voltage source cannot be isolated from the resistive components as the circuit model might suggest. Rather than employing a conventional DC resistance measurement, the measurement of fuel cell resistance requires an AC measurement or a pseudo-AC measurement. In either case, a perturbation, a ΔI, created by the load results in a ΔV (ΔU) across the fuel cell; and fuel cell resistance, $R = \Delta V (\Delta U) / \Delta I$.

* "Fuel cell" and "fuel cell stack" will be used interchangeably in the application note.

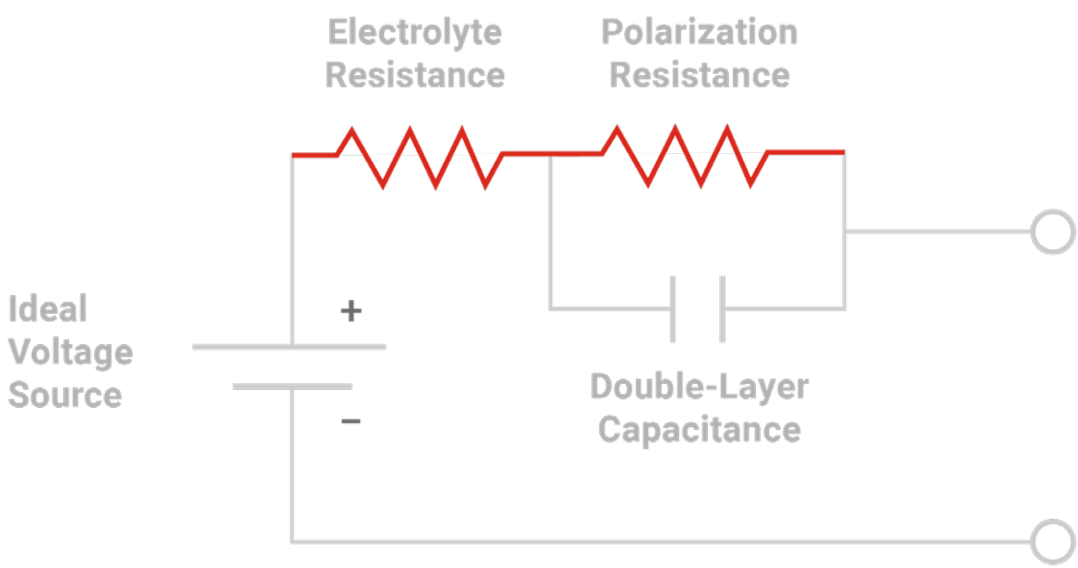
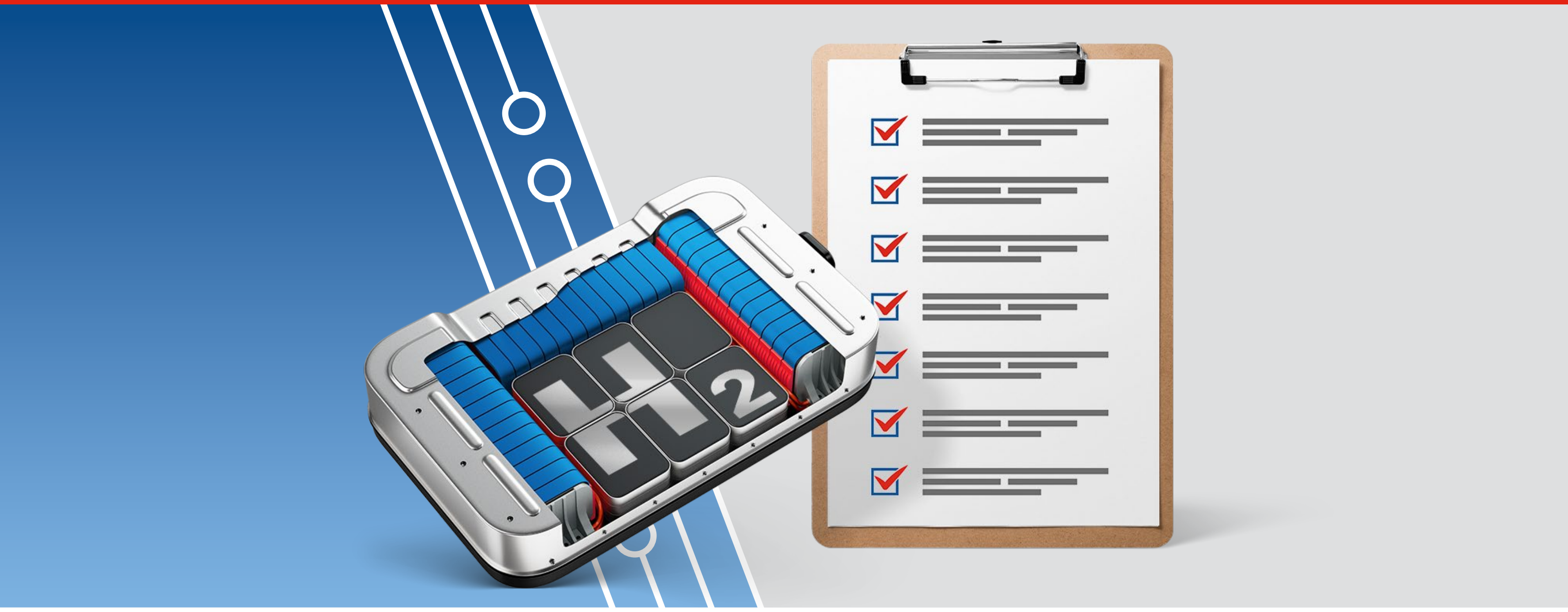


Figure 2
Simplified model of a fuel cell



The pseudo-AC measurement is known as the current interrupt method. This method, as the name describes, creates a ΔI by instantaneously switching the load current from a steady state value to 0 A. The fuel cell voltage rises to its open circuit voltage from the voltage reduced by the product of the load current and the fuel cell resistance. Figure 3 shows a voltage pulse resulting from the momentary turn-off of the current. While only an electronic load is required for this method, it has the disadvantage of creating a large perturbation on the cell.

Figure 3 shows an ideal voltage for illustration, but cable inductance, L·di/dt, creates ringing on the edges of the voltage pulse when the current transitions. This can make obtaining an accurate reading of the voltage peak difficult. Keeping test cables between the load and the fuel cell-under-test as short as possible can reduce the ringing effect. Figure 4 shows the test setup for the current interrupt test. The second disadvantage of this method is that it overestimates the resistance of the fuel cell by 10 to 20%.

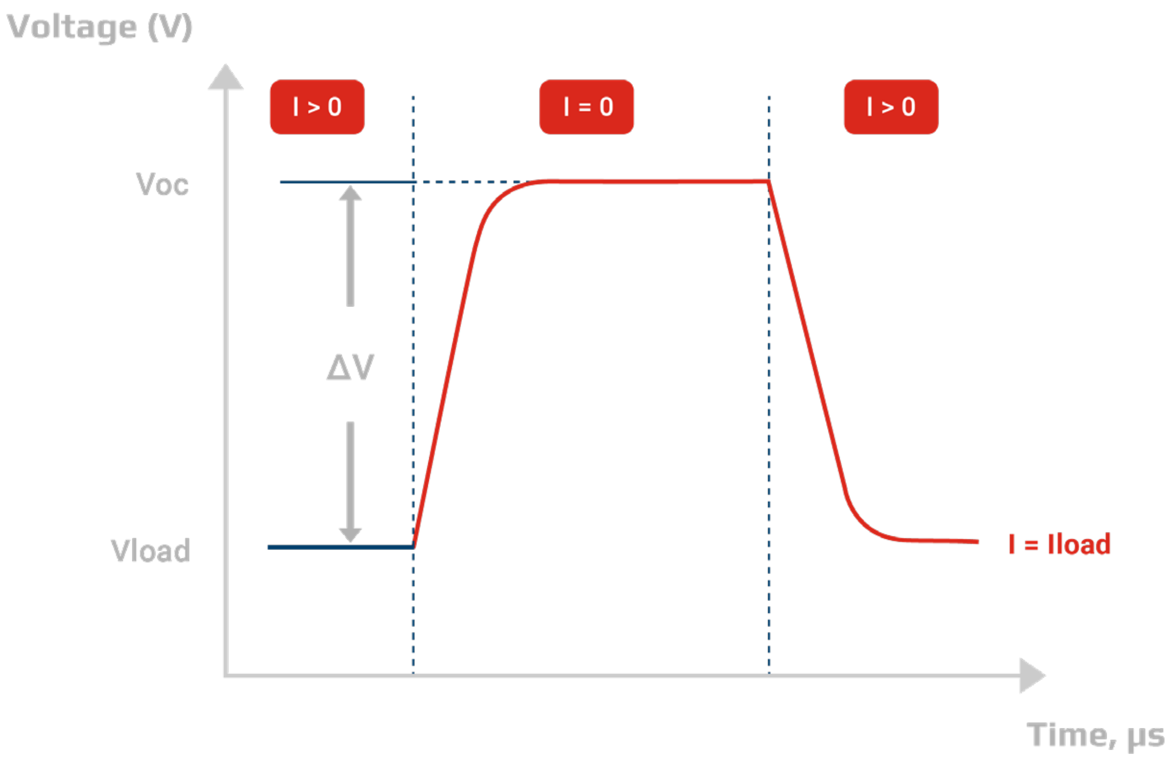
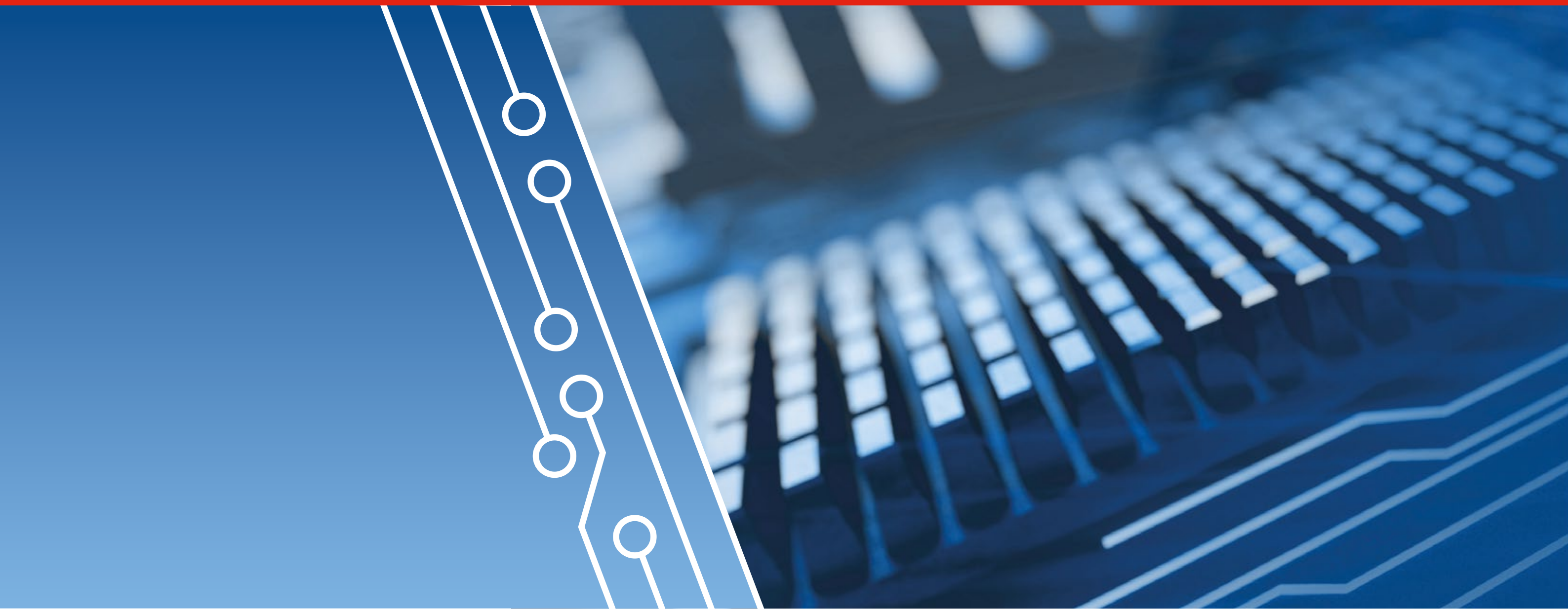


Figure 3
An ideal fuel cell response to a load current interrupt. The actual output would have oscillation (ringing) on the rising edge and falling edge of the voltage pulse due to the inductance of the cabling. The transition is an AC effect so the cables act like an R-L-C transmission line during the transition of the load.



NOTE 1 Use 4-wire remote sensing (Kelvin wiring) to more accurately measure the fuel cell output voltage and eliminate measuring the voltage drop due to the current in the source lines. The 2-wire system would measure a lower voltage.

NOTE 2 Twist the remote sense leads together and separate them from the source leads to reduce inductive coupling of noise into the sense lines.

NOTE 3 Keep the test leads as short as possible to reduce transmission line ringing effects when a step load change occurs.

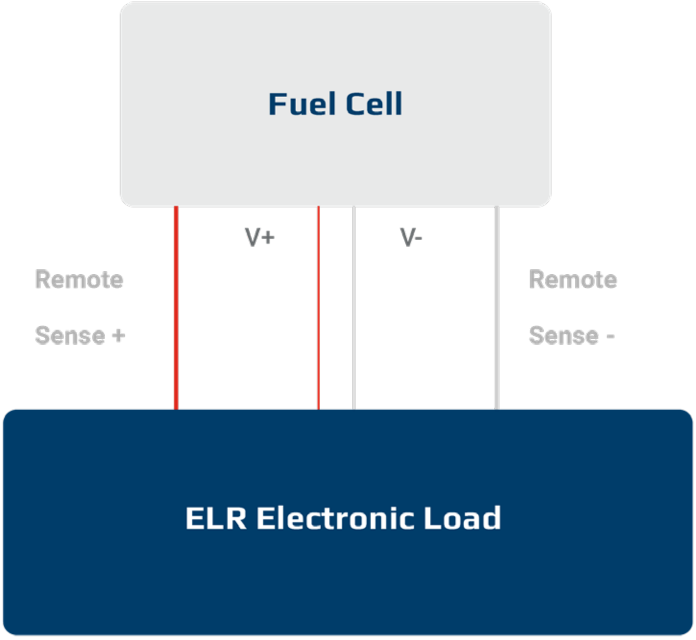


Figure 4
Test setup for measuring fuel cell resistance with the current interrupt method

The EA Elektro-Automatik Power Control software which controls EA power supplies and electronic loads simplifies the task of creating the sine wave on the DC load level. The screenshot, shown in Figure 5, displays the creation of a 1 kHz sine wave with a 5 Vrms amplitude. No coding is required for the Power Control software. If the electronic load needs to be integrated into other control software, the load's library of SCPI instrument commands provides the instrument communication and control. Table 1 lists the commands that would generate the sine wave. The SCPI commands can be coded as read and write commands in programming languages such as C and Python.

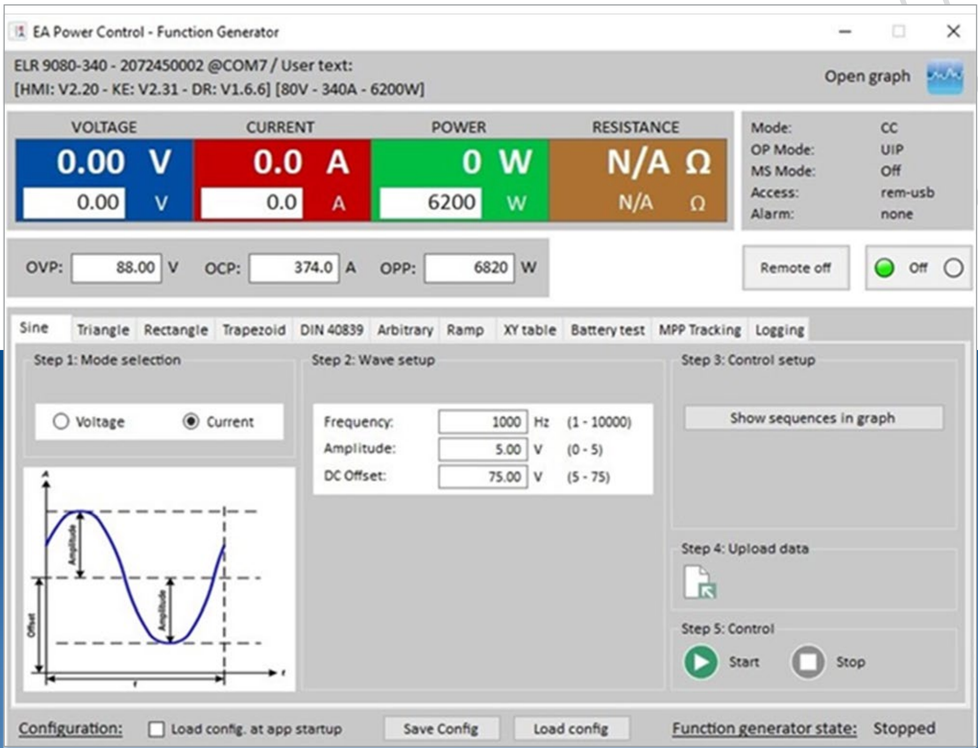


Figure 5
Screen shot of the Power Control software creating a 5 V_{RMS} sine wave at 1 kHz on a 75 A_{DC} load level.

Given that the device is already in remote control and the DC input or DC output is off, following command sequence would be necessary:

```
FUNC:GEN:SEL CURR            ;SELECTS ARBITRARY GENERATOR FOR CURRENT.
FUNC:GEN:WAVE:LEV 1          ;SELECTS STEP 1
FUNC:GEN:WAVE:IND 5          ;SELECTS BEGINNING AC OFFSET CURRENT VALUE
FUNC:GEN:WAVE:DATA 75        ;SETS AC OFFSET CURRENT START VALUE OF 75A
FUNC:GEN:WAVE:IND 6          ;SELECTS ENDING AC OFFSET CURRENT VALUE
FUNC:GEN:WAVE:DATA 75        ;SETS ENDING AC OFFSET CURRENT VALUE OF 75A
FUNC:GEN:WAVE:IND 2          ;SELECTS BEGINNING AC FREQUENCY
FUNC:GEN:WAVE:DATA 1000      ;SETS BEGINNING AC FREQUECY OF 1KHZ
FUNC:GEN:WAVE:IND 3          ;SELECTS ENDING AC FREQUENCY
FUNC:GEN:WAVE:DATA 1000      ;SET ENDING AC FREQUENCY TO 1KHZ
FUNC:GEN:WAVE:IND 0          ;SELECTS BEGINNING AC AMPLITUDE
FUNC:GEN:WAVE:DATA 5         ;SETS BEGINNING AC AMPLITUDE OF 5A
FUNC:GEN:WAVE:IND 1          ;SELECTS ENDING AC AMPLITUDE
FUNC:GEN:WAVE:DATA 5         ;SET ENDING AC AMPLITUDE OF 5A
FUNC:GEN:WAVE:IND 7          ;SELECTS DURATION OF STEP IN SECONDS
FUNC:GEN:WAVE:DATA 10        ;SETS DURATION OF STEP TO BE 10 SECONDS
FUNC:GEN:WAVE:END 1          ;SET START SEQUENCE STEP TO 1
FUNC:GEN:WAVE:START 10       ;SET END SEQUENCE STEP TO 10
```

Table 1
SCPI code to create the 5 V_{RMS} sine wave at 1 kHz on a 75 A_{DC} load offset

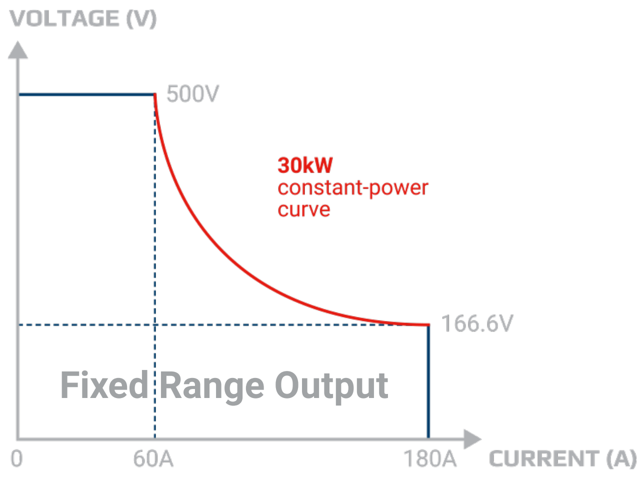


Figure 6
Autoranging input compared with a fixed range load. Note how much higher voltage input and how much more power handling at more current settings an autoranging load offers.

Testing a fuel cell stack which can output as much as MW levels of power requires high power instrumentation for testing. Models of ELR loads can sink up to 30 kW and operate with voltages up to a maximum of 2000 V and current of 1000 A. The loads have this capacity due to their autoranging input shown in Figure 6. Autoranging enables the load to absorb full power across a larger operating range than a fixed range load and avoids having to use a higher power load to sink either a higher voltage or a higher current. Autoranging also provides flexibility in testing more types of fuel cells due to the load's wider voltage and current operating ranges.

For the large fuel cell stacks used for back-up power generation, up to 64 ELR loads can be paralleled to sink up to 64 kA. ELR load assemblies can test any fuel cell stack.

Fuel Cell Performance Testing

Once the parameters of a fuel cell stack are characterized, engineers can quantify the fuel cell's output performance. For repeatable data, the fuel cell should be in a controlled environment in which fuel cell temperature, pressure, humidity, and fuel flow rates are held constant. Voltage output is determined as a function of load current. The load current starts with no load to enable measurement of open circuit voltage. The load is increased by a fixed step size until the fuel cell's output voltage drops to around 20 % of its open circuit voltage. Each load current change requires the fuel cell to re-establish equilibrium conditions; thus, a delay is necessary before taking data at each new load level. Figure 7 shows an example of a polarization curve.

In section 1 non-linear electro-kinetic effects result in a non-linear voltage drop with increasing load current.

In section 2 the ohmic resistance of the fuel cell dominates the fuel cell characteristic and generates a linear segment.

In section 3 the voltage drops off exponentially as energy is consumed faster than the hydrogen and oxygen chemical reactions can supply new energy.

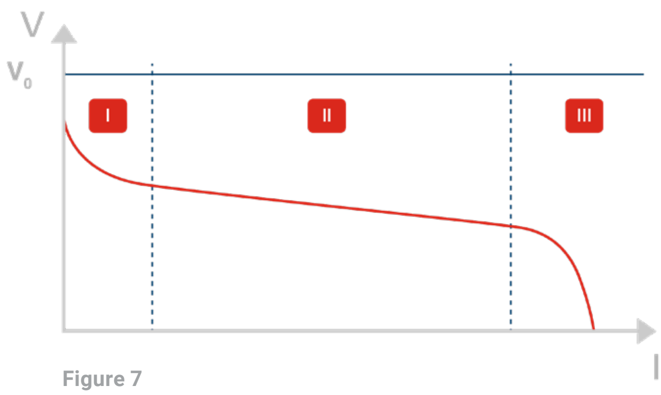


Figure 7
Fuel cell voltage-current output curve

The ELR loads can easily create a load current step sequence using either the Power Control software or SCPI commands.

Figure 8 shows the Power Control software with a setup that increases the load current from 0 A to 100 A in 10 A steps. The figure is showing the second step of the sequence in which the load current is increasing from 10 A to 20 A. Table 2 shows the SCPI commands that perform the same step load test.

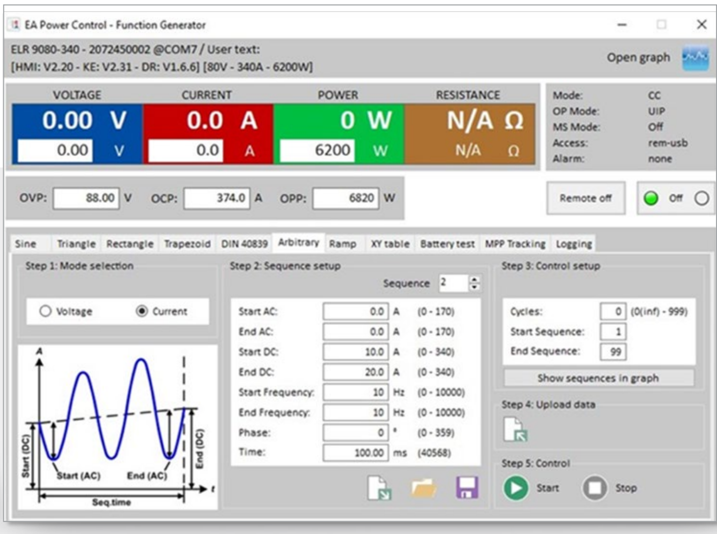


Figure 8
Use of Power Control software to create a current step sequence from 0 A to 100 A.

```
FUNC:GEN:SEL CURR          ;SELECTS ARBITRARY GENERATOR FOR CURRENT
.                          ;STEP ONE SKIPPED TO SHOW STEP 2 ONLY
.
.
FUNC:GEN:WAVE:LEV 2        ;SELECTS STEP 2
FUNC:GEN:WAVE:IND 5        ;SELECTS BEGINNING DC CURRENT VALUE
FUNC:GEN:WAVE:DATA 10      ;SETS DC CURRENT START VALUE OF 10A
FUNC:GEN:WAVE:IND 6        ;SELECTS ENDING DC CURRENT VALUE
FUNC:GEN:WAVE:DATA 20      ;SETS ENDING DC CURRENT VALUE OF 20A
FUNC:GEN:WAVE:IND 7        ;SELECTS DURATION OF STEP IN SECONDS
FUNC:GEN:WAVE:DATA 10      ;SETS DURATION OF STEP TO BE 10 SECONDS
.                          ;SKIP STEPS 3-10 WHICH INCREMENT UP 10A EACH
.
.
FUNC:GEN:WAVE:END 1        ;SET START SEQUENCE STEP TO 1
FUNC:GEN:WAVE:START 10     ;SET END SEQUENCE STEP TO 10
```

Table 2
Portion of SCPI code to create the 0 A to 100 A step sequence. Step 2 of the 10 steps is illustrated.

Fuel cell durability testing

The most important step in testing fuel cells is to ensure their safety and stability. For automotive applications, a fuel cell stack must have a 5,000 hour operating lifetime. Back-up power systems must have a 10,000 hour operating life. Feasible testing requires accelerated stress testing in which a fuel cell stack is subjected to cycles of step load changes or load current ramps for over 100 hours.

The load current change should result in the fuel cell voltage changing by about 50 %. The period of the square wave step change and the ramp cycle should be around 50 s.

Using the built-in waveform generator, the ELR load Power Control software, shown in Figure 9, can set up a ramp test with a ramp having a 50 s period. Equivalent SCPI code is shown in Table 3.

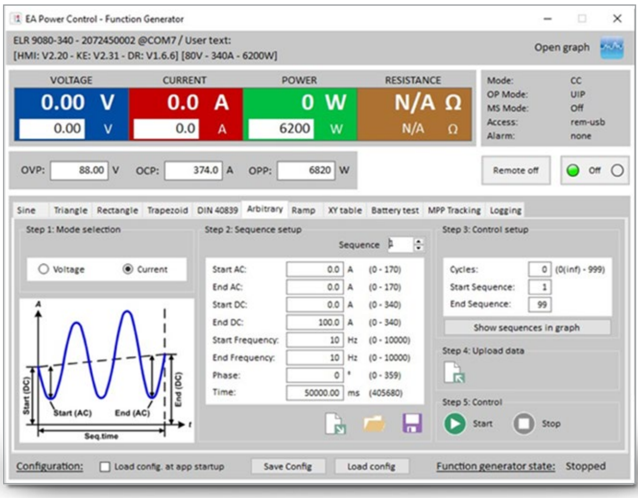


Figure 9
Power Control software screenshot showing the creation of a load current ramp from 0 A to 100 A with a 50 s period.

FUNC:GEN:SEL CURR	;SELECTS ARBITRARY GENERATOR FOR CURRENT
FUNC:GEN:WAVE:LEV 1	;SELECTS STEP 1
FUNC:GEN:WAVE:IND 0	;SELECTS BEGINNING DC CURRENT VALUE
FUNC:GEN:WAVE:DATA 0	;SETS DC CURRENT START VALUE OF 0A
FUNC:GEN:WAVE:IND 6	;SELECTS ENDING DC CURRENT VALUE
FUNC:GEN:WAVE:DATA 100	;SETS ENDING DC CURRENT VALUE OF 100A
FUNC:GEN:WAVE:IND 7	;SELECTS DURATION OF STEP IN SECONDS
FUNC:GEN:WAVE:DATA 50	;SETS DURATION OF STEP TO BE 50 SECONDS
FUNC:GEN:WAVE:END 1	;SET START SEQUENCE STEP TO 1
FUNC:GEN:WAVE:START 1	;SET END SEQUENCE STEP TO 1

Table 3
SCPI code that creates a ramp equivalent to the ramp defined in Figure 9.

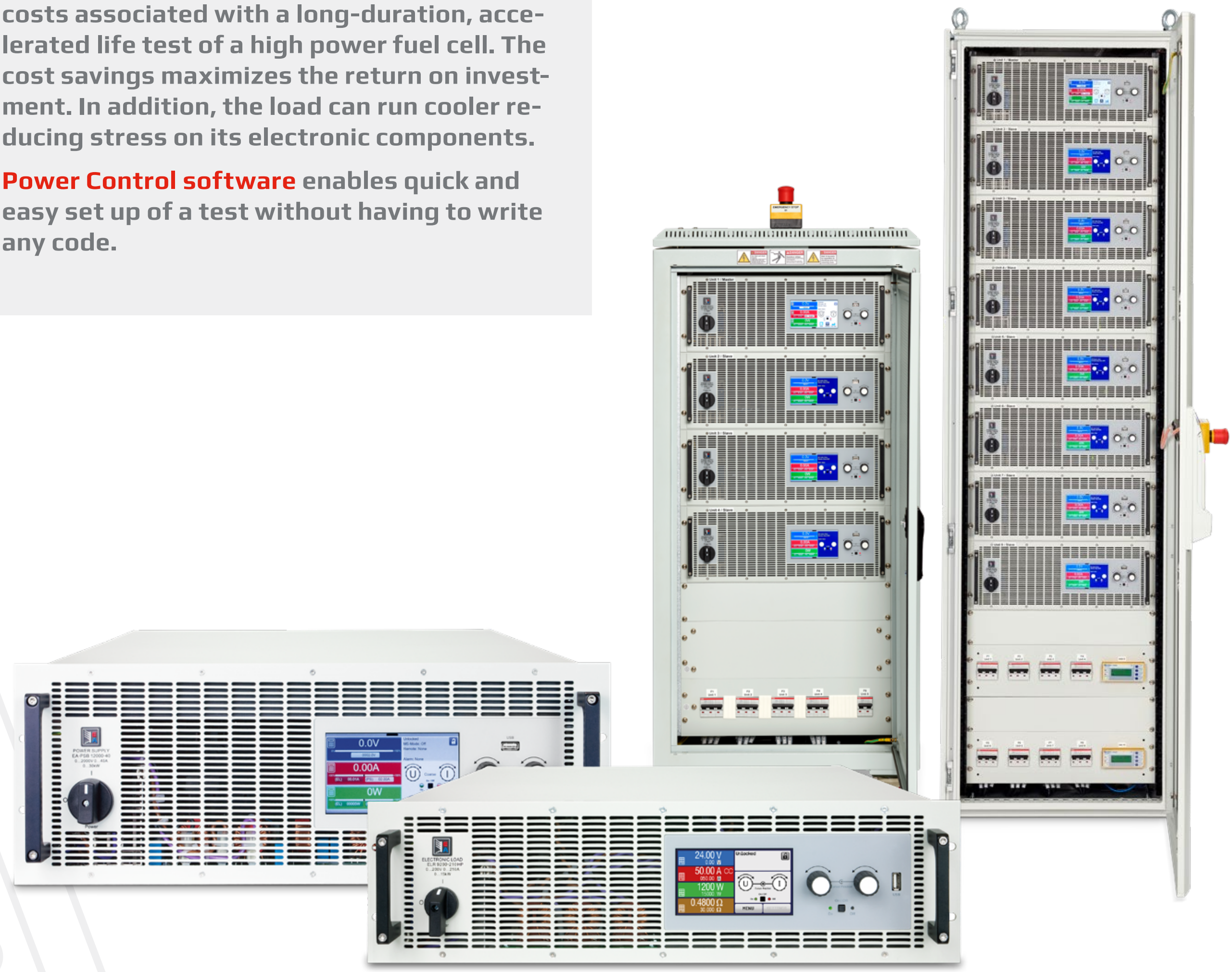
A 100-hour test on a high-power fuel cell stack consumes a lot of energy. ELR loads can save substantial energy during an accelerated stress test. The loads have regenerative energy recovery which can sink power and return the power to the electrical grid with up to 96 % efficiency. Not having to dissipate all the consumed power allows the ELR load to run cooler compared with a traditional electronic load. These loads require a lower investment in cooling infrastructure. Using an ELR load provides a return on investment with significantly reduced utility costs.

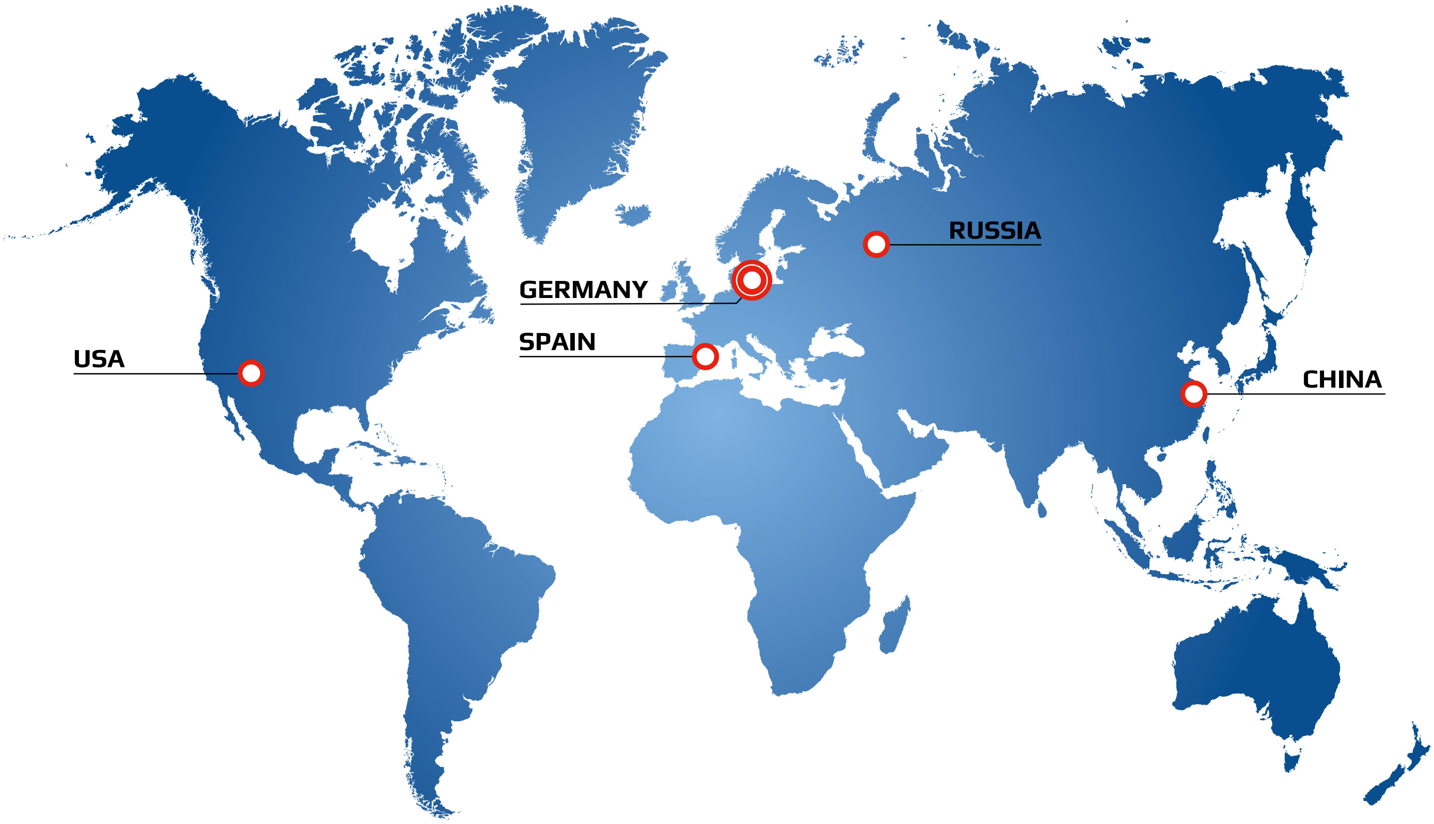
Simplified and efficient fuel cell testing

The ELR loads offer the following benefits for fuel cell testing:

- The **Built-in waveform generator** simplifies the setup and testing of fuel cells by eliminating the challenge of interfacing a low power waveform generator into a high power circuit. With the waveform generator, the ELR load can easily program sinusoidal variations on a DC load current to create the perturbations to measure fuel cell resistance. The waveform generator also can create square waves and ramps for performance and durability testing.
- **Autoranging** capacity helps to reduce the cost of the required load as the wider voltage and current levels allow optimizing the power capacity to the capacity of the fuel cell. A higher power load is often not required to reach a higher voltage or current capacity.
- **Regenerative Energy Recovery,** with up to 96 % efficiency, saves the significant utility costs associated with a long-duration, accelerated life test of a high power fuel cell. The cost savings maximizes the return on investment. In addition, the load can run cooler reducing stress on its electronic components.
- **Power Control software** enables quick and easy set up of a test without having to write any code.

While this application note has focused on the ELR load as the primary test instrument, the PSB-series bidirectional power supplies can provide the same sinking capacity. Like the ELR loads, the PSB-series supplies have a built-in waveform generator, autoranging input and output, and regenerative energy recovery. The PSB supplies can also simulate a fuel cell stack if testing the fuel cell load as well as the fuel cell is needed. See Application Note AN024 for more details on simulating a fuel cell with a PSB bidirectional power supply. Whichever instrument is selected, both provide simplified and efficient testing of fuel cells.





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