

A SYSTEM, COMPUTING DEVICE AND METHOD FOR ESTIMATING SOLAR IRRADIANCE FALLING ON A PHOTOVOLTAIC STRING

TECHNICAL FIELD

[0001] This invention relates to a system, computing device and method for estimating solar irradiance falling on a photovoltaic string. More particularly, this invention relates to a system, computing device and method for estimating solar irradiance falling on a photovoltaic string using a single irradiance sensor that may be disposed at a different tilt and/or azimuth angle as the photovoltaic string.

BACKGROUND

[0002] The following discussion of the background to the invention is intended to facilitate an understanding of the present invention only. It should be appreciated that the discussion is not an acknowledgement or admission that any of the material referred to was published, known or part of the common general knowledge of the person skilled in the art in any jurisdiction as at the priority date of the invention.

[0003] The efficiency of solar farms is typically measured as a performance ratio (PR). In an ideal situation, the PR is one when all the solar energy falling on and received by photovoltaic (PV) modules, also known as PV panels, of a solar farm is converted to electricity. However, in practice actual PR is lower than the ideal case due to various losses, such as thermal loss, soiling loss, shading loss, inverter loss, etc. If a software PV model of a solar farm can be built, and all the losses can be accurately identified and determined, then corrective actions may be taken to minimize the losses so as to improve the efficiency or PR of the solar farm.

[0004] However, current solar farm instrumentation solutions including a software PV model typically has hardware requirements that cannot be easily met. Firstly, in most solar farms, irradiance intensity on solar PV panels is typically measured using only a single irradiance sensor, e.g. a pyranometer, and that data is used as an approximation of the entire farm's irradiance value. The single pyranometer is normally placed at a 0-degree tilt angle and therefore cannot accurately measure irradiance exposure of all panels that are likely to have different tilt and azimuth angles. This leads to errors in performance and loss analysis of solar farms when using the single pyranometer's output directly. It also prevents string-level analysis

due to difference between the pyranometer's output and the actual irradiance exposure of each string, which may have different surface tilt and azimuth angles. String-level analysis is vital to achieve high accuracy of soiling loss and shading loss measurement since each string may have different orientation and locations.

[0005] Secondly, existing soiling loss analysis techniques require other data in addition to irradiance data, such as PV panel temperature and weather data (e.g. rainfall and wind). As such, additional data processing capabilities is required which increases operating costs.

[0006] Thirdly, current solar instrumentation solutions are capable of only simulating loss due to shading; they do not provide a solution for true shading loss monitoring. The ability to monitor and quantify shading loss at string level enables operations and maintenance (O&M) teams to tackle shading loss issues and thus to improve performance of existing solar farms and optimize the design of new solar farms.

[0007] Finally, despite the criticality of the pyranometer's role in a solar PV farm, there is no robust and cost-efficient way to assess the quality or health of the pyranometer. Hence, an operator cannot assess the impact due to any anomaly in pyranometer operation on the performance of a solar farm.

[0008] There is therefore a need for a system, computing device and method for estimating solar irradiance falling on a PV string which address, at least in part, one or more of the forgoing problems.

SUMMARY

[0009] According to an aspect of the present disclosure, there is provided a method of estimating solar irradiance falling on a PV string that includes multiple PV panels. The method includes obtaining a first global solar irradiance on the PV string, obtaining a second global solar irradiance on a sensor and receiving actual solar irradiance recorded by the sensor. The method further includes estimating solar irradiance falling on the PV string based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance.

[0010] In some embodiments of the method, the first global solar irradiance and the second global solar irradiance comprise a first clear-sky global solar irradiance and a second clear-sky solar irradiance respectively.

[0011] In some embodiments of the method, estimating solar irradiance falling on the PV string includes estimating solar irradiance falling on the PV string based on a difference between the first global solar irradiance and the second global solar irradiance and a ratio of the actual solar irradiance and the second global solar irradiance.

[0012] In some embodiments of the method, the difference between the first global solar irradiance (*poa_global_string*) and the second global solar irradiance (*poa_global_irr_sensor*) is given by:

$$x = poa_global_string - poa_global_irr_sensor; \text{ and}$$

a ratio of the actual solar irradiance (*irr_sensor_real*) and the second global solar irradiance is given by:

$$y = \frac{irr_sensor_real}{poa_global_irr_sensor}; \text{ and}$$

wherein the estimated solar irradiance (*string_irr_estimated*) is given by:

$$string_irr_estimated = x(ay^3 + by^2 + cy + d)$$

wherein a, b, c, and d are coefficients.

[0013] In some embodiments of the method, the coefficients are derived based on past estimated solar irradiance on the PV string and past output current of the PV string.

[0014] In some embodiments of the method, the coefficients are derived by determining loss based on the past estimated solar irradiance and the past output current, adjusting the coefficients based on the loss to generate another estimated solar irradiance and repeating determining loss and adjusting the coefficients until the loss is at a desired level.

[0015] In some embodiments of the method, the method further includes receiving an output current of the PV string and determining a soiling loss of the PV string based on the estimated solar irradiance and the output current.

[0016] In some embodiments of the method, the method further includes receiving an output current of the PV string and determining a shading loss of the PV string based on the estimated solar irradiance and the output current.

[0017] In some embodiments of the method, the method further includes determining a soiling ratio including the estimated solar irradiance. And determining a shading loss includes determining a shading loss of the PV string based on the soiling ratio.

[0018] In some embodiments of the method, the method further includes determining a shading zone and wherein determining a shading loss includes determining a shading loss in the shading zone.

[0019] In some embodiments of the method, the method further includes determining again another soiling ratio by excluding estimated solar irradiance in the shading zone, determining another shading zone based on the another soiling ratio and repeating determining again another soiling ratio and determining again another shading zone until a stable shading zone is obtained. And determining a shading loss in the shading zone includes determining the shading loss in the stable shading zone.

[0020] In some embodiments of the method, the method further includes obtaining a further global solar irradiance on the PV string, obtaining a further global solar irradiance on the sensor, receiving a further output current of the PV string and estimating an output of the sensor based on the further global solar irradiance, the further global solar irradiance, the further output current, the estimated solar irradiance obtained earlier and the output current received earlier.

[0021] According to another aspect of the present disclosure, there is provided a computing device. The computing device includes a processor that is operable to obtain a first global solar irradiance on a PV string, obtain a second global solar irradiance on a sensor, receive actual solar irradiance recorded by the sensor and estimate solar irradiance falling on the PV string based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance.

[0022] In some embodiments of the computing device, the processor is further operable to receive an output current of the PV string and determine a soiling loss of the PV string based on the estimated solar irradiance and the output current.

[0023] In some embodiments of the computing device, the processor is further operable to receive an output current of the PV string and determine a shading loss of the PV string based on the estimated solar irradiance and the output current.

[0024] In some embodiments of the computing device, the processor is further operable to obtain a further global solar irradiance on the PV string, obtain a further global solar irradiance on the sensor, receive a further output current of the PV string and estimate an output of the sensor based on the further global solar irradiance on the PV string, the further global solar irradiance on the sensor, the further output current, the estimated irradiance obtained earlier and the output current received earlier.

[0025] According to another aspect of the present disclosure, there is provided a system. The system includes a computing device having a processor that is operable to obtain a first global solar irradiance on a PV string, obtain a second global solar irradiance on a sensor, receive actual solar irradiance recorded by the sensor and estimate solar irradiance falling on the PV string based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance.

[0026] In some embodiments of the system, the processor is further operable to receive an output current of the PV string and determine a soiling loss of the PV string based on the estimated solar irradiance and the output current.

[0027] In some embodiments of the system, the processor is further operable to receive an output current of the PV string and determine a shading loss of the PV string based on the estimated solar irradiance and the output current.

[0028] In some embodiments of the system, the processor is further operable to obtain a further global solar irradiance on the PV string, obtain a further global solar irradiance on the sensor, receive a further output current of the PV string and estimate an output of the sensor based on the further global solar irradiance on the PV string, the further global solar irradiance on the sensor, the further output current, the estimated solar irradiance obtained earlier and the output current obtained earlier.

[0029] In some embodiments of the system, the system further includes the PV string, a current sensor coupled between the computing device and the PV string to provide the computing device with the output current of the PV string and the sensor.

[0030] According to another aspect of the present disclosure, there is provided a method of obtaining a model of a PV string for estimating solar irradiance falling on the PV string. The method includes obtaining a first global solar irradiance on the PV string, obtaining a second global solar irradiance on a sensor, receiving actual

solar irradiance recorded by the sensor and estimating solar irradiance falling on the PV string using a PV string model based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance. The method further includes receiving output current of the PV string, determining loss based on the estimated solar irradiance and the output current, refining the PV string model based on the loss to generate another estimated solar irradiance; and repeating determining loss and refining the PV string model until the loss is at a desired level.

[0031] According to another aspect of the present disclosure, there is provided a method of obtaining a model of a sensor for estimating an output of the sensor. The method includes receiving a first output current of a PV string, obtaining an estimated solar irradiance falling on the PV string, obtaining a first global solar irradiance on the PV string, obtaining a first global solar irradiance on a sensor, receiving a second output current of the PV string, and estimating, using a sensor model, an output of the sensor based on the first global solar irradiance, the second global solar irradiance, the second output current, the estimated solar irradiance and the first output current to obtain an estimated output. The method further includes receiving actual solar irradiance recorded by the sensor, determining loss based on the estimated output and the actual solar irradiance, refining the sensor model based on the loss to generate another estimated output, and repeating determining loss and refining the sensor model until the loss is at a desired level.

[0032] Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

BRIEF DESCRIPTION OF DRAWINGS

[0033] The invention will be better understood with reference to the drawings, in which:

Figure 1 is block diagram of a PV system including a computing device, a PV string and an irradiance sensor, according to an embodiment of the invention;

Figure 2 is block diagram of hardware components of the computing device in Figure 1;

Figure 3 is a drawing showing inputs and outputs of methods implemented in the computing device in Figure 1 for estimating solar irradiance falling on the PV string in Figure 1 and for estimating output of the irradiance sensor in Figure 1;

Figure 4 is a graph of theoretical clear-sky global solar irradiance over the irradiance sensor in Figure 1 and theoretical clear-sky global solar irradiance over the PV string in Figure 1 in a day;

Figure 5 is a flow diagram showing a method of obtaining a PV string model that can be used in the method in Figure 3 for estimating solar irradiance falling on the PV string;

Figure 6 is a histogram of error percentage for estimated solar irradiance using the PV string model in Figure 5 and actual solar irradiance as recorded by the irradiance sensor when compared to output current of the PV string;

Figure 7 are graphs of soiling ratio and rainfall against time;

Figure 8 is a graph of estimated solar irradiance and irradiance obtained based on output current of the PV string, for identifying a shading zone where there is reduction in output current of the PV string attributable to shading loss;

Figure 9 is a flow diagram showing a method of obtaining a sensor model that can be used in the method in Figure 3 for estimating output of the irradiance sensor; and

Figure 10 is a table of sum of output recorded by the irradiance sensor and estimated output using the sensor model in Figure 9.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0034] Throughout this document, unless otherwise indicated to the contrary, the terms “comprising”, “consisting of”, “having” and the like, are to be construed as non-exhaustive, or in other words, as meaning “including, but not limited to.”

[0035] Furthermore, throughout the specification, unless the context requires otherwise, the word “include” or variations such as “includes” or “including” will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

[0036] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as is commonly understood by a skilled person to which the subject matter herein belongs.

[0037] As shown in the drawings for purposes of illustration, the invention may be embodied in a novel and fairly accurate method for estimating solar irradiance falling on a PV string using a single irradiance sensor that may be disposed at a different tilt and/or azimuth angle as the PV string. Existing solar irradiance methods require an irradiance sensor to be orientated in a same direction as the PV string to be accurate. Since not all PV strings in a PV system are oriented in the same direction, each PV string will require an irradiance sensor that is oriented in the same direction as the PV string. The method embodying the invention generally includes obtaining a first global solar irradiance on the PV string, obtaining a second global solar irradiance on a sensor, and receiving actual solar irradiance recorded by the irradiance sensor. The method further includes estimating solar irradiance falling on the PV string based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance.

[0038] Specifically, the method is implemented in a PV system 2 shown in Figure 1. The PV system 2 includes multiple PV strings 4 and an inverter 6. Each PV string 4 includes individual solar panels (not shown), typically eight to twelve panels, electrically connected in series. The output of each PV string is coupled to the inverter 6. The inverter 6 converts the direct current (DC) power of the solar panels into three phase alternating current (AC) power for use by commercial power systems (not shown). The three phase AC power output of the inverter 6 is received by a switchgear (not shown) of a facility where the AC output of the PV system 2 is matched to supply power to the facility or to a utility grid.

[0039] Measurement hardware, such as DC current sensors 8 for detecting the output current of the PV strings 4 is coupled between the PV strings 4 and the inverter 6. In some embodiments, the DC current sensors 8 may be separate from the inverter 6, or the DC current sensors 8 may be incorporated into the inverter 6. Accordingly, each DC current sensor 8 detects output current that is associated with a PV string 4. This output current is received by a data logger 9 coupled to the DC current sensors 8. Examples of DC current sensors 8 include, but are not limited to, current transformers (CT), and Hall Effect sensors, and other suitable current sensors known to those skilled in the art.

[0040] The PV system 2 further includes an irradiance sensor 16 for measuring solar irradiance. The irradiance sensor 16 may be a pyranometer although other

sensors such as a reference cell and a photodiode may be used. The pyranometer 16 is also coupled to the data logger 9 for the data logger 9 to receive measured solar irradiance therefrom. The data logger 9 is coupled to a network 12 to store data relating to the PV string output current and measured solar irradiance in a storage device (not shown) coupled to the network 12.

[0041] For cost reasons, PV systems 2 may include only one pyranometer 16 which has a tilt angle and an azimuth angle of 0. However, the PV strings 4 may be fixed in their orientation based on the site's design or track the sun and are thereby orientated differently than the pyranometer 16. As a result, solar irradiance received by each PV string 4 will differ from the pyranometer's output due to the differences in tilt and azimuth angles. The method according to an embodiment of this disclosure is able to estimate solar irradiance falling on each PV string based solely on the output of one single pyranometer located nearby.

[0042] The PV system 2 further includes a computing device 10 coupled to the network 12. The computing device 10 is able to obtain one or more data associated with a PV string 4 based on the output current of the PV string 4. The one or more data includes, but is not limited to, estimated solar irradiance falling on the PV string 4, soiling loss of the PV string 4 and shading loss at the PV string 4 due to shading in the weather, etc. The computing device 10 may be a general purpose personal computers (including, merely by way of example, personal computers and/or laptop computers running various versions of Microsoft Corp.'s Windows™ and/or Apple Corp.'s Macintosh™ operating systems) and/or workstation computers running any of a variety of commercially-available UNIX™ or UNIX-like operating systems. Alternatively, the computing device 10 may be any other electronic device, such as a thin-client computer, Internet-enabled mobile telephone, personal digital assistant, and/or one or more cloud computing devices. The computing device 10 accesses the storage device to retrieve data stored thereon for performing the method.

[0043] Referring to Figure 2, an example computing system 20 including a computing device 10 is provided that may be used in the PV system 2 for executing the method disclosed herein. More specifically, Figure 2 illustrates one embodiment of a computing system 20. The computing system 20 includes hardware elements that are electrically coupled via a communication bus 22. The hardware elements include the computing device 10, one or more input devices 24 (e.g., a mouse, a

keyboard, etc.), and one or more output devices 26 (e.g., a display device, a printer, etc.). The computing system 20 may also include one or more storage devices 28. By way of example, storage device(s) 28 may be disk drives, optical storage devices, solid-state storage device such as a random access memory ("RAM") and/or a read-only memory ("ROM"), which can be programmable, flash-updateable and/or the like. The computing system 20 may additionally include a computer-readable storage media reader 30.

[0044] The computing device 10 includes one or more central processing units (CPUs) 205 or simply processors 32, a communications system 34 (e.g., a modem, a network card (wireless or wired), an infra-red communication device, etc.); and working memory 38, which may include RAM and ROM devices as described above. In some embodiments, the computing device 10 may also include a processing acceleration unit 36, which can include a GPU, a DSP, a special-purpose processor and/or the like. The computing device 10 may also include software elements, shown as being currently located within a working memory 38, including an operating system 40 and/or other code 42, such as program code implementing the method of estimating solar irradiance. It should be appreciated that alternate embodiments of a computing device 10 may have numerous variations from that described above. For example, customized hardware might also be used and/or particular elements might be implemented in hardware, software or both.

[0045] A method 50 of determining a PV string model 52 for estimating solar irradiance on a PV string 4 is next described with the aid of Figures 4 and 5. The method 50 starts in a GENERATE GLOBAL SOLAR IRRADIANCE step 54 (Figure 3), where in the computing device 10 takes as input metadata, such as a date and time, latitude, longitude, and altitude of the site where the PV string 4 is located, PV string tilt angle, PV string azimuth angle, pyranometer tilt angle and pyranometer azimuth angle; and executes software related to a scientific model 56 based on the inputs to generate a theoretical clear-sky global solar irradiance over the pyranometer (*poa_global_irr_sensor*) 58 and a theoretical clear-sky global solar irradiance over the PV string (*poa_global_string*) 60. The scientific model 56 may be any model known to those skilled in the art including, but not limited to, the GTI DIRINT model, the Modelchain model, a model using the NREL SPA algorithm, the Kasten and Yang 1989 Airmass model, the Spencer Extra Radiation, the Ineichen

and Perez clear sky model, the Hay and Davies' Diffuse Irradiation model, etc. Accordingly, the theoretical clear-sky global solar irradiance over the pyranometer (*poa_global_irr_sensor*) 58 and a theoretical clear-sky global solar irradiance over the PV string (*poa_global_string*) 60 are obtained.

[0046] It is observed that these data obtained are quite accurate after comparing them with actual measurements under clear-sky conditions. However, the absolute values of the scientific model output is not critical to the accuracy of the PV string model 52 so long as the trend of the output of the scientific model 56 is consistent. Figure 4 is a graph showing an example of *poa_global_irr_sensor* 58 and *poa_global_string* 60 obtained between sunrise and sunset at five minute intervals on a given day. However, it should be noted that other periods and intervals can also be used in the method 50.

[0047] The method 50 next proceeds to an ESTIMATE SOLAR IRRADIANCE step 51, wherein the PV string model 52 is executed by the computing device 10 to estimate the solar irradiance falling on the PV string 4, i.e. received by the PV string 4. The input to the PV string model 52 are the *poa_global_irr_sensor* 58 and *poa_global_string* 60 obtained from the scientific model 56, and actual irradiance data, *poa_global_string*, 64 as captured by the pyranometer 16.

[0048] Next, a difference, x , is obtained as follows:

$$x = poa_global_string - poa_global_irr_sensor \quad (1)$$

And a ratio, y , is obtained as follows:

$$y = \frac{irr_sensor_real}{poa_global_irr_sensor} \quad (2)$$

Finally, the estimated solar irradiance, *string_irr_estimated*, 62 falling on the PV string 4 is determined as follows:

$$string_irr_estimated = x(ay^3 + by^2 + cy + d) \quad (3)$$

where a , b , c , and d are coefficients that are determined using model training of the PV string model 52 which will be described shortly.

In an ideal situation, solar irradiance falling on the PV string 4 should all be converted to electrical energy. In other words, the estimated solar irradiance 62 falling on the PV string 4 should correspond to the output current 66 of the PV string 4.

[0049] After the solar irradiance 62 falling on the PV string 4 is estimated, the method 50 next proceeds to a NORMALIZATION step 70, wherein a normalized

estimated solar irradiance, *string_irr_estimated_norm*, falling on the PV string 4 and a normalized PV string output current, *string_current_norm*, are obtained as follows:

$$string_irr_estimated_norm = \frac{string_irr_estimated}{sum(string_irr_estimated)} \quad (4)$$

$$string_current_norm = \frac{string_current}{sum(string_current)} \quad (5)$$

The normalized PV string output current is taken as the ground truth.

[0050] The method 50 next proceeds to a DETERMINE LOSS step 72, wherein the *string_irr_estimated_norm* is compared with the *string_current_norm* using a loss function to determine the amount of loss between model output and the ground truth.

The loss may be an unreduced mean-squared-error given by:

$$l(j, k) = L = \{l_1, \dots, l_N\}^T, \text{ where } l_n = (j_n - k_n)^2;$$

or

a reduced error given by:

$$l(j, k) = \begin{cases} mean(L), & \text{if reduction} = 'mean' \\ sum(L), & \text{if reduction} = 'sum' \end{cases}$$

where j is the *string_irr_estimated_norm*, k is *string_current_norm*, and N is a data sample size in a day.

Alternatively, the loss may be an unreduced mean-absolute-error given by:

$$l(j, k) = L = \{l_1, \dots, l_N\}^T, \text{ where } l_n = |j_n - k_n|;$$

or

$$l(j, k) = \begin{cases} mean(L), & \text{if reduction} = 'mean' \\ sum(L), & \text{if reduction} = 'sum' \end{cases}$$

where j is the *string_irr_estimated_norm*, k is *string_current_norm*, and N is a data sample size in a day.

[0051] The method 50 returns to the ESTIMATE SOLAR IRRADIANCE step 51, wherein the coefficients a, b, c, and d are adjusted based on the output of the

DETERMINE LOSS step 72 to refine the PV string model 52 such that the estimated solar irradiance on the PV string 4 is proportional to the output current of the PV string 4 ignoring the temperature effect so as to reduce the loss. The coefficients are adjusted using back-propagation as implemented in a deep-learning framework such as PyTorch known to those skilled in the art. With the changes to the coefficients, a new value of estimated solar irradiance, *string_irr_estimated*, 62 is obtained.

[0052] The method 50 next proceeds to the NORMALIZATION step 70 and the DETERMINE LOSS step 72 to obtained normalized data and loss information as described above based on the newly obtained *string_irr_estimated* 62.

[0053] The steps 51, 70, 72 of ESTIMATION OF SOLAR IRRADIANCE, NORMALIZATION, and DETERMINE LOSS are repeated until the loss as determined in the DETERMINE LOSS step 72 is at a minimum and cannot be reduced any further. Alternatively, the steps may be repeated until the loss falls below a threshold value. At the end of the method 50, an optimized PV string model 52 is obtained. Accordingly, the coefficients a, b, c, and d are obtained through model training as described above to be able to estimate solar irradiance falling on the PV string 4 to a reasonably degree of accuracy.

[0054] To verify accuracy of the PV string model 52 obtained using the above-described method for estimating solar irradiance falling on the PV string, the profile of the estimated solar irradiance 62 and the PV string output current 66 are compared.

[0055] First, a particular date and a PV string is chosen and the PV string's output current 66 with same timestamp as irradiance data (i.e. *poa_global_string*, *poa_global_irr_sensor*, and *string_irr_estimated*) are obtained. Both current and irradiance data should have the same number of data points. Any extra data points are removed. The following data are calculated:

- Normalized estimated irradiance data, *string_irr_estimated_norm*, given by:

$$string_irr_estimated_norm = \frac{string_irr_estimated}{sum(string_irr_estimated)} \quad (6)$$

- Normalized DC current data, *string_current_norm*, given by:

$$string_current_norm = \frac{string_current}{sum(string_current)} \quad (7)$$

- Total absolute difference between estimated irradiance and the DC current, *irr_est_err*, given by:

$$irr_est_err = \text{sum}(\text{abs}(\text{string_irr_estimated_norm} - \text{string_current_norm})) \quad (8)$$

- Error in percentage, *Est_Err_Pct*, given by:

$$Est_Err_Pct = \frac{irr_est_err}{\text{sum}(\text{string_current_norm})} \times 100 \quad (9)$$

- Normalized irradiance data, *irr_sensor_real_norm*, given by:

$$irr_sensor_real_norm = \frac{irr_sensor_real}{\text{sum}(irr_sensor_real)} \quad (10)$$

- Total absolute difference between measured irradiance and the DC current, *irr_real_err*, given by:

$$irr_real_err = \text{sum}(\text{abs}(irr_sensor_real_norm - \text{string_current_norm})) \quad (11)$$

- Error in percentage, *Real_Err_Pct*, given by:

$$Real_Err_Pct = \frac{irr_real_err}{\text{sum}(\text{string_current_norm})} \times 100 \quad (12)$$

[0056] The dataset that is selected for verifying accuracy included 7 days of data obtained on 15th Jan, 15th Feb, 15th Mar, 15th Apr, 15th May, 15th Jun and 15th Jul in 2020. These dates were randomly selected and were not used for training of the PV string model 52. The median value of *Real_Err_Pct* is 14.2% and of *Est_Err_Pct* is 10.45%. It can be observed that the estimated solar irradiance 62 obtained using the PV string model 52 reduced error by about 26.4%. Figure 6 are histograms showing error distribution.

[0057] Once the PV string model 52 is trained as described above using past data, it can be used without any further training in a method 80 to estimate the solar irradiance received by the PV string 4 based on new data. In other words, solar irradiance for any PV string 4 in the PV system 2 can be obtained using Equation (3). Accordingly, estimating solar irradiance may thus be based on the theoretical clear-sky global solar irradiance over the pyranometer (*poa_global_irr_sensor*) 58, the theoretical clear-sky global solar irradiance over the PV string 60 and actual solar irradiance 64 as recorded by the pyranometer 16.

[0058] Next soiling loss 82 associated with the PV string 4 may be obtained based on the estimated solar irradiance 62 falling on the PV string 4. To determine soiling loss 80, the method 80 proceeds to a DETERMINE SOILING LOSS step (not shown), wherein the output current 66 of the PV string 4 is converted to solar irradiance, *string_current_scaled*, based on a conversion rate available from the PV panel datasheet. For example, if the output current 66 of the PV string is 8.66A, the solar irradiance on the PV string 4 at a conversion rate of 1000W/m²/A, would be given by:

$$string_current_scaled = \frac{string_current}{8.66} \times 1000 \quad (13)$$

[0059] Next, a soiling ratio, *SR*, is calculated based on *string_current_scaled* as follows:

$$SR = \frac{sum(string_current_scaled)}{sum(string_irr_estimated)} \quad (14)$$

[0060] Due to manufacturing variations in the PV strings 4, the output current 66 of PV strings 4 are unlikely to be exactly the same for the same amount of solar irradiance falling thereon. Therefore, it is preferable that the soiling ratio, *SR*, be normalized based on a maximum soiling ratio (*SR_Max*) of each individual PV string over a given period of time, such as one year. The normalized soiling ratio, *SR_Normalized*, is defined as follows:

$$SR_Normalized = \frac{SR}{SR_Max} \quad (15)$$

SR_Max can be obtained according to a number of ways, such as, but not limited to:

- Max(*SR*)
- Max(Moving_Avg(*SR*))
- Percentile_95(*SR*)

It is thus possible that *SR_Normalized* is greater than 1 depending on how *SR_Max* is determined.

[0061] For soiling loss calculation, only the effect of *SR* calculated based on the PV string output current 66 is considered. The PV string output voltage is assumed

to be constant since there is smaller variation in the output voltage compared to the output current 66. The effect of PV panel operating temperature is also ignored since the temperature coefficient of panel output current 66 is about 10 times smaller than its voltage counterpart. As a result, the temperature effect on the *SR* calculation can be ignored. The soiling loss 82 can thus be defined as follows:

$$\text{soiling loss} = \frac{\text{Panel_Output_Energy}}{\text{SR_Normalized}} - \text{Panel_Output_Energy} \quad (16)$$

Accordingly, soiling loss may be determined based on the estimated solar irradiance 62 and the PV string output current 66.

[0062] To verify the accuracy of the soiling ratio, *SR*, the site-level *SR* is compared with the rain fall data obtained from a nearby weather station as shown in Figure 7, wherein both curves are plotted with a moving-average of 50 days. As can be seen from the graphs, the soiling ratio, *SR*, follows a similar trend as the rain fall. The correlation coefficient between them is about 0.712.

[0063] It is further possible to determine loss 84 due to shading by comparing estimated solar irradiance received by PV string, *string_irr_estimated*, 62 and the *string_current_scaled* to identify shading incidents and calculate shading loss for each PV string 4. The *string_current_scaled* is compensated by *SR* (*string_current_sr_compensated*) before comparison is given by:

$$\text{string_current_sr_compensated} = \frac{\text{string_current_scaled}}{\text{SR}} \quad (17)$$

[0064] Figure 8 is a graph of estimated solar irradiance, *string_irr_estimated*, 62 and *string_current_sr_compensated*. In the graph, a shading zone or period 86 is indicated by a shading flag 88. The difference between *string_irr_estimated* and *string_current_sr_compensated*, which is a reduction in irradiance, *irr_reduction*, in the shading zone is also shown in Figure 8.

$$\text{irr_reduction} = \text{string_irr_estimated} - \text{string_current_sr_compensated} \quad (18)$$

where shading_flag = TRUE

[0065] The shading zone 86 is therefore identified as a period where *irr_reduction* continuously exceed a threshold value for a minimum time interval. And this shading zone 86 is marked by the shading_flag 88 in Figure 8.

[0066] The shading loss in terms of percentage 84 may be defined as:

$$\text{shading_loss_percentage} = \frac{\text{sum}(\text{irr_reduction})}{\text{sum}(\text{string_irr_estimated})} \times 100 \quad (19)$$

Accordingly, the shading loss 84 may also be determined based on the estimated solar irradiance 62 and the PV string output current 66.

[0067] To improve the accuracy of determining soiling loss and shading loss, a second soiling ratio, *SR*, may be calculated by excluding data in the shading zone 86. After this second soiling ratio is obtained, a further shading zone 86 is identified. And this further shading zone 86 can again be used to determine a third soiling ratio and so on. That is, the process of determining soiling ratio and shading zone 86 may be iterative.

[0068] The PV string model 52 described above may also be used for identifying tilt and azimuth angles of other PV strings 4 in the PV system 2. The PV string model 50 is used to estimate solar irradiance falling on a PV string 4 based on different combinations of input PV string tile angles and PV string azimuth angles. An estimated solar irradiance will be obtained for each combination of tilt angle and azimuth angle. As described earlier, clear-sky data should preferably be used for better accuracy. To determine the unknown tilt and azimuth angles for a PV string 4, that PV string's output current 66 is compared with the estimated solar irradiance data for the different angle combinations. The combination of tilt and azimuth angle with estimated solar irradiance that is closest to the current PV string's output current 66, i.e. with smallest loss according to the loss function in Figure 5, will thus be taken as the tilt and azimuth angles of the PV string under investigation.

[0069] The above obtained soiling ratio may also be used to estimate the output of the irradiance sensor 16 based on the output current 66 of a PV string 4.

[0070] A sensor model 90, separate from the PV string model 52, will be similarly trained to estimate the irradiance sensor output. The inputs to the sensor model 90 will be *poa_global_irr_sensor*, *poa_global_string* and *string_current_sr_compensated* that is calculated based on a previously obtained

SR, for example, an SR obtained from a previous day. The output of the sensor model is the estimated irradiance sensor output (*irr_sensor_estimated*) 92. The sensor model training method is shown in Figure 9.

[0071] The sensor model 90 is executed by the computing device 10 to estimate the irradiance sensor output 92. As mentioned above, the input to the sensor model 90 are the *poa_global_irr_sensor* and *poa_global_string* obtained from the scientific model 56, and *string_current_sr_compensated*.

[0072] Next, a difference, *u*, as follows:

$$u = poa_global_string - poa_global_irr_sensor \quad (20)$$

And a ratio, *v*, is obtained as follows:

$$v = \frac{string_current_sr_compensated}{poa_global_irr_sensor} \quad (21)$$

Finally, the estimated irradiance sensor output, *irr_sensor_estimate*, is determined as follows:

$$irr_sensor_estimate = u(ev^3 + fv^2 + gv + h) \quad (22)$$

where *e*, *f*, *g*, and *h* are coefficients that are determined using model training which will be described shortly.

[0073] Next the *irr_sensor_estimate* is compared with the *irr_sensor_real* to determine a difference therebetween using a loss function 96. The coefficients in Equation (22) are adjusted based on the difference of the loss function to refine the sensor model 90 such that the estimated irradiance sensor output 92 is closer to the *irr_sensor_real* so as to reduce the difference. With the changes to the coefficients, a new value of estimated irradiance sensor output, *irr_sensor_estimate*, 92 is obtained.

[0074] A further difference is obtained using the loss function 96 based on the newly obtained *irr_sensor_estimate*. This is repeated until the difference falls below a threshold value or cannot be reduced further. At the end of this model training, an optimized sensor model is obtained. Accordingly, the coefficients *e*, *f*, *g* and *h* are obtained through model training as described above to be able to estimate the output of the irradiance sensor 16 to a reasonably degree of accuracy.

[0075] Since there may be hundreds of PV strings 4 in a solar farm, an estimated irradiance sensor output 92 may be obtained from each of the PV strings 4. And the

final estimated irradiance sensor output may be a median value of all the estimated irradiance sensor outputs for each time interval.

[0076] To verify the accuracy of the sensor model 90, the real sensor output 64 and estimated value 92 are summed up on a daily basis. The error in percentage, *err_pct*, is defined as follows:

$$err_pct = \frac{real_sum - est_sum}{real_sum} \times 100 \quad (23)$$

[0077] Figure 10 is a table showing the *Err_pct* for seven days' data. As seen from the table, the error in percentage which ranges from -1.5% to 2.6% is rather low. The sensor model 90 obtained is thus fairly accurate in estimating irradiance sensor output.

[0078] In the foregoing description, for the purposes of illustration, methods were described in a particular order. It should be appreciated that in alternate embodiments, the methods may be performed in a different order than that described. It should also be appreciated that the methods described above may be performed by hardware components or may be embodied in sequences of machine-executable instructions, which may be used to cause a machine, such as a general-purpose or special-purpose processor or logic circuits programmed with the instructions to perform the methods. These machine-executable instructions may be stored on one or more machine readable mediums, such as CD-ROMs or other type of optical disks, floppy diskettes, ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, flash memory, or other types of machine-readable mediums suitable for storing electronic instructions. Alternatively, the methods may be performed by a combination of hardware and software.

[0079] Advantageously, the above-described PV string model 52 can be used to estimate the solar irradiance falling on each PV string 4 with any tilt and azimuth angles based on the single pyranometer's output fairly accurately. The PV string model 52 can be used to further calculate the PV string-level soiling loss and shading loss. Furthermore, the output of the PV string model 52 can also be used to estimate a pyranometer's output based on the output current 66 of a PV string 4. This estimated output can be used to benchmark the pyranometer's output for detection of anomaly in the operation of the pyranometer 16. And when the pyranometer 16

itself is determined to be out of order, the estimated output 92 from the sensor model 90 may be used as a substitute for actual output of a working pyranometer 16.

[0080] Although the present invention is described as implemented in the above described embodiment, it is not to be construed to be limited as such. For example, although clear sky values are used in determining the PV string model and the sensor model, it should be appreciated that non-clear sky values of global irradiance may also be used.

[0081] As another example, the PV string model and the sensor model are represented by a specific polynomial function. Those skilled in the art will readily recognize that other polynomial functions may also be used. Some examples of polynomial functions include, but are not limited to, ax/y^2 and $x^3 * (ay^2 + by + c)$. Multiple polynomials can also be defined based on the value of x or y. For example,

$$\begin{aligned} & \begin{cases} x * (ay^2 + by + c), \text{ when } x \geq 0 \\ x * (dy^2 + ey + f), \text{ when } x < 0 \end{cases} \text{ or} \\ & \begin{cases} x * (ay^2 + by + c), \text{ when } y \geq 1 \\ x * (dy^2 + ey + f), \text{ when } y < 1 \end{cases} \end{aligned}$$

And for the different polynomial functions, the variables x and y may also be defined differently. For example, y may be defined as follows:

$$y = \log\left(\frac{\text{irr_sensor_real}}{\text{poa_global_irr_sensor}}\right)$$

A neural network may also be used to approximate any functions. Furthermore, the models are not limited to be represented as functions, the models may also include machine learning models, deep learning models, etc.

[0082] It should be further appreciated by the person skilled in the art that one or more of the above modifications or improvements, not being mutually exclusive, may be further combined to form yet further embodiments of the present invention.

CLAIMS

1. A method of estimating solar irradiance falling on a PV string that includes a plurality of PV panels, the method comprising:

obtaining a first global solar irradiance on the PV string;
 obtaining a second global solar irradiance on a sensor;
 receiving actual solar irradiance recorded by the sensor; and
 estimating solar irradiance falling on the PV string based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance.

2. A method according to Claim 1, wherein the first global solar irradiance and the second global solar irradiance comprise a first clear-sky global solar irradiance and a second clear-sky solar irradiance respectively.

3. A method according to Claim 1 or 2, wherein estimating solar irradiance falling on the PV string comprises:

estimating solar irradiance falling on the PV string based on:
 a difference between the first global solar irradiance and the second global solar irradiance; and
 a ratio of the actual solar irradiance and the second global solar irradiance.

4. A method according to Claim 3, wherein

the difference between the first global solar irradiance (*poa_global_string*) and the second global solar irradiance (*poa_global_irr_sensor*) is given by:

$x = poa_global_string - poa_global_irr_sensor$; and

a ratio of the actual solar irradiance (*irr_sensor_real*) and the second global solar irradiance is given by:

$$y = \frac{irr_sensor_real}{poa_global_irr_sensor}; \text{ and}$$

wherein the estimated solar irradiance (*string_irr_estimated*) is given by:

$$string_irr_estimated = x(ay^3 + by^2 + cy + d)$$

wherein a, b, c, and d are coefficients.

5. A method according to Claim 4, wherein the coefficients are derived based on past estimated solar irradiance on the PV string and past output current of the PV string.
6. A method according to Claim 5, wherein the coefficients are derived by:
 - determining loss based on the past estimated solar irradiance and the past output current;
 - adjusting the coefficients based on the loss to generate another estimated solar irradiance; and
 - repeating determining loss and adjusting the coefficients until the loss is at a desired level.
7. A method according to any of the preceding claims, the method further comprising:
 - receiving an output current of the PV string; and
 - determining a soiling loss of the PV string based on the estimated solar irradiance and the output current.
8. A method according to any of the preceding claims, the method further comprising:
 - receiving an output current of the PV string; and
 - determining a shading loss of the PV string based on the estimated solar irradiance and the output current.
9. A method according to Claim 8, the method further comprising:
 - determining a soiling ratio including the estimated solar irradiance; and
 - wherein determining a shading loss includes determining a shading loss of the PV string based on the soiling ratio.

10. A method according to Claim 9, the method further comprising:
 - determining a shading zone; and wherein determining a shading loss includes determining a shading loss in the shading zone.
11. A method according to Claim 10, the method further comprising:
 - determining again another soiling ratio by excluding estimated solar irradiance in the shading zone;
 - determining another shading zone based on the another soiling ratio;
 - repeating determining again another soiling ratio and determining again another shading zone until a stable shading zone is obtained; and
 - wherein determining a shading loss in the shading zone includes determining the shading loss in the stable shading zone.
12. A method according to Claim 8, the method further comprises:
 - obtaining a further global solar irradiance on the PV string;
 - obtaining a further global solar irradiance on the sensor;
 - receiving a further output current of the PV string; and
 - estimating an output of the sensor based on the further global solar irradiance, the further global solar irradiance, the further output current, the estimated solar irradiance obtained earlier and the output current received earlier.
13. A computing device comprising:
 - a processor operable to:
 - obtain a first global solar irradiance on a PV string;
 - obtain a second global solar irradiance on a sensor;
 - receive actual solar irradiance recorded by the sensor; and
 - estimate solar irradiance falling on the PV string based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance.
14. A computing device according to Claim 13, wherein the processor is further operable to:

receive an output current of the PV string; and
determine a soiling loss of the PV string based on the estimated solar irradiance and the output current.

15. A computing device according to Claim 13, wherein the processor is further operable to:

receive an output current of the PV string; and
determine a shading loss of the PV string based on the estimated solar irradiance and the output current.

16. A computing device according to Claim 15, wherein the processor is further operable to:

obtain a further global solar irradiance on the PV string;
obtain a further global solar irradiance on the sensor;
receive a further output current of the PV string; and
estimate an output of the sensor based on the further global solar irradiance on the PV string, the further global solar irradiance on the sensor, the further output current, the estimated irradiance obtained earlier and the output current received earlier.

17. A system comprising:

a computing device comprising:

a processor operable to:

obtain a first global solar irradiance on a PV string;
obtain a second global solar irradiance on a sensor;
receive actual solar irradiance recorded by the sensor;

and

estimate solar irradiance falling on the PV string based on the first global solar irradiance, the second global solar irradiance and the actual solar irradiance to obtain an estimated solar irradiance.

18. A system according to Claim 17, wherein the processor is further operable to:

- receive an output current of the PV string; and
determine a soiling loss of the PV string based on the estimated solar irradiance and the output current.
19. A system according to Claim 17, wherein the processor is further operable to:
receive an output current of the PV string; and
determine a shading loss of the PV string based on the estimated solar irradiance and the output current.
20. A system according to Claim 19, wherein the processor is further operable to:
obtain a further global solar irradiance on the PV string;
obtain a further global solar irradiance on the sensor;
receive a further output current of the PV string; and
estimate an output of the sensor based on the further global solar irradiance on the PV string, the further global solar irradiance on the sensor, the further output current, the estimated solar irradiance obtained earlier and the output current obtained earlier.
21. A system according to any of Claims 17-20, further comprising:
the PV string;
a current sensor coupled between the computing device and the PV string to provide the computing device with the output current of the PV string;
and
the sensor.
22. A method of obtaining a model of a PV string for estimating solar irradiance falling on the PV string, the method comprising:
obtaining a first global solar irradiance on the PV string;
obtaining a second global solar irradiance on a sensor;
receiving actual solar irradiance recorded by the sensor;
estimating solar irradiance falling on the PV string using a PV string model based on the first global solar irradiance, the second global solar

irradiance and the actual solar irradiance to obtain an estimated solar irradiance;

receiving output current of the PV string;

determining loss based on the estimated solar irradiance and the output current;

refining the PV string model based on the loss to generate another estimated solar irradiance; and

repeating determining loss and refining the PV string model until the loss is at a desired level.

23. A method of obtaining a model of a sensor for estimating an output of the sensor, the method comprising:

receiving a first output current of a PV string;

obtaining an estimated solar irradiance falling on the PV string;

obtaining a first global solar irradiance on the PV string;

obtaining a first global solar irradiance on a sensor;

receiving a second output current of the PV string; and

estimating, using a sensor model, an output of the sensor based on the first global solar irradiance, the second global solar irradiance, the second output current, the estimated solar irradiance and the first output current to obtain an estimated output;

receiving actual solar irradiance recorded by the sensor;

determining loss based on the estimated output and the actual solar irradiance;

refining the sensor model based on the loss to generate another estimated output; and

repeating determining loss and refining the sensor model until the loss is at a desired level.