

APPARATUS AND METHOD FOR MULTISPECTRAL DETERMINATION OF SPECTRAL IRRADIANCE SENSITIVITY AND VOLTAGE-DEPENDENT CURRENT BEHAVIOR OF PHOTOVOLTAIC UNITS

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FIELD OF THE INVENTION

The present invention relates to a device and a method for characterizing properties of photovoltaic units. The invention further relates to a corresponding computer program product and a computer-readable medium.

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TECHNICAL BACKGROUND

Photovoltaic units are semiconductor components which utilize the internal photoeffect in order to supply an electrical signal upon absorption of light. Photovoltaic units may generally be referred to as radiation sensors. In particular, photovoltaic units may be formed as solar cells. Solar cells serve to convert light, as radiated in particular by the sun, into electrical energy. Such solar cells are also referred to as photovoltaic cells. A plurality of solar cells may be interconnected with one another to form a solar module. Both individual solar cells and entire solar modules and other types of radiation sensors are referred to here in general terms as a photovoltaic unit, wherein photovoltaics are sometimes abbreviated to PV.

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Various physical properties of photovoltaic units are conventionally determined with the aid of different measuring devices and methods, which are usually developed specifically for an application.

For example, in order to assess a behavior of a photovoltaic unit and in particular an efficiency of the photovoltaic unit, it may be necessary to know the voltage-dependent current behavior $I(U)$ of the photovoltaic unit. This current behavior indicates how the electric current I flowing through the photovoltaic unit behaves as a function of an

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electric voltage U applied to the photovoltaic unit. In particular, information about this current behavior when the photovoltaic unit is exposed to light may be desired. In this case, the aim is regularly to illuminate the photovoltaic unit as far as possible in a way which corresponds to real use in the case of illumination with light radiated in by the sun.

In order to be able to characterize photovoltaic units as precisely and in a standardized manner as possible and in order to be able to dispense with illumination with real sunlight, the conditions which prevail in the case of illumination with real sunlight have been standardized with regard to a light intensity and a spectral distribution. In this case, a standardized solar spectrum, for example according to the AM1.5G standard, corresponds to an intensity of 1000 W/m^2 and a spectral distribution which prevail on average at the earth's surface, i.e. after passing through a 1.5-times earth's atmosphere layer. Such a standardized AM1.5G solar spectrum is therefore preferably used for characterizing terrestrial photovoltaic units. A standardized AM0 solar spectrum corresponds, with regard to intensity and spectral distribution, to solar radiation which prevails in space and is therefore used in particular for characterizing photovoltaic units for satellites and the like.

Technical apparatuses with the aid of which the voltage-dependent current behavior of photovoltaic units is intended to be characterized under radiation conditions which are as realistic as possible are also referred to as IV measuring stations with a solar simulator (sun simulator) as a light source. In general, this is a measuring station at which a photovoltaic unit may be electrically contacted by means of a contacting device in order then to be able to measure, with the aid of an evaluation device, a current flowing through the photovoltaic unit as a function of an applied electric voltage. Characteristic data such as the short-circuit current I_{SC} , the open-terminal voltage V_{OC} , the maximum power P_{max} , the fill factor FF and/or the efficiency η may then be determined from a current-voltage characteristic curve which is determined in this case, as a result of which the photovoltaic unit may be evaluated and/or characterized. The IV measuring station is

generally constructed in such a way that the photovoltaic unit may be measured under standard test conditions (sample temperature, irradiance and spectrum of the solar simulator according to the respective standard to be applied). For this purpose, the IV measuring station has an illumination source which is designed to reproduce the
5 respective standard spectrum (solar spectrum) to be applied as precisely as possible.

For this purpose, the solar simulator may be provided, for example, with a thermal light source, the radiation of which is then modified with the aid of various filters in order to simulate the standardized solar spectrum. Alternatively, modern solar simulators may have a plurality of light-emitting diodes (LEDs), the emitted light of which may

10 reproduce the standardized solar spectrum overall, optionally using filters. In this case, a greatly reduced energy consumption, lower maintenance requirements, a longer lifetime, a more rapidly switchable light emission and/or a light emission behavior which is more stable over time may be achieved by means of the LEDs. Furthermore, a spectrum may be restricted more easily to a spectral range relevant for the measurement with the aid
15 of LEDs. In order to be able to influence the light spectrum prevailing in the solar simulator with regard to its spectral distribution, various LEDs which differ with regard to the spectral distribution of the light emitted by them may be provided in the solar simulator. Optionally, these various LEDs may be drivable individually or in a plurality of groups.

20 A further type of characterization of photovoltaic units is the determination of the so-called spectral irradiance sensitivity $SR(\lambda)$ (referred to hereinafter also as spectral responsivity, SR). The spectral responsivity thus indicates which current the photovoltaic unit generates in the case of illumination with light of a wavelength or of a narrow-band wavelength range and is usually indicated with the unit $\text{mA}/(\text{W}/\text{m}^2)$ or independently of
25 an area with the unit A/W . The curves of the spectral responsivity (SR curves) are used inter alia during a development and characterization of photovoltaic units such as solar cells or solar modules and for material analysis, since the SR curve spectrally resolves the current behavior, in particular a short-circuit current I_{sc} , of the photovoltaic unit.

For example, wavelength ranges which increase or decrease the short-circuit current may be identified for material analysis. In addition, it is possible with physical modeling to attribute the shape of the SR curve to cell properties such as recombination or absorption, in order hereby to determine the cell properties.

- 5 For the calibration of photovoltaic units and the determination of their characteristic parameters under standard test conditions, SR curves are generally essentially necessary for a determination of a factor of a spectral mismatch and thus for a precise setting of the irradiance of the solar simulator. A characteristic curve of the photovoltaic unit may be determined precisely and in accordance with the standard only with the aid of this
- 10 factor of the spectral mismatch in IV measurement systems. This applies both to offline analyses and to inline measurements.

The spectral responsivity $SR(\lambda)$ of solar cells and solar modules is usually determined at special SR measurement stations (so-called DSR/SR measurement stations). This approach is referred to herein as "SR standard method". A functional principle of these

15 previous DSR/SR measurement stations consists in an irradiation of the test object with two radiation sources: (1) a temporally constant white (bias) light and (2) a quasi-monochromatic light as a small signal with significantly lower intensity. The white light is generated, for example, with an array of halogen emitters. In this case, the white light may ideally be identical or largely similar to the standard spectrum under which the

20 current-voltage characteristic curve is intended to be measured later, that is to say generally to the AM1.5G or the AM0 spectrum. The quasi-monochromatic light may be generated, for example, with a combination of a lamp with a broadband spectrum and a monochromator and/or various filters. In this case, the quasi-monochromatic light may be modulated over time, for example by means of a chopper wheel. Before the

25 measurement of the test object, the radiation contribution of the quasi-monochromatic light is calibrated with a reference solar cell. During the measurement process, the test object is kept under short-circuit conditions. The current response of the test object is then a direct current with a small pulsating component. A transimpedance converter

separates the pulsating current component from the direct current component and makes this available as a proportional voltage signal which is measured and evaluated by means of a lock-in amplifier. As a result, the differential SR of the test object follows, which is integrated via various bias irradiances and therefore delivers the sought SR of the test object. This method has been established for many decades for PV applications, but requires complex measurement technology and is time-consuming.

For a few years, there have been approaches to determining the SR curve with LEDs of various wavelengths (referred to herein as "SR-LED reference solar cell method"). This is a variant or further development of the above-described SR standard method. In this case, the test object is irradiated individually with the LEDs and the resulting short-circuit current is measured. The irradiance of the LEDs is measured beforehand with a calibrated solar cell. It has been shown that the SR curve of the test object may be determined with this method. One disadvantage of this method is that the LEDs are frequently broadband and the SR may not be determined sufficiently well in some wavelength ranges as a result. Mathematically complex methods have been proposed in order to prevent this problem. An additional difficulty is the stabilization of the light intensity of each individual LED since the monitor diodes installed in the solar simulators usually collect broadband and are optimized for other operating points. Up to now, the method has not become established for PV applications.

SUMMARY OF THE INVENTION AND OF EMBODIMENTS

There may be a need for an alternative measuring device and an alternative method for characterizing photovoltaic units. In particular, there may be a need for being able to characterize photovoltaic units with little effort, quickly, cost-effectively and/or reliably.

In addition, there may be a need for a computer program product, with the aid of which corresponding methods may be implemented, and for a computer-readable medium with such a computer program product stored thereon.

The stated needs may be fulfilled at least in part with the subject matter of one of the independent claims of the present application. Advantageous embodiments are specified in the dependent claims and in the following description and the figures.

According to a first aspect of the present invention, a measuring device for determining
5 a spectral responsivity $SR(\lambda)$ and a voltage-dependent current behavior $I(U)$ of a photovoltaic unit under standard solar conditions is described. The measuring device comprises at least one illumination source, a contacting device, a controller and an evaluation device. The illumination source is configured to selectively emit light with variable spectral distributions or with an intensity and spectral distribution which
10 correspond to a standardized solar spectrum. The contacting device is configured to electrically contact the photovoltaic unit. The controller and the evaluation device are selectively operable in a first or a second operating mode. In this case, the controller is configured (i) in the first operating mode to control the illumination source to emit light with an intensity and spectral distribution corresponding to the standardized solar
15 spectrum, and (ii) in the second operating mode to control the illumination source to successively emit light with a multiplicity N of different spectral distributions. Furthermore, the evaluation device is configured to apply an electric voltage to the photovoltaic unit via the contacting device and to measure, as a function of the applied voltage, a current flowing through the photovoltaic unit and in this case (i) in the first
20 operating mode to determine, from the measured current, the voltage-dependent current behavior $I(U)$ of the photovoltaic unit under the action of the standardized solar spectrum, and (ii) in the second operating mode to determine, from a plurality of currents $I_{\text{meas},n}$ ($n=1\dots N$) respectively measured upon illumination with the N different spectral distributions and taking into account a spectral irradiance $E_{\lambda,n}(\lambda)$ ($n=1\dots N$)
25 previously known for each of the N spectral distributions, the spectral responsivity $SR(\lambda)$ of the photovoltaic unit.

According to a second aspect of the present invention, a method for determining a spectral responsivity $SR(\lambda)$ of a photovoltaic unit by means of a measuring device for

determining a voltage-dependent current behavior $I(U)$ of a photovoltaic unit under standard solar conditions is described. The measuring device comprises an illumination source, a contacting device, a controller and an evaluation device. The illumination source is configured to selectively emit light with variable spectral distributions or with an intensity and spectral distribution which correspond to a standardized solar spectrum. The contacting device is configured to electrically contact the photovoltaic unit. The controller is configured to control the illumination source in the first operating mode to emit light with an intensity and spectral distribution corresponding to the standardized solar spectrum. The evaluation device is configured to apply an electric voltage to the photovoltaic unit via the contacting device and to measure, as a function of the applied voltage, a current flowing through the photovoltaic unit and in this case in the first operating mode to determine, from the measured current, the voltage-dependent current behavior $I(U)$ of the photovoltaic unit under the action of the standardized solar spectrum. The method comprises at least the following steps, possibly but not necessarily in the specified order:

controlling the illumination source by means of the controller in a second operating mode to successively emit light with a multiplicity N of different spectral distributions, measuring, by means of the evaluation device, in the second operating mode, currents $I_{\text{meas},n}$ ($n=1\dots N$) respectively flowing through the photovoltaic unit upon illumination with the N different spectral distributions, and determining the spectral responsivity $SR(\lambda)$ of the photovoltaic unit taking into account a spectral irradiance $E_{\lambda,n}(\lambda)$ ($n=1\dots N$) previously known for each of the spectral distributions.

According to a third aspect of the invention, a computer program product is described which has machine-readable instructions which, when executed by a processor of a measuring device for determining a current behavior under standard solar conditions of a photovoltaic unit, instruct the measuring device to execute or to control the method of an embodiment of the second aspect of the invention.

According to a fourth aspect of the invention, a computer-readable medium is described which has machine-readable instructions of a computer program product according to an embodiment of the third aspect of the invention stored thereon.

- 5 By way of introduction, a basic concept and possible advantages relating to embodiments of the invention described herein are to be explained briefly, wherein this explanation is to be interpreted as merely roughly summarizing and not as limiting the invention:

The present invention relates in particular to a measuring device with which both the
10 voltage-dependent current behavior of a photovoltaic unit during illumination with a standardized solar spectrum and the spectral responsivity of the photovoltaic unit may be determined. Therein, the measuring device comprises components such as, in particular, an illumination source, a contacting device, a controller and an evaluation device, as are frequently used in modern solar simulators. However, in particular the
15 controller and the evaluation device are configured to implement a second operating mode in addition to a functionality implemented in solar simulators within the scope of a first operating mode in which the illumination source is controlled to emit the standardized solar spectrum and the evaluation device is configured to measure a voltage-dependent current of the photovoltaic unit brought about thereby. In this
20 second operating mode, the measuring device may then determine the spectral responsivity of the photovoltaic unit.

In this case, a different approach is used for the second operating mode than is the case in the conventional methods explained in the introduction to the description, in particular the "SR standard method" or the "SR-LED reference solar cell method". In
25 particular, an approach is chosen in which the spectral responsivity may be determined largely with device components such as are frequently used in any case in a solar simulator, i.e. in which a conventional solar simulator does not need to be modified in hardware terms or needs to be modified only slightly (for example, as explained further

below, by adding a spectrometer or a spectral radiometer). In particular, it is used that modern solar simulators often have an illumination source with, for example, a plurality of differently colored LEDs and are therefore able to emit light with a variable spectral distribution. As illustrated in detail further below, this may be used to illuminate the photovoltaic unit a plurality of times with respectively different spectral distributions in the second operating mode and to measure the current brought about in each case in the process. If the associated spectral irradiance is then known for each spectral distribution, for example on the basis of an additionally carried out measurement with a spectrometer or spectral radiometer, the spectral responsivity may be determined, for example, with the aid of a calculation method which is relatively simple to implement.

The “multi-spectral determination method” described here may offer various advantages over the conventional methods described further above for determining the spectral responsivity, in particular if it is implemented in combination with the resources or components of a solar simulator or IV measuring station.

The following advantages may be mentioned, inter alia, over the SR standard method:

- The SR of the photovoltaic unit may be determined directly within an IV measuring station with a spectrally adjustable light source. A separate SR measuring station is not necessary. Costs, effort and time may be saved as a result.
- A mechanical load on the photovoltaic unit may be reduced, in particular since it has to be contacted only once in order then to be able to determine both an IV curve and an SR curve.
- No complex lock-in technology is required and also no transimpedance converter. This may be advantageous in particular for a characterization of large solar cells (M6-M12), since, to date, in most cases no transimpedance converter for the use of the standard method is commercially available for this purpose.
- A measurement duration may be reduced from approximately 20-60 min in the case of the SR standard method to a few minutes or even less than one minute.

The following advantages may be mentioned, inter alia, over the "SR-LED reference solar cell method":

- The SR curve may be determined directly at the 1-sun operating point of the solar cell or of the photovoltaic unit.

5 - The proposed methodology is mathematically simple to carry out.

- No corrections are required in the case of broadband LEDs.

In particular, instead of a calibrated reference solar cell, a spectrometer or a spectroradiometer (calibrated spectrometer) may be used as reference. Such a spectrometer or spectroradiometer may be available in sufficiently good quality, in particular commercially available.

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- The stabilization of the light intensity of the LEDs may be carried out with broadband monitor diodes which are usually used. A stabilization of each individual LED channel is not necessary.

In addition, different variants of radiation sensors may be characterized with

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embodiments of the measuring device presented here. A first variant behaves like a solar cell. A second variant of a radiation sensor has an internal shunt resistor. In the case of such radiation sensors, a voltage drop of an internally flowing current across a resistor is measured. Such sensors may also be measured with the method presented here or the measuring device presented. In addition, the approach presented here may also be used for the characterization of digital sensors which output a value which is proportional to the irradiance.

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Overall, an advantageous integration of the methodology presented here into a multichannel LED solar simulator is conceivable. As a result, for example, the spectral responsivity $SR(\lambda)$ of a solar cell to be measured may be determined in addition to a voltage-dependent current behavior of the solar cell determined with the solar simulator and thus the factor of a spectral mismatch may be determined directly. In particular, no further measuring station is necessary in this case, with the result that, inter alia,

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considerable costs and/or space requirement may be saved, for example for the equipping of a solar cell production line with inclusion of an SR measuring possibility.

Possible configurations and advantages of embodiments of the measuring device and of a method are described in more detail below:

The measuring device presented here is designed, inter alia, for an implementation of a functionality of a solar simulator. Accordingly, the measuring device may determine the voltage-dependent current behavior of an individual solar cell or of an entire solar module under standard solar conditions.

For this purpose, the illumination source of the measuring device is able to emit light which corresponds, with regard to its intensity, to that of natural sunlight, that is to say with approximately 1000 W/m², and which furthermore has a spectral distribution which largely resembles natural sunlight. For example, the illumination source is configured to emit an AM1.5G solar spectrum. In this case, the illumination source may illuminate a measurement area which covers at least the surface of the photovoltaic unit to be characterized as homogeneously as possible, that is to say for the measurement of individual solar cells a measurement area of typically between 0.1 cm² and 1000 cm², usually between 1 cm² and 500 cm², or for the measurement of entire solar modules a significantly larger measurement area with, for example, at least 0.3 m² up to a few square meters. In this case, an operation and, in particular, a power supply of the illumination source are controlled by the controller of the measuring device.

The measuring device has a contacting device with the aid of which the photovoltaic unit to be characterized may be electrically contacted and optionally suitably positioned and/or mechanically held. Via the contacting device, the evaluation device of the measuring device may apply an electric voltage to the photovoltaic unit and measure the current occurring thereupon (referred to below sometimes as "PV current"). In this case, the voltage may be varied, for example, over a range which extends at least from a

short-circuit voltage U_{SC} to an open-terminal voltage U_{OC} of the photovoltaic unit, that is to say, for example, in the case of an individual silicon solar cell over a voltage range of 0 V to approximately 0.7 V.

In addition to the solar simulator functionality, the measuring device presented is
5 configured for implementing a determination of the spectral responsivity $SR(\lambda)$.

For this purpose, the illumination source is configured in such a way that light with different spectral distributions may be emitted with its aid. In this case, the light may be emitted successively with a multiplicity N of different spectral distributions, where $N > 1$, $N > 2$, $N > 5$, preferably $N > 10$ or $N > 20$, $N > 50$, $N > 100$, $N > 200$, $N > 500$ or $N > 1000$ and/or
10 $N < 100000$, $N < 50000$, $N < 10000$, preferably $N < 5000$ or $N < 1000$, $N < 500$ or $N < 100$ may apply. Eine emittierte Spektralverteilung kann dabei über die Steuerung der Messvorrichtung gesteuert und variiert werden. In this case, the spectral distributions differ in particular with regard to a radiation power emitted at various wavelengths. In this case, differences between the spectral distributions may be at least 1% relative, at
15 least 2% relative, at least 5% relative, at least 10% relative or at least 20% relative over at least one wavelength subrange, wherein the wavelength subrange may extend, for example, over at least one wavelength interval of at least 5 nm, at least 10 nm, at least 20 nm or at least 30 nm. The illumination source may emit light with a spectral distribution over at least one illumination duration which is sufficiently long to be able to
20 measure the current occurring thereupon in the photovoltaic unit. For example, the illumination duration may be longer than 10 ms, longer than 100 ms, longer than 1 s or longer than 10 s and/or shorter than 100 s, shorter than 10 s, shorter than 1 s or shorter than 100 ms.

In this case, the evaluation device is additionally configured to measure the electrical PV
25 current $I_{meas,n}$ (with $n=1...N$) respectively resulting in the photovoltaic unit in the second operating mode for each of the N different spectral distributions radiated in by the illumination source. On the basis of this multiplicity of current measurements, as explained in detail further below for an example, the responsivity of the photovoltaic

unit may then be determined, for example, by an analytical and/or numerical calculation at least in an approximation which is sufficiently good for practical applications.

Therein, in addition to the information about the measured PV currents, an associated spectral irradiance $E_{\lambda,n}(\lambda)$ ($n=1...N$) must also be previously known in sufficient quality for each of the spectral distributions and be taken into account in the determination of the responsivity.

For this purpose, according to one embodiment, the spectral irradiance $E_{\lambda,n}(\lambda)$ may be previously known for each of the spectral distributions by measurement by means of the spectrometer or spectroradiometer. In other words, a spectrometer or spectroradiometer may be used to measure the spectral distributions to be emitted in the measuring device described herein with respect to their spectral irradiances with an accuracy which is sufficient for the determination of the spectral responsivity $SR(\lambda)$ to be carried out subsequently.

A spectrometer is configured to measure a light spectrum as intensity as a function of the wavelength. Simple spectrometers in this case detect the light intensity at the various wavelengths usually as a relative measured variable and output measured values typically as [counts].

A spectral radiometer, sometimes also referred to as spectroradiometer, is a light measuring device in the form of a calibrated spectrometer which may measure both the wavelength and the spectral irradiance of the light emitted by a light source. In contrast to a simple spectrometer which may generally measure a spectrum of incident light only with regard to its relative intensity differences at various wavelength ranges, a spectroradiometer as calibrated spectrometer may determine an absolute irradiance for each wavelength range. Spectrometers in the form of so-called array spectrometers distinguish the wavelength on the basis of a position at which the light strikes a detector arrangement, with the result that the entire spectrum may be detected with a single detection. If the light source is stable over time, the spectrum may alternatively also be

measured with a scanning system, the selection of the wavelength usually being effected by means of dispersion optics such as, for example, an optical grating, a prism or the like. The dispersion optics may be rotated stepwise in this case and the (spectral) irradiance may be measured per rotation step with a small broadband sensor, for example on a silicon basis. Most spectrometers have a basic measurement of counts which is an uncalibrated measured value and is therefore influenced by the sensitivity of the detector for each wavelength. By applying a calibration, the spectrometer as spectroradiometer is then able to supply measurements of the spectral irradiance $[W/(m^2 \cdot nm)]$, of the spectral radiance and/or of the spectral flux. These data may then be used in order to obtain, for example, measured values for irradiance (W/cm^2), illuminance (Lux or fc), radiance (W/sr), luminance (cd), luminous flux (Lumen or Watt), chromaticity, color temperature, peak value and/or dominant wavelength. Spectrometers may cover many wavelength ranges. An effective wavelength range (spectral range) of a spectrometer is determined not only by a dispersion capacity of a grating used therein, but also depends on the sensitivity range of the detectors. Limited by a band gap of the semiconductor, for example, a detector on a silicon basis responds at 200-1100 nm, while a detector on an InGaAs basis is usually sensitive for 900-1700 nm.

In order to be able subsequently to determine the spectral responsivity $SR(\lambda)$ in sufficient quality on the basis of the spectral irradiance $E_{\lambda,n}(\lambda)$, the spectral irradiance should be previously known with sufficient accuracy. For example, the spectral irradiance should be previously known with a wavelength resolution of at least 100 nm, preferably at least 50 nm, at least 20 nm or at least 10 nm. In addition, the spectral irradiance should be previously known with a spectral bandwidth of at most 100 nm, preferably at most 50 nm, at most 20 nm or at most 10 nm. Furthermore, the spectral irradiance should be previously known over a wavelength range of at least 400 nm to 800 nm, wherein a lower limit of the wavelength range may preferably lie at 380 nm, 350 nm, 330 nm or 300 nm or even lower and an upper limit of the wavelength range may preferably lie at 850 nm, 900 nm, 950 nm, 1000 nm, 1050 nm or 1100 nm or even higher. Furthermore, the spectral irradiance should be previously known with a non-linearity with respect to

the intensity of better than 20%, preferably better than 10% or better than 5%.

Furthermore, a relative intensity calibration should be better than 20%, preferably better than 10% or better than 5%. Finally, a relative wavelength calibration should be better than 40 nm, preferably better than 10 nm or even better than 3 nm. In particular, the spectral irradiance may be measured with the aid of a high-quality spectroradiometer which is designed for measuring the spectral irradiance with the abovementioned properties. Furthermore, such a spectroradiometer should, as far as possible, have a computer interface in order to be able to communicate the measured spectral irradiance and optionally other data to other components of the measuring device described here.

By using the spectrometer or spectroradiometer, the spectral irradiance $E_{\lambda,n}(\lambda)$ of each of the spectral distributions radiated in by the illumination source onto the photovoltaic unit may be measured with high accuracy and individually for the spectral distribution actually radiated in onto the photovoltaic unit. On the basis of such measured values $E_{\lambda,n}(\lambda)$ together with the information about the respectively measured currents $I_{\text{meas},n}$, the spectral responsivity $SR(\lambda)$ may then be determined computationally with high accuracy and sufficient resolution.

If the spectral irradiance was measured with an uncalibrated spectrometer, information about the relative spectral responsivity may be derived on the basis of the measured values. If, in contrast, the spectral irradiance was measured with a calibrated spectroradiometer, information about the absolute spectral responsivity may be derived on the basis of the measured values. An absolute value for the short-circuit current I_{SC} of the solar cell may then be calculated from this information about the absolute spectral responsivity.

For this purpose, according to one embodiment, the spectrometer or spectroradiometer may be integrated into the measuring device in order to be able to measure the spectral irradiance $E_{\lambda,n}(\lambda)$ currently for each of the spectral distributions emitted within the measuring device. However, it is pointed out that, although it appears advantageous to measure the spectral irradiance for each irradiated spectral distribution individually with

the aid of a spectrometer or spectroradiometer integrated directly into the measuring device, this is not absolutely necessary for the determination of the spectral responsivity, however, as long as the spectral irradiance is previously known at least from other information sources. For example, the spectral irradiance may also be calculated or
5 determined from other measurement data and/or simulations.

In this case, it is generally necessary to measure the emission properties of the illumination source used in the measuring device at least once with the aid of a spectrometer or spectroradiometer, i.e. either simultaneously together with the measurement of the respective currents $I_{\text{meas},n}$ or at another point in time, i.e. an earlier
10 point in time or a later point in time.

For example, the spectrometer or spectroradiometer may be provided externally or may only be installed temporarily in the measuring device. In this case, with the aid of the spectrometer or spectroradiometer, the spectral irradiance $E_{\lambda,n}(\lambda)$ for each of the spectral distributions to be emitted within the measuring device may be measured and stored
15 once in advance or at certain time intervals, so that then, at a point in time at which the spectral distributions are actually emitted in the measuring device, the spectral irradiance $E_{\lambda,n}(\lambda)$ thereof no longer needs to be measured currently, but rather the stored values may be called up. Possibly, the emission spectra of individual light sources such as, for example, individual LEDs which, in a plurality, jointly form the illumination source
20 of the measuring device, may be measured in advance with the aid of the spectrometer or spectroradiometer. In this case, the emission spectra of each individual light source should be measured with different activations, i.e. with different emission intensities. From the measurement data determined in this way, possibly later in the operation of the measuring device, the light emitted overall by the illumination source with its
25 spectral distribution and its spectral irradiance may then be determined, i.e. calculated, for example.

In such an approach, it is assumed that the illumination source of the measuring device may reproduce the different spectral distributions very precisely and stable over time, for

example by targeted activation of the individual light sources thereof. Should such a precise reproduction of different spectral distributions not be possible or not ensured, a spectrometer or spectroradiometer should preferably be provided directly in the measuring device and each activated spectral distribution should be measured currently
5 with the aid of this spectrometer or spectroradiometer with regard to its spectral irradiance.

According to a further specified embodiment, the spectrometer or spectroradiometer is configured and arranged in such a way that it receives light from a position adjacent to and/or in a plane with the photovoltaic unit to be contacted in the contacting device.

10 In other words, the spectrometer or spectroradiometer may be arranged in the measuring device or be optically coupled to the measuring device in such a way that, just like the photovoltaic unit to be measured, it is irradiated with light emitted by the illumination source and in this case the light reaching the photovoltaic unit differs qualitatively and/or quantitatively only insignificantly from the light reaching the
15 spectrometer or spectroradiometer. The spectrometer or spectroradiometer should preferably be arranged in such a way that the spectral irradiance of the light reaching the photovoltaic unit differs overall and/or at each wavelength within the effective spectral range of the spectrometer or spectroradiometer by less than 10%, less than 5%, less than 2%, less than one percent, less than 0.5% or even less than 0.1% from the light
20 reaching the spectroradiometer.

The spectrometer or spectroradiometer may be arranged, for example, at a distance of less than 20 cm, less than 10 cm, less than 5 cm or even less than 2 cm from an edge of the contacting device or an edge of the photovoltaic unit to be fixed in the contacting device. In this case, a detection area of the spectrometer or spectroradiometer may
25 extend in or parallel to a surface of the photovoltaic unit to be held in the contacting device or at an angle of less than 30°, less than 20°, less than 10°, less than 5° or even less than 2° thereto.

Alternatively, although the spectrometer or spectroradiometer may be arranged remotely from the photovoltaic unit to be fixed in the contacting device, it may be optically coupled into a beam path reaching the photovoltaic unit at a position close to the photovoltaic unit fixed in this way. For example, a beam splitter such as, for example,
5 a glass plate may be arranged in the beam path, which beam splitter couples out a portion of the light directed onto the photovoltaic element and directs it onto the spectrometer or spectroradiometer.

According to one embodiment, the illumination source has a plurality M of light sources which may be driven independently of one another by the controller to emit different
10 emission spectra and/or different emission intensities each differing for different ones of the light sources.

In other words, the illumination source may be provided not as an individual light source but rather composed of a plurality of light sources, wherein each of the light sources or groups of a plurality of light sources may be controlled independently of one another by
15 the controller and, on account of such a controlling, then emit light with different emission spectra and/or different emission intensities. The light emitted thereupon overall by the illumination source therefore results, with regard to its intensity and spectral distribution, from a superposition of the light portions emitted by the individual light sources. In particular, the spectral distribution of this light emitted overall may
20 therefore be varied in a simple manner by the individual light sources being varied with regard to their emitted light intensity, that is to say in particular with regard to their power. In other words, the spectral distribution of the light emitted by the illumination source may be varied in a technically simple manner by the individual light sources being supplied with different powers in a manner controlled by the controller.

25 In particular, according to one embodiment, the illumination source may have a plurality M of light sources which may be driven independently of one another by the controller in the form of LEDs with different emission spectra.

LEDs typically have a low energy requirement in comparison with thermal light sources. Accordingly, in particular in the case of high irradiation times, as are regularly required for the operation of a solar simulator, energy may be saved significantly by the use of LEDs. In addition, LEDs with greatly different emission spectra are available in the
5 meantime. For example, LEDs exist which emit in the near UV spectral range, in various subranges of the visible spectral range and/or in the infrared spectral range. A spectral range which is sufficient for illumination within the scope of a measurement of the responsivity in most cases may therefore be covered by the use of various LEDs in the illumination source. Such a spectral range extends, for example, from at least 400 nm,
10 from at least 350 nm, preferably from at least 280 nm, from at least 250 nm or from at least 200 nm and/or up to at least 1100 nm, up to at least 1150 nm, up to at least 1180 nm, up to at least 1300 nm, up to at least 1500 nm or even preferably up to 2500 nm.

In this case, it is considered to be advantageous to select the light sources and their emission spectra in such a way that at least one of the light sources emits light with
15 significant intensity within the entire spectral range. In this case, the LEDs may differ with regard to semiconductor materials used in them since, in particular, for example, a band gap of such semiconductor materials decisively influences an emission spectrum emitted by an LED. The LEDs may also be equipped with optical filters in order to influence the emission spectrum. The emission spectra of different LEDs may differ from one another
20 with regard to a central emission wavelength and/or with regard to a wavelength-dependent distribution of the emission intensity.

According to one embodiment, the multiplicity N of different spectral distributions is greater than the plurality M of light sources.

In other words, it is considered to be advantageous to select the multiplicity of
25 illuminations of the photovoltaic unit with different spectral distributions to be greater than the plurality of individually controllable light sources provided in the illumination source. In other words, although it is generally considered to be advantageous to determine the spectral responsivity by measuring PV currents in the case of illumination

with a multiplicity N of different spectral distributions which is as large as possible, for example $N > 10$, $N > 20$, $N > 50$ or $N > 100$. For this purpose, however, it is not necessarily also necessary for the number of light sources to be provided in the illumination source to be very high. Theoretically, an arbitrary number of different spectral distributions may already be generated with two light sources with different emission spectra by varying their respective emission intensities. For use in the measuring device presented, an illumination source with a plurality M of light sources with different emission spectra with $M > 2$, $M > 5$, $M > 10$ or $M > 20$ and/or $M < 100$, $M < 50$, $M < 20$ or $M < 10$ appears advantageous. In this case, there may be in each case groups of a plurality of light sources with the same emission spectrum.

According to one embodiment, the controller and the illumination source are configured to control the illumination source in the second operating mode to successively emit light in such a way that each of the multiplicity of different spectral distributions has an emission power which is different from zero at each wavelength within an emission band of at least 400 nm to 1100 nm.

In other words, the light emitted by the illumination source should have a significant emission power for each of the successively emitted spectral distributions in each case within an entire emission band at each wavelength. The formulation "an emission power which is different from zero" may be understood here to mean that a minimum emission power is emitted at each wavelength, which minimum emission power enables a sufficiently precise measurement of the PV current generated in this case. In other words, the spectral distribution should not have any gaps within the emission band in which no light intensity or a light intensity which is insufficient to evaluate a PV current brought about thereby is emitted within partial wavelength intervals. It is assumed that a presence of such gaps in one or more spectral distributions is disadvantageous in the determination of the spectral responsivity, that is to say may lead, for example, to an inaccurate determination of the responsivity in the wavelength range corresponding to the gap. Accordingly, it may be advantageous to select the light sources used in the

illumination source in such a way that their emission spectra extend in a distributed manner over the entire spectral range to be detected and/or at least partially overlap and therefore no gaps result.

According to one embodiment, the controller and the evaluation device are configured to control the illumination source in the second operating mode to successively emit light with at least ten different spectral distributions and to measure the current $I_{\text{meas},n}$ flowing through the photovoltaic unit in this case for each of the spectral distributions.

By selecting the multiplicity N of different spectral distributions with which the photovoltaic unit is successively irradiated by the illumination source to be sufficiently large, that is to say with $N \geq 10$, $N \geq 50$ or even $N \geq 100$, an accuracy with which the spectral responsivity may ultimately be determined may be increased. In this case, it is assumed to be advantageous if at least some of the different spectral distributions differ from one another in such a way that ultimately two or more spectral distributions which differ from one another in this wavelength range exist for each wavelength range within the entire spectral range to be detected.

According to one embodiment, the evaluation device is configured to create and solve a system of equations for determining the spectral responsivity $SR(\lambda)$ of the photovoltaic unit, wherein

- an entire wavelength range within which the spectral responsivity $SR(\lambda)$ is to be determined is divided into a plurality of K wavelength intervals $[\lambda_k, \lambda_{k+1}]$ with $(k=1 \dots K)$,
- for each of the N different spectral distributions and each of the K wavelength intervals, an irradiance $P_{k,n}$ related to the respective wavelength interval is determined by integrating the spectral irradiance $E_{\lambda,n}(\lambda)$ over the respective wavelength interval $[\lambda_k, \lambda_{k+1}]$, and

- a proportional spectral responsivity SR_k related to each of the K wavelength intervals is determined approximately by solving the following system of equations:

$$\begin{pmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,K} \\ P_{2,1} & P_{2,2} & \cdots & P_{2,K} \\ \vdots & \vdots & \ddots & \vdots \\ P_{N,1} & P_{N,2} & \cdots & P_{N,K} \end{pmatrix} \begin{pmatrix} SR_1 \\ SR_2 \\ \vdots \\ SR_K \end{pmatrix} \approx \begin{pmatrix} I_{\text{meas},1} \\ I_{\text{meas},2} \\ \vdots \\ I_{\text{meas},N} \end{pmatrix}$$

Details of a possible configuration of such an approximate and analytical calculation are explained further below with reference to an exemplary embodiment.

- 5 According to a further more specific embodiment, the proportional spectral responsivity SR_k for each of the K wavelength intervals is assumed to be constant within the wavelength interval.

As explained in more detail further below with reference to the exemplary embodiment, the assumption that the proportional spectral responsivity may be considered to be
 10 approximately constant within each of a plurality of wavelength intervals may enable or simplify an analytical and/or numerical calculation of the entire spectral responsivity.

According to one embodiment, the spectral responsivity $SR(\lambda)$ is determined taking into account a relative spectral irradiance $E_{\lambda,n}(\lambda)$ previously known for each of the N spectral distributions or taking into account an absolute spectral irradiance $E_{\lambda,n}(\lambda)$ previously
 15 known for each of the N spectral distributions.

For some applications, it may suffice to determine only a relative spectral responsivity. For example, such a relative spectral responsivity may be sufficient for a determination of a factor of the spectral mismatch, but not for a determination of a short-circuit current. For determining the relative spectral responsivity, it may generally suffice to know the
 20 relative spectral irradiance thereof for each of the N spectral distributions. A measurement of such relative spectral irradiances may be simpler than a measurement of corresponding absolute values. If, however, absolute spectral irradiances may be measured for all spectral distributions, for example by means of a sufficiently precise spectroradiometer, these values may be used to determine the absolute spectral
 25 responsivity.

According to one embodiment, the controller is configured to control the illumination source in the second operating mode to emit light with an intensity of between 60% and 140%, preferably between 80% and 120%, of the standardized solar spectrum or with an intensity of less than 30% of the standardized solar spectrum.

5 In other words, the controller of the measuring device in a first variant of the second operating mode may be configured to make the illumination source to emit light, as is essentially also used during operation within the first operating mode for implementing the solar simulator functionality. In this case, the light may be directed onto the photovoltaic unit with an intensity equal to that of the standardized solar spectrum, i.e.,
10 for example, in the case of a standardized AM1.5G spectrum with 1000 W/m^2 , wherein a tolerance range with respect to the emitted light intensity should be at most 20%, at most 10% or at most 5%. The different spectral distributions successively activated in this case in the second operating mode may resemble the spectral distribution of the standardized solar spectrum at least within a tolerance range. For example, the spectral
15 distributions of the light successively varying by the illumination device during the second operating mode may differ from the standardized solar spectrum by less than 30%, preferably less than 20% or less than 10%, for each wavelength or each wavelength subrange within the entire spectral range. Accordingly, the spectral responsivity may then be determined under illumination conditions which correspond to the conditions
20 prevailing in real use.

In an alternative second variant of the second operating mode, the illumination source may be controlled by the controller to emit light with an intensity which is greatly reduced in comparison with the standardized solar spectrum. For example, the emitted light intensity may make up less than 30%, less than 20%, less than 10% or even less
25 than 5% of that of the standardized solar spectrum. On account of the reduced irradiated-in light intensity, excessive heating of the photovoltaic unit during the measurement of the responsivity may be avoided, for example. As a result, in particular effects such as falsification of the measurements on account of changing temperatures

of the photovoltaic unit may be prevented or at least reduced. In this case, a relative spectral distribution of the light emitted during the second operating mode may be the same as in the case of the standardized solar spectrum within a tolerance range of, for example, less than 20%, less than 10% or less than 5%. That is to say, the spectral
5 distributions emitted during the second operating mode may be considered to be a scaled-down solar spectrum within the tolerance range.

Embodiments of the method according to the second aspect of the invention may be configured to the effect that a measuring device in the form of a solar simulator may be
10 operated in a second operating mode in addition to its original function in a first operating mode for determining a voltage-dependent current behavior of a photovoltaic unit during illumination with a standardized solar spectrum. In the second operating mode, in this case, the spectral responsivity of the photovoltaic unit may be determined with the components of the solar simulator with the aid of a skillfully adapted process
15 management and suitably configured signal and data processing regulations without a separate measuring station having to be provided for this purpose. In this case, the method is designed to realize the properties, described here above and below, of embodiments of the measuring device for implementing the second operating mode. Accordingly, the features, described here above and below, of embodiments of the
20 measuring device may be transferred analogously to the method.

The method may be implemented in particular with the aid of a programmable measuring device. In this case, in particular, the controller and/or the evaluation device of the measuring device may be programmable. In this case, the measuring device may have one or more processors and one or more data memories. A computer program
25 product according to the third aspect of the invention may be stored in the data memory. In this case, the machine-readable instructions of the computer program product may be formulated in any arbitrary computer language and instruct the processor to carry out or to control embodiments of the method described here. The

computer program product may, as software, enable a hardware of a measuring device such as, for example, a solar simulator to also implement a functionality of determining the spectral responsivity in addition to its original functionality of measuring IV curves under standard solar illumination.

- 5 The computer program product may be stored in an arbitrary computer-readable medium according to the fourth aspect of the invention. The computer-readable medium may store data which reproduce the computer program product in any arbitrary physical manner, for example magnetically, optically, electrostatically, etc. For example, the computer-readable medium may be a portable data memory such as, for example, a
- 10 CD, DVD, flash memory, RAM memory, ROM memory, PROM memory, EPROM memory, etc. Alternatively, the computer-readable medium may be a data memory which is accommodated in a separate computer, server or a data cloud (cloud) and from which the computer program product may be downloaded, for example, via a network, in particular the Internet.
- 15 It is pointed out that possible advantages and configurations of embodiments of the invention are described here in part with reference to a measuring device according to the invention and in part with reference to a method according to the invention. A person skilled in the art recognizes that the described features may be transferred, adapted, exchanged or modified in a suitable manner in order to arrive at further
- 20 embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention are described below with reference to the appended drawings, wherein neither the drawings nor the description are to be interpreted as

25 limiting the invention.

FIG. 1 shows a measuring device according to an embodiment of the present invention.

FIG. 2 shows an exemplary spectral distribution.

FIG. 3 shows an exemplary responsivity.

The figures are merely schematic and not true to scale. Identical reference signs denote identical or identically acting features.

5

DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 1 shows an embodiment of a measuring device 1 according to the invention. The measuring device 1 is configured to be able to determine both a spectral responsivity $SR(\lambda)$ and a voltage-dependent current behavior $I(U)$ for a photovoltaic unit 3 upon
10 irradiation with a standardized solar spectrum.

For this purpose, the measuring device 1 comprises an illumination source 5. In the example illustrated, the illumination source 5 has a plurality of light sources 21 in the form of LEDs 23. In this case, at least some of the LEDs 23 differ with regard to their emission spectrum 25 (see FIG. 2). The illumination source 5 is therefore able to
15 selectively emit light 13 with variable spectral distributions 15. In addition, the illumination source 5 is designed to emit light 13, as in the case of a conventional solar simulator, with an intensity and a spectral distribution which correspond to a standardized solar spectrum.

The measuring device 1 further has a contacting device 7 with the aid of which the
20 photovoltaic unit 3 may be electrically contacted. For this purpose, the contacting device 7 has, for example, two or more reversibly attachable contacts 31 with which contact structures such as, for example, busbars or fingers on the photovoltaic unit 3 may be contacted.

Furthermore, the measuring device 1 comprises a controller 9 and an evaluation device
25 11.

The controller 9 is connected to the illumination source 5 and is designed to individually control the illumination source 5 and in particular the different light sources 21 thereof in such a way that light 13 is either emitted approximately with the standardized solar spectrum in a first operating mode or light 13 is successively emitted with a multiplicity of different spectral distributions 15 in a second operating mode.

In this case, FIG. 2 illustrates an exemplary spectral distribution 15 which results from a superposition of a plurality of different emission spectra 25 of the different light sources 21 of the illumination source 5. In this case, a spectral range of the entire spectral distribution 15 extends, by way of example, from approximately 340 nm to approximately 1180 nm, wherein the achievable spectral range depends in particular on the available light sources 21 and their emission spectra.

The evaluation device 11 is connected to the contacting device 7 and may tap and measure the PV current I_{meas} flowing or generated in the photovoltaic unit 3 via said contacting device. For this purpose, the evaluation device 11 has, inter alia, a processor 29. In the first operating mode, the evaluation device 11 may in this case determine, with the aid of the measured current, the voltage-dependent current behavior $I(U)$ of the photovoltaic unit 3 under the action of the standardized solar spectrum. In the second operating mode, the evaluation device 11 may, as an alternative to this, measure the different PV currents $I_{\text{meas},n}$ as are generated in the photovoltaic unit 3 upon illumination of the photovoltaic unit 3 with each of the N different spectral distributions 15.

In this case, a spectral irradiance $E_{\lambda,n}(\lambda)$ may be previously known for each of the spectral distributions 15, for example by measuring it with the aid of a spectrometer preferably in the form of a calibrated spectroradiometer 19. For this purpose, the spectroradiometer 19 may preferably be arranged adjacent to the position at which the photovoltaic unit 3 is held on the contacting device 7 and/or in an identical plane with the latter, with the result that the spectroradiometer 19 receives essentially the same light 13 as the photovoltaic unit 3. Alternatively, the spectroradiometer 19 may be arranged at a remote position and light directed onto the photovoltaic unit 3 may be coupled out

proportionally, for example by means of a beam splitter (not illustrated), and directed onto the spectroradiometer 19.

Details of a possible configuration of the measuring device described herein and of the method, which may be carried out therewith, of the multispectral determination of the spectral responsivity are described below with reference to an exemplary embodiment.

At least three components are required for the application of the multispectral determination method of the spectral responsivity $SR(\lambda)$ of a test object (solar cell or solar module):

- a spectrally adjustable light source of an illumination source. This may be realized, for example, by LEDs with various colors. Lasers, lamps with a broadband spectrum in combination with filters, mirrors and similar optical components or light sources whose spectral distribution may be changed are also conceivable.

- a spectrometer or spectroradiometer for measuring the spectral irradiance in the plane of the test object. Alternatively to the spectrometer or spectroradiometer, the spectral irradiance in the plane of the test object may also be calculated/determined from other measurement data or simulations.

- a current measurement means of the test object to be examined. This usually consists of a contacting unit and a current sink.

To carry out the method, the spectrally adjustable light source is configured such that N different spectra are generated. For each configuration of the light source,

(a) the spectrum $E_{\lambda,n}(\lambda)$ is determined and

(b) the current response $I_{\text{meas},n}$ of the test object (for example the short-circuit current I_{SC} or the current I_{MPP} at the point of maximum power) is measured.

In this case, $n=1 \dots N$. The spectrum $E_{\lambda,n}(\lambda)$ and the current response $I_{\text{meas},n}$ may be recorded both simultaneously and sequentially. It is also possible first to measure (or to determine/calculate) all the spectra and at a different point in time to measure the

current contribution of the test object, provided that the spectral irradiance in the plane of the test object is sufficiently stable over time.

The relationship between the current response of the test object, spectral irradiance and SR of the test object is determined via the formula

$$I_{\text{meas},n} = \int d\lambda E_{\lambda,n}(\lambda) SR(\lambda)$$

which applies to each of the N spectra and current responses ($n=1 \dots M$).

To solve this equation, the integral is represented by a sum,

$$I_{\text{meas},n} = \int_{\lambda_1}^{\lambda_2} d\lambda E_{\lambda,n}(\lambda) SR(\lambda) + \int_{\lambda_2}^{\lambda_3} d\lambda E_{\lambda,n}(\lambda) SR(\lambda) + \dots + \int_{\lambda_{K-1}}^{\lambda_K} d\lambda E_{\lambda,n}(\lambda) SR(\lambda).$$

This equation may be simplified by assuming a spectral responsivity which is constant in the respective interval $[\lambda_k, \lambda_{k+1}]$.

$$I_{\text{meas},n} \approx SR_1 P_{1,n} + SR_2 P_{2,n} + \dots + SR_K P_{K,n}$$

In this case, $P_{1,n}, P_{2,n}, \dots, P_{K,n}$ correspond to the irradiances in each wavelength interval k ,

$$P_{k,n} = \int_{\lambda_k}^{\lambda_{k+1}} d\lambda E_{\lambda,n}(\lambda),$$

with $k = 1 \dots K$. This results in a system of equations with N equations and K unknowns

SR_1 to SR_K . This system of equations may be represented by

$$\begin{pmatrix} P_{1,1} & P_{1,2} & \dots & P_{1,K} \\ P_{2,1} & P_{2,2} & \dots & P_{2,K} \\ \vdots & \vdots & \ddots & \vdots \\ P_{N,1} & P_{N,2} & \dots & P_{N,K} \end{pmatrix} \begin{pmatrix} SR_1 \\ SR_2 \\ \vdots \\ SR_K \end{pmatrix} \approx \begin{pmatrix} I_{\text{meas},1} \\ I_{\text{meas},2} \\ \vdots \\ I_{\text{meas},N} \end{pmatrix}$$

This system of equations may be solved by known numerical and/or analytical methods (regression methods, inverse matrices,...). As a result, the values SR_1 to SR_k follow. A wavelength value within the interval $[\lambda_k, \lambda_{k+1}]$, typically the mean value, is assigned to each of these values. For example, the wavelength $(\lambda_1 + \lambda_2)/2$ is assigned to the value SR_1 .

5 As a result, the SR curve of the test object follows.

As described above, there are various applications for the evaluation and use of the SR curves, inter alia the determination of the factor MM of the spectral mismatch. As an alternative to the application of the MM factor (and thus the use of a reference solar cell), the short-circuit current I_{sc} may be determined directly from the SR curve by

10
$$I_{sc} = \int d\lambda E_{\lambda,ref}(\lambda) SR(\lambda)$$

In this case, $E_{\lambda,ref}(\lambda)$ is the tabulated target reference solar spectrum, for example the AM1.5G spectrum.

15 It is pointed out that, in principle, knowledge of the relative spectral irradiance $E_{\lambda,rel}(\lambda)$ is sufficient for the application of the multispectral determination method for determining a relative spectral responsivity (sufficient for the determination of the factor of the spectral mismatch, but not for the determination of a short-circuit current). This relative spectral irradiance is related to the absolute spectral irradiance $E_{\lambda}(\lambda)$ via a constant scaling factor C ,

20
$$E_{\lambda}(\lambda) = C \cdot E_{\lambda,rel}(\lambda).$$

If only the relative spectral irradiance is known, the application of the method delivers the relative spectral responsivity $SR_{rel}(\lambda)$ of the test object. This in turn is related to the
25 absolute spectral responsivity $SR(\lambda)$ and the constant scaling factor C via

$$SR(\lambda) = C \cdot SR_{rel}(\lambda)$$

With knowledge of the absolute spectral irradiance $E_\lambda(\lambda)$, the absolute spectral responsivity $SR(\lambda)$ results directly and, via the abovementioned equation, the short-circuit current I_{sc} under standard test conditions.

- 5 Exemplary experiments for implementing the approach described herein are explained below.

A first experiment of the methodology was carried out on an IVmj measurement system with an LED lamp system (Wavelabs SinusGUI 360 Plus). This lamp system consists of 27 LEDs of various wavelengths, which may each be controlled separately. A WPVS
10 reference solar cell (active cell area 4 cm²) served as test object.

The spectrometer and the solar cell were irradiated by the lamp system with $N=108$ different spectra. These 108 spectra are based on channel settings for an approximation of an AM1.5G spectrum with classification A++ . For each spectrum, a channel modulation of two channels (channel spacing 10, that is to say, for example, channel 1
15 and 11) is multiplied by a factor 0, 1 or 2 (combinations chosen here: 0–0, 0–1, 2–0 and 2–1). First, the 108 spectra were measured with a spectroradiometer and, in the second step, 108 short-circuit currents were measured.

For the analysis of the measurement data, the wavelength range from 340 nm to 1180 nm is divided into $K=27$ equidistant subintervals (interval width of 31.1 nm) and the
20 irradiances $P_{k,n}$ for each wavelength interval k are calculated. This results in a matrix M of dimension 108×27 (108 rows, 27 columns). Together with the measured currents $I_{meas,n}$ (vector with 108 entries), a system of equations of 108 equations and 27 unknowns results.

This system of equations is solved by a “least square” regression method. The result of
25 the regression method results in an SR curve similar to that shown in FIG. 3.

It should be emphasized that the resulting SR curve of the multispectral determination method does not necessarily require scaling since the absolute spectral irradiance $E_{\lambda}(\lambda)$ was determined directly with the spectroradiometer. The calibration methods for spectroradiometers required for this are available at various calibration institutions, inter alia at the ISFH CalTeC operated by the applicant of the present patent application. In contrast to the method described here, the SR standard method in the case of classic DSR/SR measurement stations generally regularly requires additional subsequent scaling of the data, in particular for large solar cells.

It should be pointed out that terms such as "having", "comprising", etc. do not exclude any other elements or steps and terms such as "a" or "an" do not exclude a multiplicity. It should further be pointed out that features or steps which have been described with reference to one of the above exemplary embodiments may also be used in combination with other features or steps of other exemplary embodiments described above.

Reference signs in the claims should not be considered to be a restriction.

LIST OF REFERENCE SIGNS

	1	Measuring device
	3	Photovoltaic unit
5	5	Illumination source
	7	Contacting device
	9	Controller
	11	Evaluation device
	13	Light
10	15	Spectral distribution
	17	Spectral responsivity
	19	Spectroradiometer
	21	Light sources
	23	LED
15	25	Emission spectrum
	27	Wavelength interval
	29	Processor
	31	Reversibly attachable contact

Claims:

- 5 1. Measuring device (1) for determining a spectral responsivity $SR(\lambda)$ (17) and a voltage-dependent current behavior $I(U)$ under standard solar conditions of a photovoltaic unit (3),
wherein the measuring device (1) has:
an illumination source (5),
a contacting device (7),
10 a controller (9), and
an evaluation device (11),
wherein the illumination source (5) is configured to selectively emit light (13) with variable spectral distributions (15) or with an intensity and spectral distribution which correspond to a standardized solar spectrum,
15 wherein the contacting device (7) is configured to electrically contact the photovoltaic unit (3),
wherein the controller (9) and the evaluation device (11) are selectively operable in a first or a second operating mode,
wherein the controller (9) is configured
20 - in the first operating mode to control the illumination source (5) to emit light (13) with an intensity and spectral distribution corresponding to the standardized solar spectrum, and
- in the second operating mode to control the illumination source (5) to successively emit light (13) with a multiplicity N of different spectral
25 distributions (15),
and
wherein the evaluation device (11) is configured to apply an electric voltage U to the photovoltaic unit (3) via the contacting device (7) and to measure, as a

function of the applied voltage, a current I_{meas} flowing through the photovoltaic unit and in this case

- in the first operating mode to determine, from the measured current I_{meas} , the voltage-dependent current behavior $I(U)$ of the photovoltaic unit (3)

under the action of the standardized solar spectrum, and

- in the second operating mode to determine, from a plurality of currents $I_{\text{meas},n}$ ($n=1\dots N$) respectively measured upon illumination with the N different spectral distributions (15) and taking into account a spectral irradiance $E_{\lambda,n}(\lambda)$ ($n=1\dots N$) previously known for each of the N spectral distributions (15), the spectral responsivity $SR(\lambda)$ (17) of the photovoltaic unit (3).

2. Measuring device according to Claim 1,

wherein the spectral irradiance $E_{\lambda,n}(\lambda)$ is previously known for each of the spectral distributions (15) by measurement by means of a spectrometer, preferably a spectroradiometer (19).

3. Measuring device according to Claim 2,

wherein the measuring device further comprises an integrated spectrometer or spectroradiometer (19) in order to be able to measure the spectral irradiance $E_{\lambda,n}(\lambda)$ currently for each of the spectral distributions emitted within the measuring device.

4. Measuring device according to Claim 3,

wherein the spectrometer or spectroradiometer (19) is configured and arranged in such a way that it receives light from a position adjacent to and/or in a plane with the photovoltaic unit (3) to be contacted in the contacting device (7).

5. Measuring device according to one of the preceding claims,

wherein the illumination source (5) has a plurality M of light sources (21) which

may be driven independently of one another by the controller (9) to emit different emission spectra (25) and/or different emission intensities which are different for different ones of the light sources (21).

- 5 6. Measuring device according to one of the preceding claims,
 wherein the illumination source (5) has a plurality M of light sources (21) which
 may be driven independently of one another by the controller (9) in the form of
 LEDs (23) with different emission spectra (25).
- 10 7. Measuring device according to one of Claims 5 and 6,
 wherein the multiplicity N of different spectral distributions (15) is greater than
 the plurality M of light sources (21).
- 15 8. Measuring device according to one of the preceding claims,
 wherein the controller (9) and the illumination source (5) are configured to control
 the illumination source (5) in the second operating mode to successively emit
 light (13) in such a way that each of the multiplicity of different spectral
 distributions (15) has an emission power which is different from zero at each
 wavelength within an emission band of at least 400 nm to 1100 nm.
- 20 9. Measuring device according to one of the preceding claims,
 wherein the controller (9) and the evaluation device (11) are configured to control
 the illumination source (5) in the second operating mode to successively emit
 light (13) with at least ten different spectral distributions (15) and to measure the
25 current $I_{\text{meas},n}$ flowing through the photovoltaic unit (3) in this case for each of the
 spectral distributions (15).
10. Measuring device according to one of the preceding claims,
 wherein the evaluation device (11) is configured to create and solve a system of

equations for determining the spectral responsivity $SR(\lambda)$ (17) of the photovoltaic unit (3), wherein

- an entire wavelength range within which the spectral responsivity $SR(\lambda)$ (17) is to be determined is divided into a plurality of K wavelength intervals (27) $[\lambda_k, \lambda_{k+1}]$

5 with $(k=1...K)$,

- for each of the N different spectral distributions (15) and each of the K wavelength intervals (27), an irradiance $P_{k,n}$ related to the respective wavelength interval (27) is determined by integrating the spectral irradiance $E_{\lambda,n}(\lambda)$ over the respective wavelength interval (27), and

10 - a proportional spectral responsivity SR_k related to each of the K wavelength intervals (27) is determined approximately by solving the following system of equations:

15

$$\begin{pmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,K} \\ P_{2,1} & P_{2,2} & \cdots & P_{2,K} \\ \vdots & \vdots & \ddots & \vdots \\ P_{N,1} & P_{N,2} & \cdots & P_{N,K} \end{pmatrix} \begin{pmatrix} SR_1 \\ SR_2 \\ \vdots \\ SR_K \end{pmatrix} \approx \begin{pmatrix} I_{\text{meas},1} \\ I_{\text{meas},2} \\ \vdots \\ I_{\text{meas},N} \end{pmatrix}$$

11. Measuring device according to Claim 10,

wherein the proportional spectral responsivity SR_k for each of the K wavelength intervals (27) is assumed to be constant within the wavelength interval (27).

20 12. Measuring device according to one of the preceding claims,

wherein the spectral responsivity $SR(\lambda)$ (17) is determined taking into account a relative spectral irradiance $E_{\lambda,n}(\lambda)$ previously known for each of the N spectral distributions (15) or taking into account an absolute spectral irradiance $E_{\lambda,n}(\lambda)$ previously known for each of the N spectral distributions.

25

13. Measuring device according to one of the preceding claims,

wherein the controller (9) is configured to control the illumination source (5) in the second operating mode to emit light (13) with an intensity of between 60%

and 140%, preferably between 80% and 120%, of the standardized solar spectrum or with an intensity of less than 30% of the standardized solar spectrum.

14. Method for determining a spectral responsivity $SR(\lambda)$ (17) of a photovoltaic unit

5 (3) by means of a measuring device (1) for determining a voltage-dependent current behavior $I(U)$ of the photovoltaic unit (3) under standard solar conditions, wherein the measuring device has:

an illumination source (5),

a contacting device (7),

10 a controller (9), and

an evaluation device (11),

wherein the illumination source (5) is configured to selectively emit light (13) with variable spectral distributions (15) or with an intensity and spectral distribution which correspond to a standardized solar spectrum,

15 wherein the contacting device (7) is configured to electrically contact the photovoltaic unit (3),

wherein the controller (9) is configured to control the illumination source (5) in the first operating mode to emit light (13) with an intensity and spectral distribution corresponding to the standardized solar spectrum,

20 wherein the evaluation device (11) is configured to apply an electric voltage U to the photovoltaic unit (3) via the contacting device (7) and to measure, as a function of the applied voltage U , a current I_{meas} flowing through the photovoltaic unit (3) and in this case in the first operating mode to determine, from the measured current I_{meas} , the voltage-dependent current behavior $I(U)$ of the photovoltaic unit (3) under the action of the standardized solar spectrum,

25 wherein the method comprises:

- controlling the illumination source (5) by means of the controller (9) in a second operating mode to successively emit light (13) with a multiplicity N of different spectral distributions (15),

- measuring, by means of the evaluation device (11), in the second operating mode, currents $I_{\text{meas},n}$ ($n=1...N$) respectively flowing through the photovoltaic unit (3) upon illumination with the N different spectral distributions (15), and
- determining the spectral responsivity $SR(\lambda)$ (17) of the photovoltaic unit (3) taking into account a spectral irradiance $E_{\lambda,n}(\lambda)$ ($n=1...N$) previously known for each of the spectral distributions (15).

15. Method according to Claim 14,

wherein the spectral irradiance $E_{\lambda,n}(\lambda)$ is previously known for each of the spectral distributions (15) by measurement by means of a spectrometer or a spectroradiometer (19).

16. Computer program product having machine-readable instructions which, when executed by a processor (29) of a measuring device (1) for determining a current behavior under standard solar conditions of a photovoltaic unit (3), instruct the measuring device (1) to carry out or to control the method according to Claim 14.

17. Computer-readable medium having machine-readable instructions of a computer program product according to Claim 16 stored thereon.