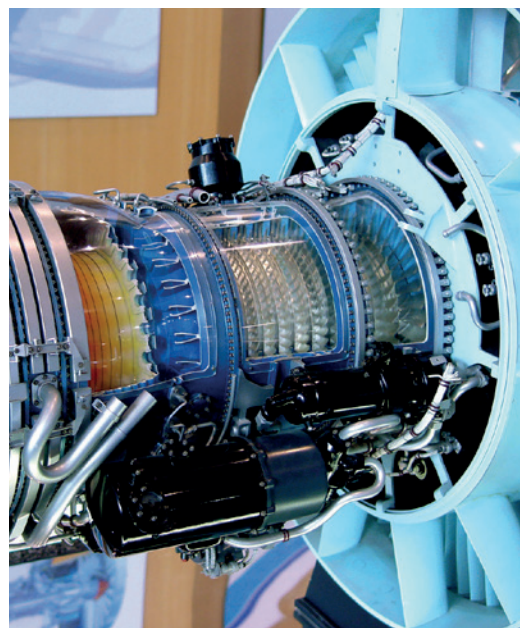
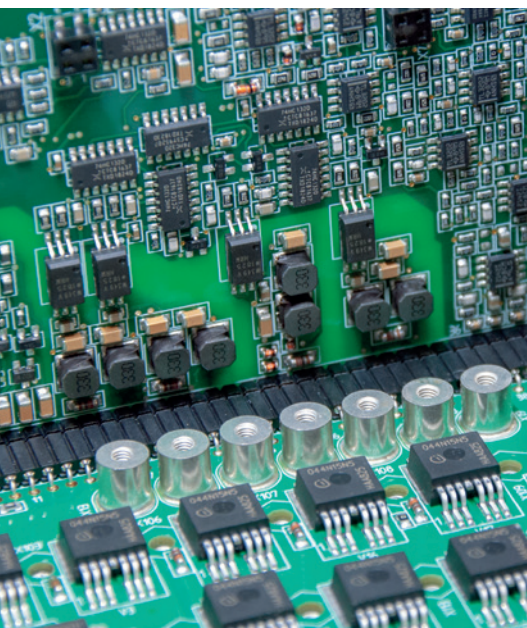




Elektro-Automatik



APPLICATION NOTE: SIMULATING SOLAR CELLS



SIMULATING SOLAR CELLS WITH EA-PSB SERIES BIDIRECTIONAL DC POWER SUPPLIES

As the effects of climate change intensify, carbon-neutral, renewable energy sources become more important. Solar power is a clean energy source for areas of the planet that receive a large amount of annual sunlight. Since solar cells convert sunlight to electrical energy with low efficiencies under 50%, the solar cell generation system including the solar inverter which converts DC solar panel output to AC for distribution on the grid needs to be as efficient as possible. Testing the ability of the inverter to maximize the output of the solar cell is the critical performance requirement for the inverter. Using a power supply instead of a solar cell provides a controlled, repeatable output for testing solar inverters. A power supply that can simulate the output characteristics of a solar cell offers a more realistic simulated source to allow more accurate testing of solar inverter performance.

Solar cells are a variable source of electrical energy that output a voltage and current based on the characteristic I-V curve of the solar cell. The output of the solar cell is a function of sunlight intensity on the cell, its temperature, and the characteristic I-V curve of the solar cell based on its material. When testing how a

load performs when the load is powered by a solar cell, having control over the solar cell output enables repeatable and controlled characterization of the load's performance. For example, a DC-AC converter, an inverter, converts the DC output of the solar cell to AC line power to connect the solar cell output to the power grid. The quality of the inverter is a measure of how well the inverter can maintain maximum output efficiency, its tracking efficiency, when powered by the variable output of the solar cell. Thus, the inverter's response to the variable output of the solar cell needs to be determined.

A power supply can provide a controlled voltage output to enable testing of an inverter's performance. However, the power supply needs to have the output characteristic of a solar cell to provide the most realistic source for determining inverter performance. Elektro Automatik (EA) PSB Series Bidirectional DC Power Supplies have the necessary features to enable the supply to simulate a solar cell. Combined with EA's Power Control software, PSB power supplies can simulate multiple types of solar cells and an array of solar cells.

MATERIALS USED FOR SOLAR CELLS

Most commercial solar cells are crystalline silicon-based devices. Silicon has a bandgap low enough for photons from sunlight to impinge on the silicon and energize electrons to transition into the conduction band and create current flow. Other types of solar cells are thin film structures that can be developed from materials such as amorphous silicon and copper-indium-gallium-diselenide (CIGS). CIGS has a bandgap close to the energy of photons radiated from the sun.

Extensive research is ongoing worldwide to find new materials that have higher light-electrical power conversion efficiencies. Versions of crystalline silicon have efficiencies of 25% which are

close to the Shockley-Queisser limit, the maximum theoretical efficiency of a single p-n junction solar cell which is approximately 30% based on silicon's bandgap of 1.1 eV. Cells composed of multiple layers designed to capture a wider spectrum of light from the sun can exceed the Shockley-Queisser limit. Emerging materials such as organic materials and perovskites are under study as next generation solar cells. Currently, multijunction cells consisting of InGaP, GaAs, and InGaAs can reach efficiency levels of 38%, and perovskite thin films have reached 22% efficiencies. Research will continue to advance solar cell technology toward the goals of low cost, materials with limited degradation, simplified manufacturing processes and high efficiency.

SOLAR CELL CIRCUIT MODEL, ITS I-V CURVE, AND PRIMARY PARAMETERS

A solar cell is essentially a p-n junction and can be modeled as shown in Figure 1. The solar light input on the cell creates a current resulting from electrons increasing in the conduction band of the n-doped side of the p-n junction material and holes increasing in the p-doped side. The net electric field across the diode, the p-n junction, develops the voltage which drives the output current. The series and shunt resistances

represent the losses in a real solar cell. The series resistance represents the resistance of the solar cell semiconductor material and the metal connections to the semiconductor material. The shunt resistance represents the insulation resistance defined by the leakage current through the p-n junction. Having a lower series resistance and a higher shunt resistance increases the efficiency of the solar cell.

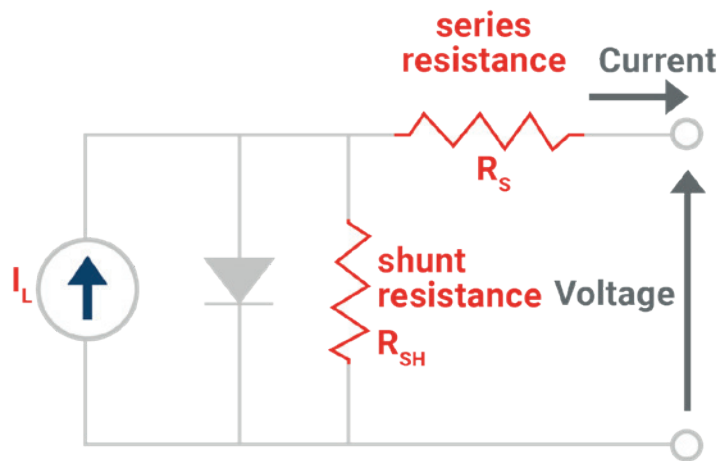


Figure 1
Circuit model for a solar cell

Figure 2 shows the I-V characteristic curve for a solar cell. The key parameters that define the curve are the solar cell's short circuit current, I_{SC} , its open circuit voltage, V_{OC} , and the point where the solar cell's power output is a maximum, the maximum power point, MPP. The I_{SC} and the V_{OC} are the maximum

current and voltage that the solar cell can generate. At the maximum power, MMP, the solar cell's output on its I-V curve is defined as V_{MP} and I_{MP} . The solar cell should be operated at this point on its I-V curve to generate the maximum power output.

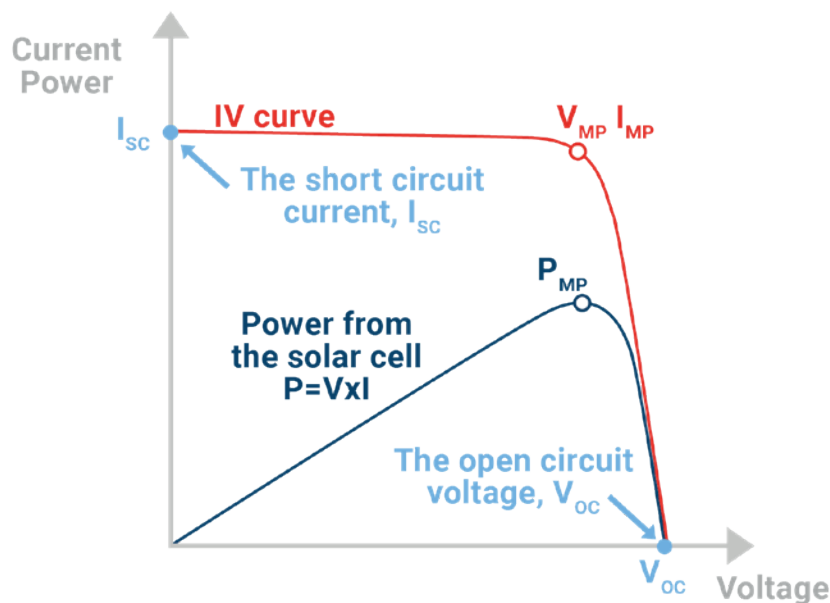


Figure 2
I-V curve of a solar cell. The power vs voltage curve is also shown. The power is a maximum when the solar cell is operating at V_{MP} and I_{MP} .

Another important parameter of a solar cell is its Fill Factor. The Fill Factor is a measure of the maximum power that the solar cell can deliver. The Fill Factor, FF, is defined as:

$$\text{Fill Factor} = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}}$$

Geometrically, the Fill Factor defines how large a rectangle can fit under the I-V curve. The larger the square, the higher the solar cell's maximum power (see Figure 3). Maximum power defined in terms of the Fill Factor is:

$$P_{MP} = V_{OC} \cdot I_{SC} \cdot FF$$

Changing the light intensity on a solar cell results in changes of all solar cell parameters including I_{SC} , V_{OC} , the Fill Factor, efficiency, and the effects of the series resistance and the shunt resistance. The power from the sun, defined as one sun, is 1 kW/m². Solar cell modules designed to operate under conditions representing one sun are known as flat plate modules. Solar modules operating under higher levels of light intensity are known as concentrators. The light intensity on a solar panel varies with the varying angle of the sun on the panel over the course of the day and the quantity of clouds in the sky on a given day. Lower light intensity shifts the I-V curve downward and reduces the power available from the solar cell.

As with any semiconductor device, the temperature of the solar cell affects its I-V curve. An increase in temperature on a solar cell causes a reduction in the bandgap of the semiconductor. Less energy is required to transition an electron into the conduction band. Thus, V_{OC} decreases effectively shifting the I-V curve to the left and changing the parameters of the maximum power point. Temperature and the light intensity impinging on the solar cell are the two main parameters that cause variations in solar cell output.

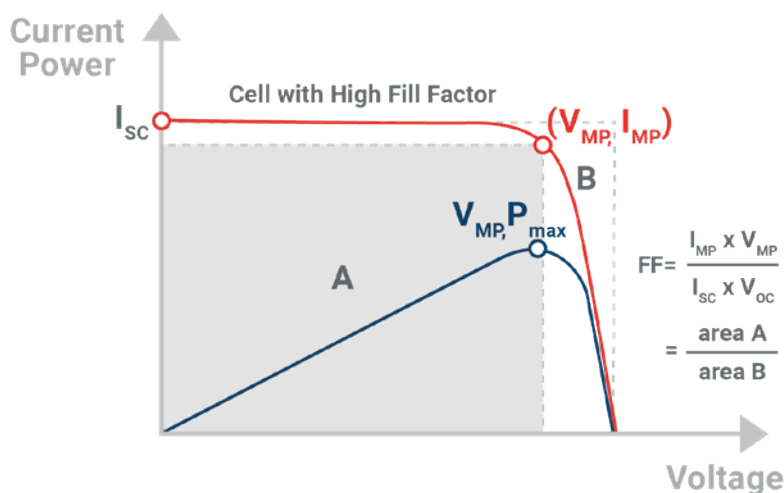


Figure 3
The Fill Factor is the ratio of the total area of the maximum power rectangle divided by the $I_{SC} \cdot V_{OC}$ rectangle and is a determinant of a solar cell's maximum output power.



PSB SERIES BI-DIRECTIONAL DC POWER SUPPLIES CAN MEET THE CHALLENGE OF SOLAR CELL SIMULATION

To simulate a solar cell or an array of solar cells which form a solar panel requires creating its I-V curve. Manufacturers of solar cells provide the needed parameters. Their specifications include I_{SC} , V_{OC} , and P_{MP} . They may provide the I-V curves and maximum power curves. This data can be used to derive the Fill Factor.

Thus, to simulate a solar cell, a solar panel or a solar array, an I-V curve of the device or system's output must be created based on available data and the Fill Factor must be determined. An instrument that can operate along the I-V curve of the solar device is needed. The instrument must also have sufficient power to output up to the maximum capacity of the solar panel or solar array.



The PSB Series DC power supplies have the following features that enable simulation of a solar cell, panel or array:

- A virtual variable output resistance to enable the output voltage to vary with changes in the load current so that the PSB supplies operate on the I-V curve of the solar panel
- A built-in function generator with an XY generator that can store the I-V curve in a table
- Models of the PSB supplies that can output up to 30 kW and can combine in parallel to supply up to 1.92 MW of power
- Built-in solar simulator (photovoltaic) operating modes
- EA Power Control software that uses the XY generator to create the I-V curve and allows execution of tests which simulate an array of solar panels.



SETTING UP A PSB SUPPLY FOR SOLAR PANEL SIMULATION

The steps to simulate a solar panel are:

- 1 With the output de-energized, tap the Function Gen icon on the main screen 
- 2 Next select the PV table (PS) tab shown in Figure 4.
- 3 Enter V_{OC} , I_{SC} , V_{MPP} and I_{MPP} . If the parameters at the maximum power point are unknown, use typical values of $I_{MPP} = 0.9 \cdot I_{SC}$ and $V_{MPP} = 0.8 \cdot V_{OC}$. The PSB creates the I-V curve. To save the I-V curve to a USB memory stick, press the "Import/Export" button and follow the on-screen instructions.
- 4 Ensure that the maximum voltage and maximum power settings for the supply are greater than or equal to V_{OC} and $V_{OC} \cdot I_{SC}$ respectively.
- 5 Press  to show the PV table (PS) display screen. See Figure 5.
- 6 Connect a load such as a solar cell inverter to the PSB output terminals.
- 7 Activate the PSB output.

While the PV simulation is running, the user can adjust the Irradiance to emulate the light intensity on the solar panel. The irradiance can be set from 0% (total darkness) to 100% representing full intensity from the sun. Varying the irradiance shifts the I-V curve along the I-axis as shown in Figure 6. The irradiance can be changed either by entering a new reading on the display or turning either rotary knob on the PSB's front panel

The display shows the output voltage, current and power. Also shown is the irradiance and a chart showing the magnitude of the power output compared to the maximum power point.

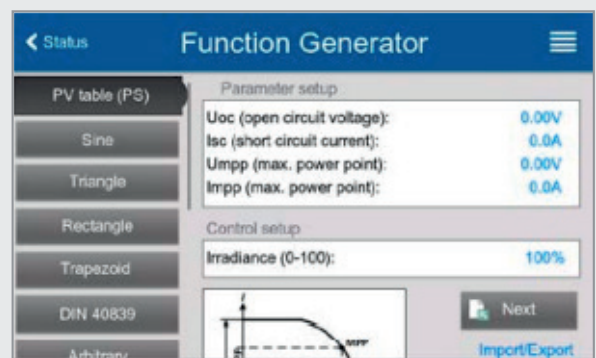


Figure 4
PV Table (PS) tab shown on the PSB's Function Generator display window

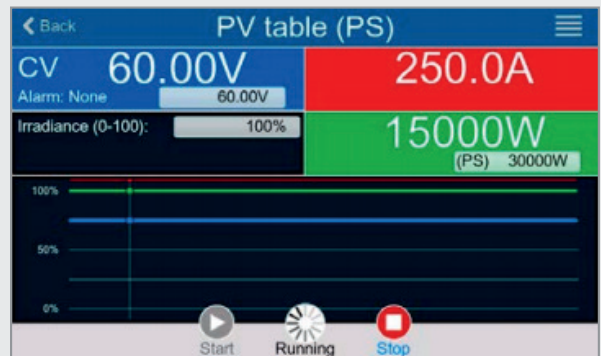


Figure 5
Solar panel main display window showing the measured output parameters, the controlled variable, solar irradiance in this display, and how close the panel is operating to its maximum power point.

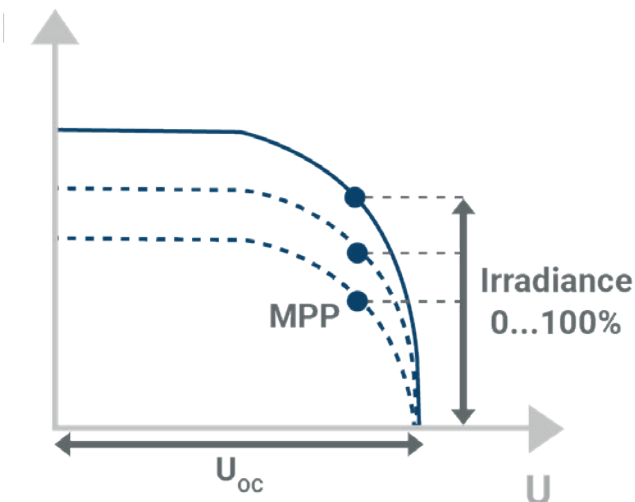


Figure 6
Shift of I-V curve as a function of irradiance on the solar panel

TESTING SOLAR INVERTERS USING A PSB DC SUPPLY

Ensuring that solar inverters can track or maintain the solar cell's operation at the maximum power point is a critical function of a solar inverter. Keeping the solar cell at its maximum power point enables the system to transfer the maximum available power to the power distribution grid. The PSB's solar simulator operating mode can evaluate the inverter's efficiency in compliance with a European standard, EN 50530 **Overall efficiency of grid connected photovoltaic inverters**. The standard is published by the European Committee for Electrotechnical Standardization (CENELEC). The current version is dated April 1, 2010.

The PSB has an EN50530 test mode which adds more detailed parameters for solar cell simulation. The user can select pre-programmed parameters for either a crystalline silicon solar panel or a panel consisting of thin film material. The user also can enter specific parameters for another type of solar cell. These parameters include Fill Factor and temperature parameters.

The EN50530 test function has four operating modes.

Two modes permit manual adjustment of solar cell parameters.

- The U/I mode allows variation of the maximum power point setting to determine how an inverter load responds to the change.
- The E/T mode enables varying the irradiance on the solar panel and the surface temperature of the solar panel. Changes in both parameters affect solar cell power output.

Two modes permit automated simulation over an extended time period. These modes are called "day trend" modes and permit a test over as many as 100,000 data points consisting of two solar cell parameters and a dwell time.

- The Day U/I simulation steps through programmed data points with V_{MPP} and I_{MPP} as the controlled variables.
- The Day E/T simulation steps through with irradiance and temperature as the controlled variables.

In the Function Generator menu, select the PV EN50530 (PS) tab as shown in Figure 7. Perform the steps to define the parameters of the simulation. If one of the day trend simulation modes is selected, the user is prompted to load the data file from a USB memory stick or from a PC. The user can choose to have step transitions between data points or smooth curves for transitioning between data points. The smoothing of the transitions between data points is the "Interpolation" option. The user has the option to store voltage and current readings and transfer them to a USB memory stick or a PC through a PC interface. This is the "Recording" option. When all the options of the EN50530 mode have been programmed, the main display is shown. The simulation can begin operation. The display shows the output of the simulated solar panel and the values of the controlled parameters. See Figure 8.

Figure 7
Two PV EN50530 (PS) windows showing parameter setup, Figure 7a, and choice of the simulation mode, Figure 7b.

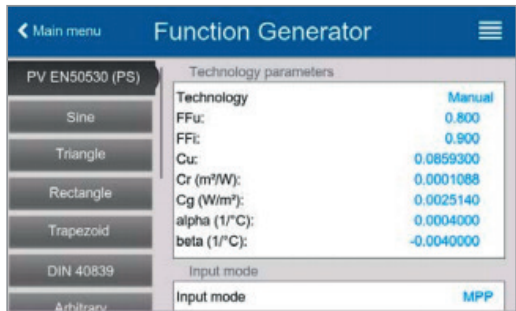


Figure 7a
Parameter set up window

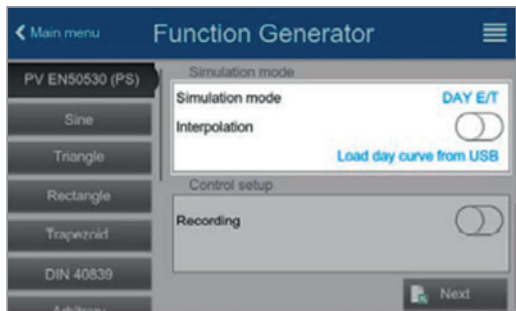


Figure 7b
Window showing options for the simulation mode, interpolation of transitions, and data storage

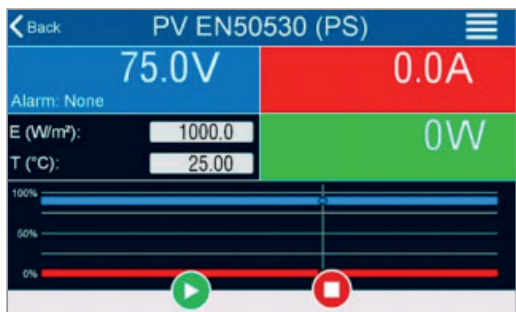


Figure 8
PV EN50530 operating display window showing measured parameters, the controlled variables, and the output relative to the maximum power point.

SIMULATING A SOLAR ARRAY WITH THE EA POWER CONTROL SOFTWARE

The EA Power Control software has a mode, solar array simulation (SAS), that can simulate an array of solar panels either with individual power supplies or with a set of power supplies in parallel. In this mode, the user enters the power supplies used and the I-V curve for the panel that each supply represents. The SAS mode conducts two tests, a static test and a dynamic maximum power point test. See Figure 9.

The static test used a fixed maximum power point for each panel (power supply). The control variable is irradiance which is defined by percentage values. The solar panel maximum power point shifts with the irradiance. The solar inverter tracks the change in the maximum power point and establishes its own maximum power point. The ratio of the MPP of the solar array, a function of the irradiance, to the measured MPP determined by the solar inverter defines the inverter efficiency.

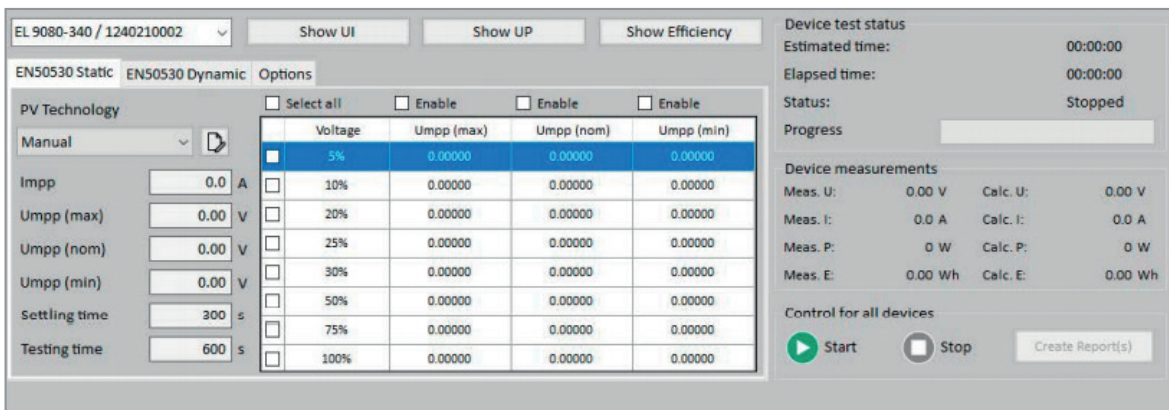


Figure 9 Power Control software window for the solar array static test

In the dynamic test, the power supplies simulate the output variation resulting from cycles with different irradiation levels, ramp up times, dwell times at the peak of the rise, ramp down times, and dwell times at the end of the ramp down. Up to 50 rows of configuration data can be loaded into the software. The window, Figure 10, shows the measured data and test status of the selected power supply from the drop-down list.

When the test is completed, the test results are available on the windows shown in Figures 9 and 10. The complete set of data for all power supplies in the simulated array is available for saving to a file using the "Create Report" button.

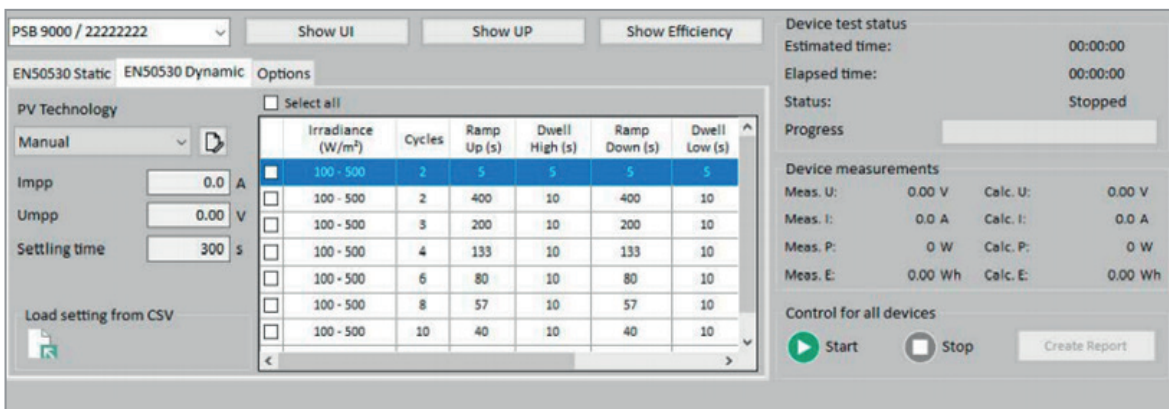


Figure 10 Power Control software window for the solar array dynamic test

PSB DC POWER SUPPLIES AND POWER CONTROL SOFTWARE PROVIDE ALL THE ESSENTIALS FOR SOLAR PANEL AND SOLAR ARRAY SIMULATION

Simulating solar panels with a power supply enables realistic, but repeatable and controlled output compared with testing using actual solar panels that require fixed light intensity and temperature control of the solar panels. Setting up constant light intensity sources, using actual solar panels, and controlling the solar panel temperature is neither particularly feasible nor conducive for automated testing of solar inverters in design and production facilities. Testing with a solar panel array could not be done in a reasonably sized manufacturing facility. The cost of floor space along with the difficulty of controlling light intensity and temperature of the individual panels would cost-prohibitive and generate test data that could not be easily reproduced and validated.

The PSB Series power supplies solve the challenges of solar panel simulation. They have unique capabilities for solar cell simulation. These capabilities include:

- Variable output resistance to enable simulation of a solar panel's I-V characteristics
- Built-in function generator that allows creation of a solar panel I-V output curve
- Solar cell test modes that enable testing defined by the EN 50530 standard
- Models with sufficient power, up to 30 kW to simulate any solar panel or group of solar panels
- Power Control software that controls multiple power supplies to simulate an array of solar panels.

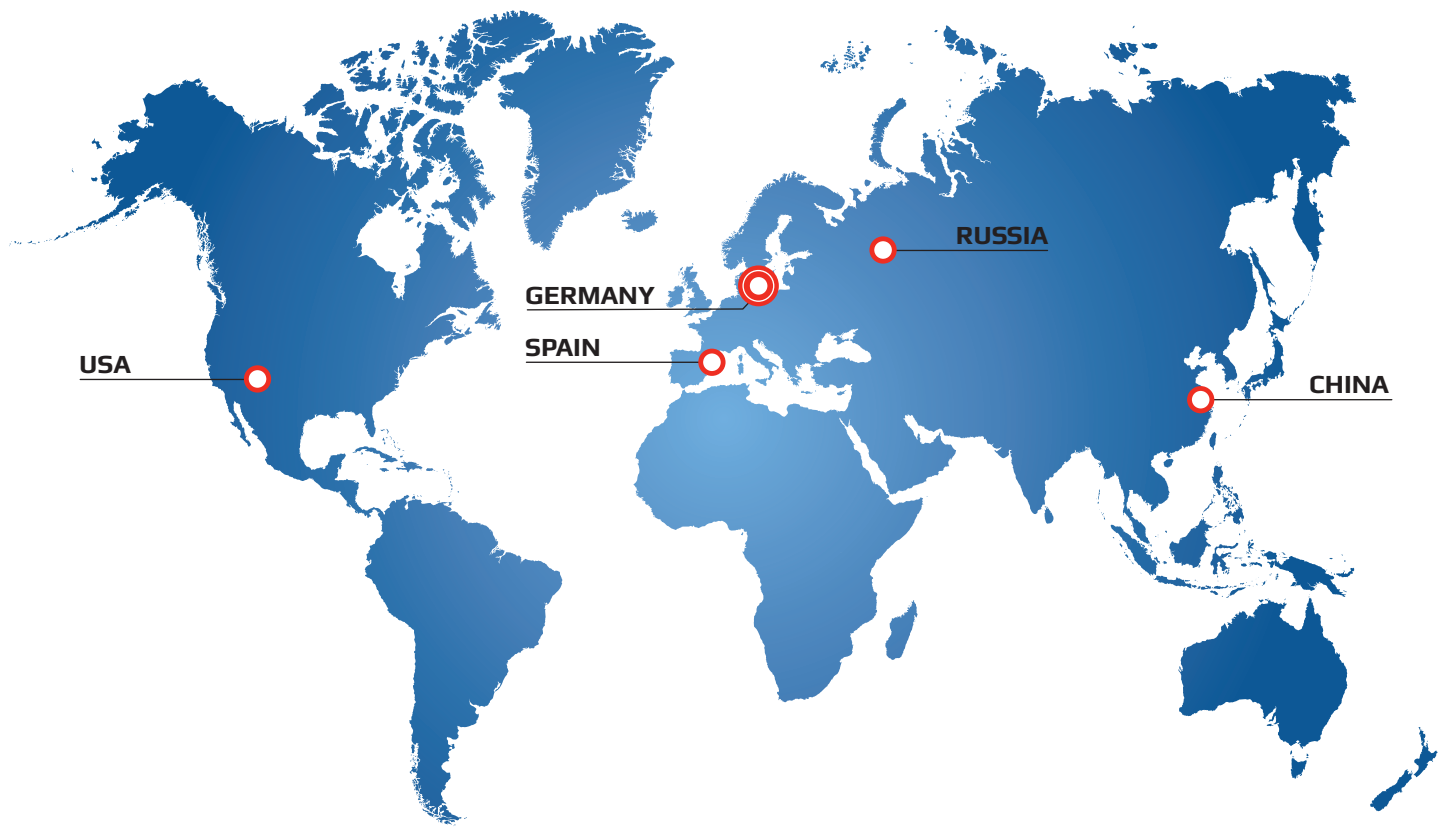
The PSB Series Bidirectional DC power supplies with the Power Control software enable simplified and flexible simulation of solar panels and arrays of solar panels enabling quality testing of solar inverters.



References

C.B. Honsberg and S.G. Bowden, "Photovoltaics Education Website," www.pveducation.org, 2019.

Operating Guide PSB 10000 4U Bidirectional DC Power Supply
User Guide to EA Power Control Version 2.17



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At the headquarter in Germany in the industrial centre of North Rhine Westphalia more than 200 qualified associates, in a facility of 18000 m², research, develop and manufacture high-tech equipment for laboratory power supply, high power mains adaptors and electronic loads with or without power feedback. The sales network includes branches in China and USA, sales offices in Russia and Spain and an extensive partner network.

