

- (51) International Patent Classification:
G01J 1/02 (2006.01) H02S 50/00 (2014.01)
- (21) International Application Number:
PCT/US2014/028702
- (22) International Filing Date:
14 March 2014 (14.03.2014)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
61/792,210 15 March 2013 (15.03.2013) US
- (71) Applicants: ON BEHALF OF THE REGENTS OF THE UNIVERSITY OF COLORADO, A BODY CORPORATE, [US/US]; 1800 Grant Street, 8th Floor, Denver, Colorado 80203 (US). UNIVERSITA DEGLI STUDI ROMA TRE [IT/IT]; Via Ostiense, 159, I-00154 Rome (IT).
- (72) Inventors; and
- (71) Applicants : MANCILLA-DAVID, Fernando [US/US]; Department of Electrical Engineering, Campus Box 110, P.

O. Box 173364, Denver, Colorado 80217 (US). **RIG-ANTI-FULGINEI, Francesco** [IT/IT]; Universita di Roma Tre, Dipartimento di Elettronica Applicata, Via della Vasca Navale 84, I-00154 Rome (IT). **LAUDANI, Antonino** [IT/IT]; Universita di Roma Tre, Dipartimento di Elettronica Applicata, Via della Vasca Navale 84, I-00154 Rome (IT). **SALVINI, Alessandro** [IT/IT]; Universita di Roma Tre, Dipartimento di Elettronica Applicata, Via della Vasca Navale 84, I-00154 Rome (IT).

- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

[Continued on next page]

- (54) Title: NEURAL NETWORK SOLAR IRRADIANCE SENSOR

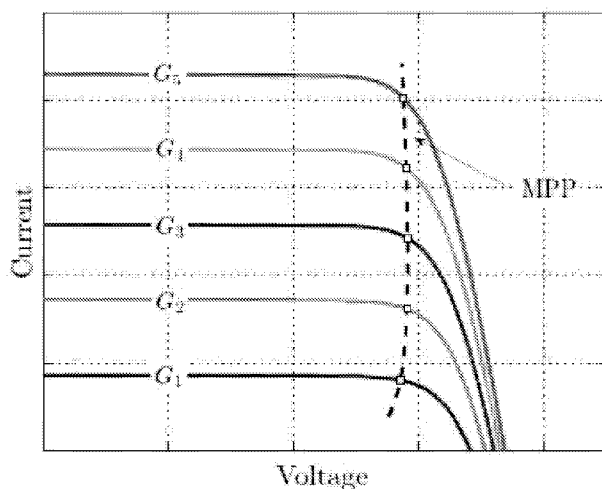


FIG. 1

- (57) Abstract: The present disclosure provides a novel approach for solar irradiance measurement based on neural networks, which may be used in photovoltaic power plants to sense solar irradiance and hence enhance efficiency. An irradiance sensor may be implemented through one or more of: a photovoltaic cell, a temperature sensor, and a low-cost microcontroller. The use of a microcontroller allows for a straightforward calibration and interfacing, via RS232, RS485, Ethernet, or any other communication device known in the art, with the rest of the PV power plant control system. The microcontroller may implement one or more neural networks using accurate double-precision mathematic library, C compilers and integrated development environment. Calibration of cell irradiance may be performed utilizing a PV cell model obtained, for example, from manufacturer datasheets or laboratory testing.



(84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

NEURAL NETWORK SOLAR IRRADIANCE SENSOR

FIELD OF THE INVENTION

[0001] The present disclosure is related to photovoltaic (PV) array systems.

BACKGROUND

[0002] Solar irradiance plays a role in efficiency of photovoltaic power plants. However, devices for solar irradiance measurement, such as pyranometers and pyrheliometers, are often expensive and difficult to calibrate. As a result, such devices are often undesirable for use in photovoltaic power plants.

[0003] In order to reduce the need for specialized solar irradiance equipment, researchers have developed different algorithms to perform Maximum Power Point tracking (MPPT) in photovoltaic (PV) array systems. Some MPPT functions avoid a direct measurement of solar irradiance, and rely on a concave shape of the PV array power-voltage curve and search for the Maximum Power Point (MPP) through iterative processes, without knowledge of solar irradiance. Examples of these methods include perturb and observe (P&O) and incremental conductance algorithms, respectively. However, these methods may oscillate around the MPP and may respond poorly under rapidly changing irradiance.

[0004] Other approaches to perform MPPT functions include a prediction/estimation of the solar irradiance from equations which describe a PV array model and then use the predicted/estimated value to perform the MPPT function. However, in many deployments relatively precise solar irradiance sensing is necessary for optimal operation, and PV power plants often span over a relatively large geographical area which may result in non-uniform irradiance. Known as shading effect, this adversely affects the overall efficiency of the power extraction process when

prediction/estimation techniques are implemented. More precise estimations/predictions may be obtained from (i) a modularization of a PV power plant into various segments using one power converter and a separate MPP tracking algorithm per segment, and (ii) a dynamic reconfiguration of the PV panels' interconnection with only one power converter.

SUMMARY OF THE INVENTION

[0005] Since a precise tracking of the irradiance at various locations through the power plant is desired and/or necessary in one or more of the examples above, low-cost irradiance sensors are highly desirable. One aspect of the present disclosure provides a novel approach for solar irradiance measurement based on neural networks, which may be used in photovoltaic power plants to sense solar irradiance and hence enhance efficiency. Although other low-cost irradiance sensors have been proposed, one advantage of the approach proposed herein lies in the simplicity of construction, leading to low cost, along with enhanced accuracy.

[0006] The foregoing has outlined rather broadly the features and technical advantages of examples according to the disclosure in order that the detailed description that follows may be better understood. Additional features and advantages will be described hereinafter. The conception and specific examples disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present disclosure. Such equivalent constructions do not depart from the spirit and scope of the appended claims. Features which are believed to be characteristic of the concepts disclosed herein, both as to their organization and method of operation, together with associated advantages will be better understood from the following description when considered in connection with the accompanying figures. Each of the figures is provided for the purpose of illustration and description only, and not as a definition of the limits of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] A further understanding of the nature and advantages of the present invention may be realized by reference to the following drawings.

[0008] FIG. 1 is a graph depicting current versus voltage ($I - V$) relationships for various levels of irradiance on a photovoltaic cell, according to various aspects of the disclosure;

[0009] FIG. 2 is a graph depicting current versus voltage ($I - V$) relationships for various temperatures of a photovoltaic cell, according to various aspects of the disclosure;

[0010] FIG. 3 is a block diagram illustrating an irradiance sensing system, according to various aspects of the disclosure;

[0011] FIG. 4 is a block diagram illustrating a PV array circuit mathematical model, according to various aspects of the disclosure;

[0012] FIG. 5 is a graph depicting mean squared error for training exemplary neural networks, according to various aspects of the disclosure;

[0013] FIG. 6 is a block diagram illustrating a neural network according to various aspects of the disclosure;

[0014] FIG. 7 is a graph depicting measurements made using a sensor of the present disclosure and a commercially available irradiance sensor, according to various aspects of the disclosure;

[0015] FIG. 8 is another graph depicting measurements made using a sensor of the present disclosure and a commercially available irradiance sensor, according to various aspects of the disclosure;

[0016] FIG. 9 is a graph depicting solar irradiance and temperature measurements made using a sensor of the present disclosure and a commercially available irradiance sensor, according to various aspects of the disclosure; and

[0017] FIG. 10 is another graph depicting solar irradiance and temperature measurements made using a sensor of the present disclosure and a commercially available irradiance sensor, according to various aspects of the disclosure.

DETAILED DESCRIPTION

[0018] Solar irradiance is a key parameter for maximum power point (MPP) tracking (MPPT) in photovoltaic (PV) power plants. This is because the operating point at which a PV array delivers its maximum power changes as a function of the solar irradiance and cell temperature. This is illustrated in FIGS. 1 and 2 through typical current–voltage ($I - V$) curves for a PV array. FIG. 1 shows typical $I - V$ performance curves 100 for different irradiance values with $G1 < G2 < G3 < G4 < G5$, while FIG. 2 shows typical $I - V$ performance curves 200 for different cell temperature values with $T1 < T2 < T3 < T4 < T5$.

[0019] Using ideas developed for both MPPT and solar irradiance estimation, a novel low–cost solar irradiance sensor is provided according to certain examples of the present disclosure. One approach comprises using one or a small number of PV cells together with a neural network (NN) algorithm appositely tailored for the solution of an inverse problem. In some examples, NNs are used to track the MPP without the knowledge of the solar irradiance. In various examples provided herein implementation of a NN approach is provided to sense the irradiance, which in turn can be also used to track the MPP.

[0020] One exemplary sensor is implemented through one or more of: a photovoltaic cell, a temperature sensor, and a low–cost microcontroller. The use of a microcontroller allows for a straightforward calibration and interfacing, via RS232, RS485, Ethernet, or any other communication device known in the art, with the rest of the PV power plant control system. Such communication may enable remote–control through an embedded web server. An initial

estimate suggests the device proposed herein may cost less than 10% with respect to its commercially available counterparts, making it attractive for a large deployment in photovoltaic power plants. The use of a microcontroller allows for relatively easy calibration, updates, and enhancement by simply adding code libraries.

[0021] In one embodiment, referred to herein as accurate double, one or more NNs are implemented in the microcontroller(s) with the use of accurate double-precision mathematic library, C compilers and integrated development environment. Calibration of cell irradiance may be performed utilizing a PV cell model obtained, for example, from manufacturer datasheets. In other examples, calibration of cell irradiance may be performed utilizing a PV cell model obtained through laboratory measurements, which may reduce potential errors due to parasitic elements and/or inaccuracies on datasheets.

[0022] Turning now to FIG. 3, a block diagram illustrates a sensor 300 according to one embodiment of the disclosure. As seen, one, or a small number of PV cells 305 may be arranged in series and/or parallel, forming a small sensing PV panel 310. The sensing PV panel 310 may receive irradiance 311 (indicated as G), and may provide an output current in response to the received irradiance 311. The sensing PV panel 310 may be then electronically coupled to a known testing resistor (R_{test}) 315, and a voltage 320 across the testing resistor 315 may be measured. Such an approach may inexpensively and easily measure and provide the voltage 320 across the cell terminals of the sensing PV panel 310 and may also be used to measure the cell temperature. In some examples, a separate temperature sensor 325 may provide a temperature measurement 330, and may be located on or adjacent to the PV panel 310. In certain examples, these voltage and temperature values are provided to a microcontroller 335. The microcontroller may compute a current value 345 according to the voltage 320 divided by the value of R_{test} .

Using the current value 345, voltage value 320, and temperature value 330, the microprocessor 335 may execute a properly trained NN algorithm 340 based on a PV cell model such as described above, which then computes the measured solar irradiance 350 (G_m) with great accuracy.

[0023] Such a sensor 300 may be located, for example, next to a power-producing PV panel or may even be integrated with a power producing PV panel. This features the advantage that the sensing PV panel 310 will “see” the same solar irradiance and temperature as that “seen” by the power-producing PV panel, leading to improved performance.

[0024] The NN training process and hence the performance of the sensor 300 relies on a knowledge of the PV array’s 310 $I - V$ performance curves 100 and 200 for different irradiance and temperature values, such as those illustrated in FIGS. 1 and 2, respectively. Performance $I - V$ curves 100 and 200 for PV cells can be obtained using their mathematical model along with standard information provided by manufacturer’s datasheets, for example. Additionally or alternatively, operating points may be experimentally generated in the laboratory under controlled environmental conditions.

[0025] According to certain examples, illustrated in FIG. 4, a training-set may be generated using a PV array mathematical model 400, which may include a circuitual model for a single PV cell and its generalization to a number of cells in series using a current source 405 representing the current generated at a particular irradiance G , an anti-parallel diode, a series resistance 415 and shunt resistance 420. One embodiment may also use a modified circuit which replaces the anti-parallel diode 410 by an external control current source 410 as illustrated in FIG. 4. One advantage of this model is that it allows for including an arbitrary number of cells connected in series and/or parallel into a single circuitual representation including all details of each cell. The

FIG. 4 model corresponds to a building block to generate performance $I - V$ utilized to train the NN 320 of FIG. 3, for example.

[0026] The output current of the PV cell of FIG. 4 may be expressed as $I = I_{\text{irr}} - I_{\text{dio}} - I_{\text{p}}$. In one embodiment, I_{irr} is the photo current or irradiance current 405, which may be generated when the cell is exposed to sunlight. I_{dio} may comprise the current flowing through the anti-parallel diode or external control current source 410, which may induce the non-linear characteristics of the PV cell. I_{p} may be a shunt current due to the shunt resistor 415 branch. Substituting relevant expressions for I_{dio} and I_{p} , in the above equation, the equation becomes: $I = I_{\text{irr}} - I_0[\exp(q((V+IR_S)/nkT)) - 1] - (V + IR_S)/R_P$, where $q = 1.602 \times 10^{-19}$ C is the electron's electric charge, $k = 1.3806503 \times 10^{-23}$ J/K is the Boltzmann constant, T is the temperature of the cell, I_0 is the diode saturation current or cell reverse saturation current, n is the ideality factor or the ideal constant of the diode, and R_S and R_P represent the series 420 and shunt 415 resistance, respectively. A voltage 425 across the anti-parallel diode or external control current source 410 may be provided and the output of the above equation may be determined at 430 and provided as an input to the external control current source 410 of FIG. 4 to generate performance $I - V$ for the training sets.

[0027] This model can be generalized to an arbitrary number of cells connected in series, say N_S , and in parallel, say N_P , to form a small array of $N_S \times N_P$ cells. This may be needed to match voltage/current levels needed by the microcontroller. One such generalized model may take the form of $I = I'_{\text{irr}} - I'_0[\exp((q(V + IR'_S)/N_SnkT)) - 1] - (V + IR'_S)/R'_P$. In such an embodiment, various “prime” values may be interpreted according to Table 1:

SUBSTITUTIONS FOR THE MODEL OF A PV ARRAY

Original Expression	Substitution
$N_P I_{irr}$	I'_{irr}
$N_P I_0$	I'_0
$(N_S/N_P)R_S$	R'_S
$(N_S/N_P)R_P$	R'_P

TABLE 1

[0028] The $I - V$ performance characteristic of a single PV cell and an array described by the equations above, the parameters I_{irr} , I_0 , R_P , R_S , and n depend on the solar irradiance (G), the cell temperature (T), and certain reference parameters, namely G_{ref} , T_{ref} , $I_{irr,ref}$, $I_{0,ref}$, $R_{P,ref}$, $R_{S,ref}$ and n_{ref} , as described by: $I_{irr} = I_{irr,ref} G/G_{ref} (1 + \alpha'_T (T - T_{ref}))$; $I_0 = I_{0,ref} (T/T_{ref})^3 \exp((E_{g,ref}/kT_{ref}) - (E_g/kT))$; $R_P = R_{P,ref} (G/G_{ref})$; and $R_S = R_{S,ref}$; $n = n_{ref}$.

[0029] α'_T may comprise the relative temperature coefficient of the short-circuit current, which may represent the rate of change of the short-circuit current with respect to temperature. Manufacturers may occasionally provide the absolute temperature coefficient of the short-circuit current, α_T , for a particular panel. The relationship between α'_T and α_T is $\alpha_T = \alpha'_T I_{irr,ref}$. Furthermore, E_g may comprise the bandgap energy for silicon in eV. Analytical expressions for E_g may be obtained through curve fitting from experimental measurements, for example, and may vary. One expression for E_g comprises $E_g = (1.16 - 7.02 \times 10^{-4} \times (T^2/(T - 1108))) \times q$. The $I-V$ curves described above, in addition to the breakdown of the various constituent parameters described above provide a representation for the performance of a PV cell or array and may be used to train the NN. The reference parameters may be PV-cell specific and may be obtained based at least in part on information available on manufacturers' datasheets.

[0030] Operating points making up the training-set can alternatively or additionally be generated in the laboratory under controlled environmental conditions. The sensing PV cell can be exposed to an adjustable controlled irradiance level and the PV cell loaded at various levels — for example through using a rheostat— followed by direct measurement of the PV array output voltage and current and cell temperature. This methodology may overcome inaccuracies stemming from: (i) parasitic elements existing on the circuitual realization of the proposed sensor; (ii) differences between the PV array's datasheet and the actual PV array being used; and (iii) tolerance of the testing resistor.

[0031] When using NNs for applications, the training process often requires a high level of accuracy and depends on the design of the various stages —size of hidden layer, size of training and validation sets, early stopping, etc.— for a specific problem. A well trained NN may adapt to data outside the training set which translates into finding suitable matrices of synaptic weights and bias vectors in terms of a nonlinear optimization problem. In one embodiment, the Levenberg–Marquardt algorithm may be used for the training process. Furthermore, to reduce computation cost and memory usage in the microcontroller, a NN configuration may be chosen with a lowest number of neurons possible. One adopted NN, illustrated in FIG. 6, has a feed-forward architecture and is characterized by a three-layer structure 600 with: (i) three input neurons (with linear activation function) 605; (ii) eight neurons 610 for the hidden layer with tansig activation function; and (iii) one output neuron (with linear activation function) 615 for prediction of the measured irradiance, G_m .

[0032] In one embodiment, a suitable training-set may be constructed by using N different $I - V$ curves depending on the irradiance using a constant temperature. Likewise, M different $I - V$

curves may be obtained by varying the temperature at a constant irradiance. Thus, $N \times M$ training-set patterns may be created by simulating a PV cell model.

[0033] Additionally, the NN may be trained to return G_m from the operating point identified by the voltage (V) and current (I) at the PV cell terminals and the temperature on the PV cell surface (T). The trio $x = [V, I, T]$ may correspond to the NN's input vector, as illustrated in FIG.

6. Furthermore, in the PV cell model described by the equations above, a one to one relationship may exist between the operating points x and the single values of G . Yet further, in certain hardware implementations only V and T have to be measured. Indeed, direct measurement of I may be avoided through using a known testing resistor, R_{test} , so the current I can be computed using Ohm's Law. In order to improve accuracy and make the various numerical processes more robust, the value of R_{test} may be selected so that most of the operating points lie around the elbow of the PV cell's $I - V$ curves, thus benefiting from a greater range of values for all three variables $[V, I, T]$.

[0034] One training process may define maximum and minimum values for V , I , T and G , return the matrices of synaptic weights W_1 and W_2 , and bias vectors B_1 and B_2 for the first and second layer, respectively. The measured irradiance G_m may be computed through the following three-step procedure: (1) Normalization of the input data, according to the formulae: $x_j^n = (x_j - x_j^{\min}) / (x_j^{\max} - x_j^{\min})$ for $j = 1, 2, 3$ and where x_j corresponds to V , I and T for $j = 1, 2$, and 3 , respectively, $x_j^{\max}$ and $x_j^{\min}$ are the maximum and minimum values of V , I and T , and x_j^n is the normalized input value within the range $[-1 \ 1]$; (2) Computation of the normalized irradiance: $G^n = W_2 \times \text{tansig}(W_1 \times x^n + B_1) + B_2$, where the activation function tansig is: $\text{tansig}(A) = (2 / (1 + e^{-2A})) - 1$; and (3) De-normalization of G_n in order to obtain the actual solar irradiance value $G_m = (G^{\max} - G^{\min})G_n + G^{\min}$.

[0035] In one example, the circuit schematic of FIG. 3 may include a sensing PV array realized by a prepackaged eight-cell array manufactured by IXYS, part # KXOB22-01X8, rated at 3.4 V/3.8 mA at MPP under standard testing conditions. Using the specifications available on the manufacturer's datasheet, a complete mathematical model for the performance of the array may be built using the procedure outlined above.

[0036] In one example, a NN training set was implemented in a MATLAB® environment through ten different operating points at equidistant irradiance values from 100 to 1500 W/m² and five different operating points at equidistant temperature values from 260 to 360 (K), which leads a training set size of 50 operating points $[V, I, T]$. Given the PV array characteristics, the resistance of the testing resistor was selected to be $R_{\text{test}} = 921 \, \Omega$ and was realized through a simple axial-lead resistor. This allowed operating points to be selected around the elbow of the PV array $I - V$ curve. The goal for mean square error (MSE) on the training set was fixed equal to 8×10^{-3} and the learning process took around 2 minutes. FIG. 5 shows a graph 500 of the mean square error (MSE) during the NN training. After 4125 epochs the target value of 10^{-2} for MSE was reached.

[0037] According to certain examples, a PV array terminal voltage may be measured using an internal analog/digital (AD) converter embedded in the microcontroller (e.g., microcontroller 335 of FIG. 3). A temperature sensor, in one example, was realized using a one-wire sensor Maxim Integrated® model # DS18B20, and the microcontroller used for data processing was a PIC18F6627 manufactured by Microchip Technology Inc. This device belongs to the low-cost low-power PIC18/8-bit family, featuring a 4 kB RAM memory and a 96 kB reprogrammable flash memory; 12 AD converters; and SPI, I2C, and RS232/RS485 interfaces. Of course, one of

skill in the art will readily recognize that these components are merely exemplary, and that numerous other components may be utilized in other examples.

[0038] In some embodiments, the microcontroller may comprise an 8-bit microcontroller that may be configured to implement one or more accurate double-precision mathematic libraries which are available for the development of the firmware of microcontrollers. The NN algorithm described above may be adapted to run in the microcontroller, and may be coded in C language, in some embodiments. The C code may comprise a set of initializing functions and a main process. The latter may control the peripheral units, manage the communication protocol(s), acquires the input data, execute the implemented NN routine, and output the computed irradiance. The routines for control and communication processes may be developed by means of the MPLABTM X IDE and compiled through a compiler such as the Microchip C 18 compiler. This may reconstitute a HEX code file which may be downloaded into the microcontroller, such as via an Ethernet connection, for example. Furthermore, the microcontroller may be interfaced to a personal computer (or other computer) through a RS232/RS485 or an Ethernet cable. The aforementioned features of the microcontroller may allow for easy update, recalibration, or the inclusion of new customized features. The entire NN routine, in some embodiments, may occupy about 5904 bytes of program memory and 186 bytes of data memory.

[0039] Table II shows the cost of the main components for the hardware realization of one exemplary embodiment. The overall cost of all components is around USD \$50, a small fraction of the cost of most commercially available irradiance sensors.

EXPERIMENTAL SETUP COMPONENTS AND COST

Component	Off-the shelf part #	Cost (USD \$)
-----------	----------------------	---------------

PV cell	KXOB22-01X8	5.8
Temperature Sensor	DS18B20	4.5
Microcontroller	PIC18F6627	11.0
Other components	Connectors, case, etc.	10.0/30.0

Total Cost: 41.3/51.3

TABLE II

[0040] Several outdoor experiments were performed using the hardware prototype described above. The exemplary sensor was contrasted against a commercial sensor. The device available for comparison is a laser power sensor part # LM-10 HTD manufactured by Coherent, Inc.

[0041] The PV cells utilized in exemplary sensors may correspond to a monocrystalline silicon cell pack, which may absorb light within the wavelength range of 0.3–1.1 μm . On the other hand, the LM-10 HTD device may also comprise a thermopile-based sensor calibrated to measure irradiance within the spectrum 0.25–10.6 μm . Due to the mismatch in the wavelength spectrum, monocrystalline silicon cell and thermopile-based sensors may not yield substantially similar readings. Therefore, experimental procedures were developed to quantify these differences through the definition of mismatch ratio (MR). In the case of irradiance measured by a sensor based on monocrystalline silicon cells (G_{Pv}) versus one based on a thermopile (G_{Tp}), the mismatch ratio ($MR = G_{\text{Pv}}/G_{\text{Tp}}$) is 0.946. This correction was applied to the outdoor measurements in order to compare the sensor readings.

[0042] FIG. 7 shows data per comparison collected at a time of relatively constant irradiance around noon, while FIG. 8 shows data collected at a period of rapidly changing irradiance during dusk. The correlation among the readings is evident. Furthermore, Figs. 9 and 10 present the same data as those of Figs. 7 and 8, respectively resampled every 3 minutes and plotted using a linear fit. Temperature readings are also shown in the bottom plot in the figures. As the figures

suggest, the irradiance readings in the LM-10 HTD sensor —designed for indoor laser power measurements in the absence of wind— are affected by fluctuations in the temperature due to the wind, while the NN sensor proposed herein is insensitive to these fluctuations.

[0043] As discussed herein, a novel low-cost NN-based solar irradiance sensor conceived to be utilized in large PV power plants for precise tracking of solar irradiance within the PV power plant layout is disclosed. A mathematical model as well as a practical realization of the sensor has been described and outdoor measurements have been used to validate the sensor. A feature of the approach proposed herein lies in the simplicity of construction along with increased accuracy, thanks to the use of the NN implemented in an embedded system through a microcontroller. Furthermore, the use a microcontroller allows for updates, enhancement, and customization by simply by adding code libraries. Moreover, it can be interfaced via RS232 or RS485 with other instruments or connected via Ethernet and remote controlled through its embedded web server. One advantage of the sensor is that it can be conveniently located next to a power-producing PV panel or even integrated with it. As a result, the sensing PV panel will “see” exactly the same solar irradiance and temperature as what is “seen” by the power-producing PV panel, leading to precise irradiance tracking which can in turn be used for improved MPPT performance.

[0044] With reference now to FIG. 11, a flowchart 1100 of operational steps for MPPT of a PV array is described. The operations of flowchart 1100 may be performed, for example, by microcontroller 335 of FIG. 3. As will be readily understood by one of skill in the art, numerous other alternatives may be implemented to perform operations similar to those of FIG. 11 to provide MPPT. In the example of FIG. 11, temperature information is received from a temperature sensor associated with at least one PV cell of an irradiance sensor, as indicated at

block 1105. PV current information associated with the at least one PV cell is received at block 1110, and PV voltage information associated with the at least one PV cell is received at block 1115. At block 1120, an irradiance present at the PV cell is determined based on the PV current, PV voltage, and temperature. The PV array may then be controlled for MPPT based at least in part of the determined irradiance.

[0045] The detailed description set forth above in connection with the appended drawings describes exemplary embodiments and does not represent the only embodiments that may be implemented or that are within the scope of the claims. The term "exemplary" when used in this description means "serving as an example, instance, or illustration," and not "preferred" or "advantageous over other embodiments." The detailed description includes specific details for the purpose of providing an understanding of the described techniques. These techniques, however, may be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form in order to avoid obscuring the concepts of the described embodiments.

[0046] The various illustrative blocks and modules described in connection with the disclosure herein may be implemented or performed with a general-purpose processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general-purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination

of a DSP and a microprocessor, multiple microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[0047] The functions described herein may be implemented in hardware, software executed by a processor, firmware, or any combination thereof. If implemented in software executed by a processor, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. Other examples and implementations are within the scope and spirit of the disclosure and appended claims. For example, due to the nature of software, functions described above can be implemented using software executed by a processor, hardware, firmware, hardwiring, or combinations of any of these. Features implementing functions may also be physically located at various positions, including being distributed such that portions of functions are implemented at different physical locations. Also, as used herein, including in the claims, “or” as used in a list of items prefaced by “at least one of” indicates a disjunctive list such that, for example, a list of “at least one of A, B, or C” means A or B or C or AB or AC or BC or ABC (i.e., A and B and C).

[0048] The previous description of the disclosure is provided to enable a person skilled in the art to make or use the disclosure. Various modifications to the disclosure will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other variations without departing from the spirit or scope of the disclosure. Throughout this disclosure the term “example” or “exemplary” indicates an example or instance and does not imply or require any preference for the noted example. Thus, the disclosure is not to be limited to the examples and designs described herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

1. An irradiance sensor apparatus, comprising:
at least one photovoltaic (PV) cell;
a temperature sensor associated with the PV cell; and
a controller coupled with the PV and the temperature sensor that determines a PV current and a PV voltage output by the PV cell, a temperature of the PV cell, and determines an irradiance present at the PV cell based on the PV current, PV voltage, and temperature.
2. The apparatus of claim 1, wherein the controller comprises a neural network algorithm that computes the irradiance based on the PV current, PV voltage, and temperature of the PV cell.
3. The apparatus of claim 2, further comprising a voltage determination circuit coupled between the PV cell and the controller that outputs the PV voltage.
4. The apparatus of claim 3, wherein the voltage determination circuit comprises a test resistor coupled with output terminals of the PV cell.
5. The apparatus of claim 4, wherein the controller receives a PV voltage measurement and determines a value of the PV current based on the PV voltage measurement and a resistance value of a test resistor used to determine the PV voltage measurement.

6. The apparatus of claim 5, wherein the value of the PV current is determined by dividing the voltage measurement by the resistance value.
7. The apparatus of claim 1, wherein the at least one PV cell comprises a plurality of PV cells arranged in series and/or parallel.
8. The apparatus of claim 1, wherein the temperature sensor is located adjacent to the at least one PV cell.
9. The apparatus of claim 1, wherein the controller comprises a microcontroller and an external interface.
10. The apparatus of claim 9, wherein the microcontroller is configured to output control information for a PV array based at least in part on the determined irradiance.
11. The apparatus of claim 10, wherein the control information comprises irradiance tracking information used for Maximum Power Point tracking (MPPT) of a PV array associated with the irradiance sensor.
12. The apparatus of claim 9, wherein the microcontroller comprises an embedded web server configured to output irradiance data for remote control of an associated PV array.

13. The apparatus of claim 9, wherein the external interface comprises one or more of an RS232 interface or an RS485 interface.

14. A method for Maximum Power Point tracking (MPPT) of a photovoltaic (PV) array, comprising:

receiving temperature information from a temperature sensor associated with at least one PV cell of an irradiance sensor;

receiving PV current information associated with the at least one PV cell;

receiving PV voltage information associated with the at least one PV cell;

determining an irradiance present at the PV cell based on the PV current, PV voltage, and temperature; and

controlling the PV array for MPPT based at least in part of the determined irradiance.

15. The method of claim 14, wherein the determining comprises computing the irradiance present at the PV cell using a neural network algorithm.

16. The method of claim 15, further comprising:

training the neural network algorithm based on a plurality of irradiance levels and PV cell temperature levels.

17. The method of claim 16, wherein the training comprises:

receiving a first plurality of different $I - V$ curves each depending on irradiance of the at least one PV cell at a constant temperature;

receiving a second plurality of different $I - V$ curves each depending on temperatures of the at least one PV cell at a constant irradiance; and

evaluating the first and second pluralities of $I - V$ curves.

18. The method of claim 15, wherein the neural network algorithm is a feed-forward network comprising a three-layer structure with: (i) three input neurons with a linear activation function; (ii) eight neurons for a PV cell hidden layer with a tansig activation function; and (iii) one output neuron with a linear activation function.

19. The method of claim 18, wherein the temperature information, PV voltage information, and PV current information are each provided to an associated input neuron, and wherein the output neuron outputs the determined irradiance based at least in part on one or more of the temperature information, PV voltage information, PV current information; or PC cell hidden layer information.

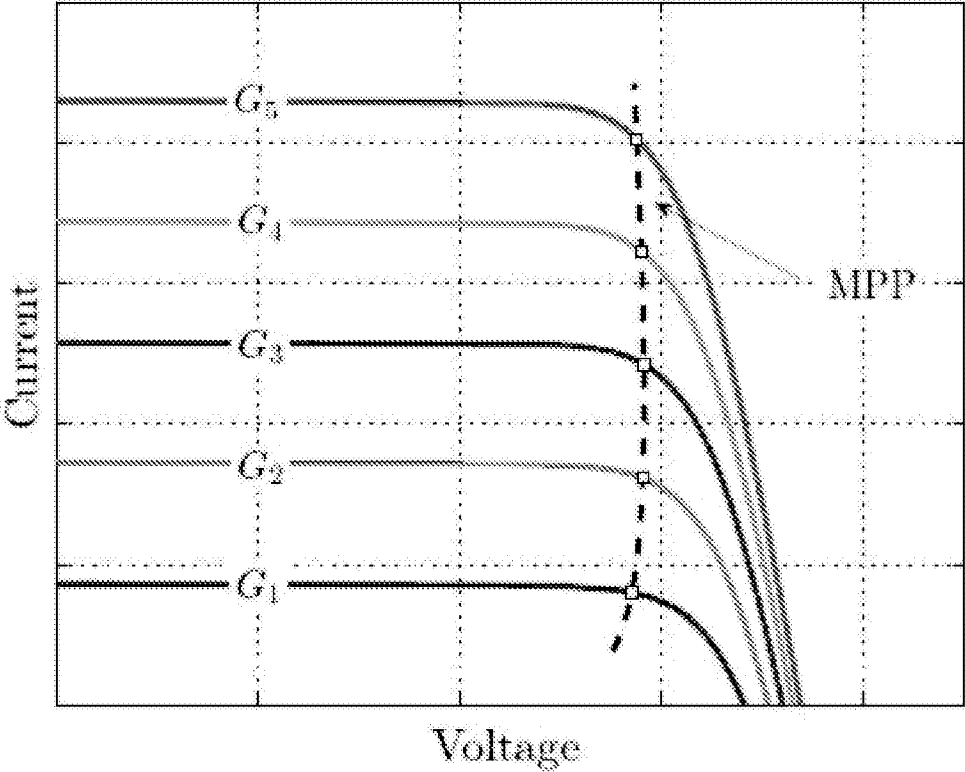


FIG. 1

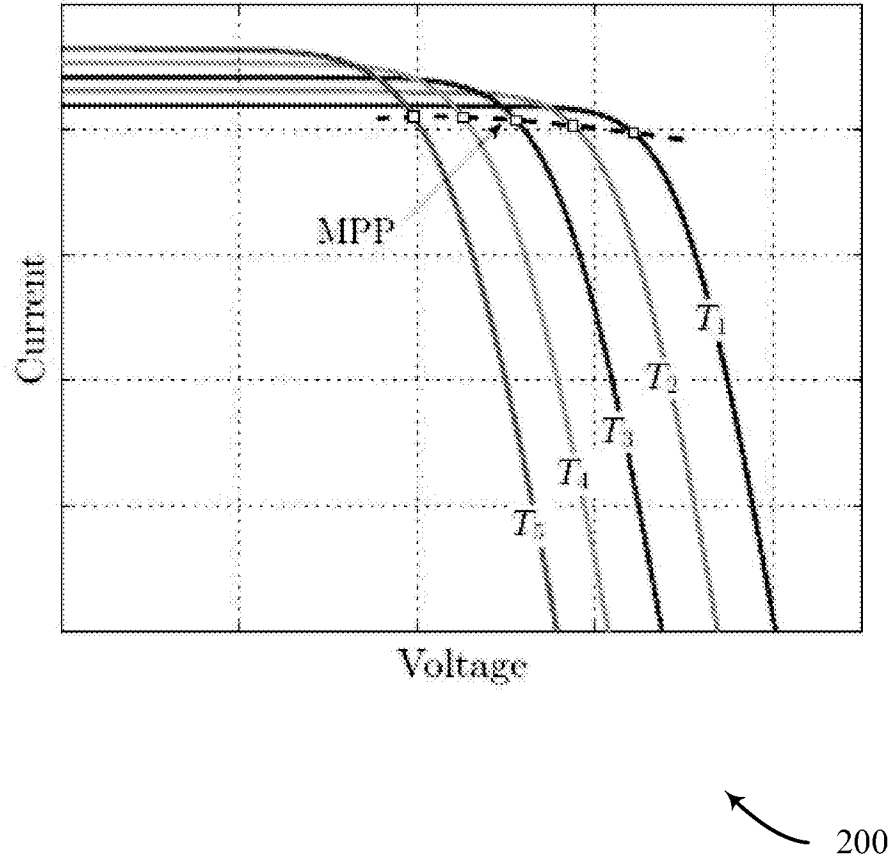


FIG. 2

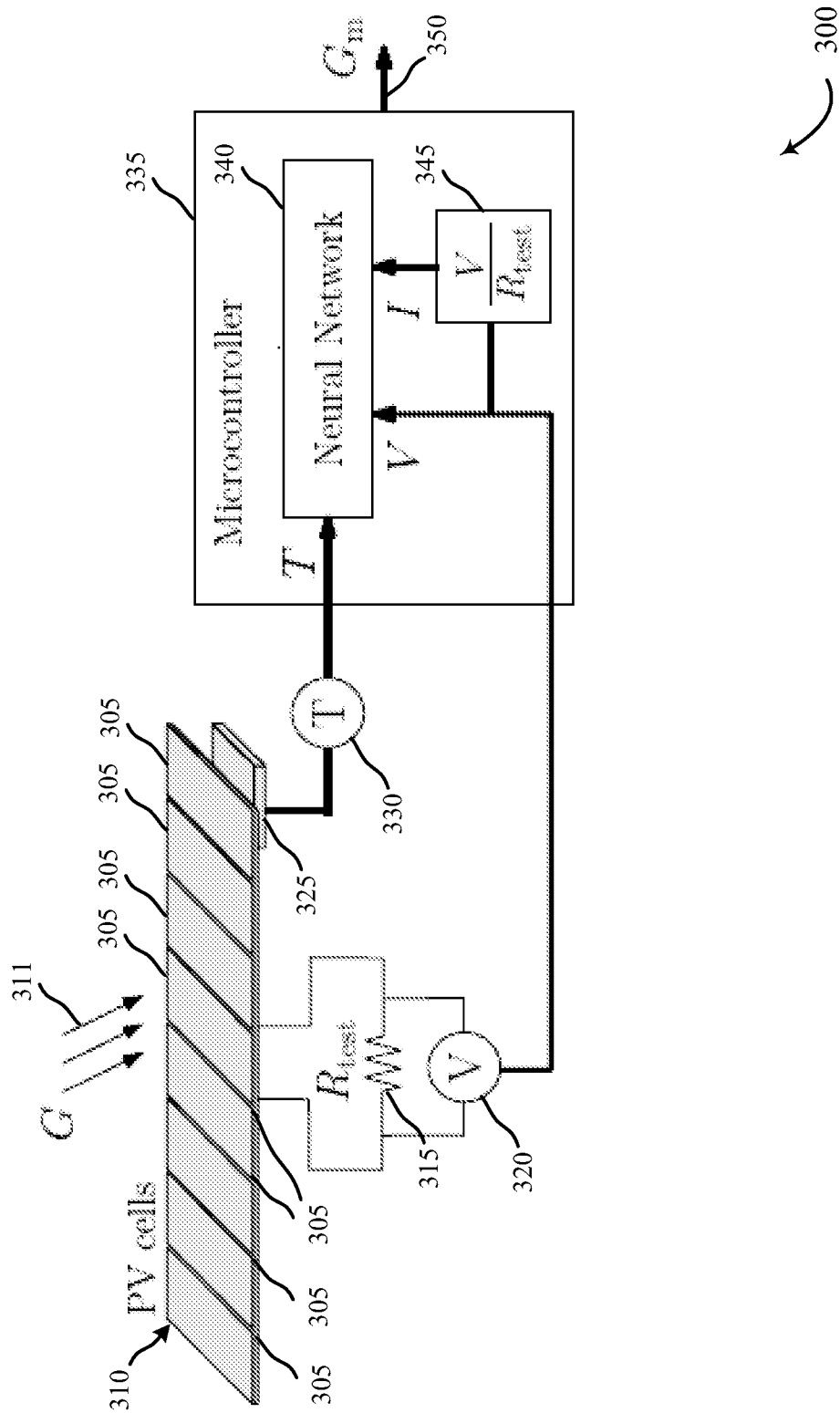


FIG. 3

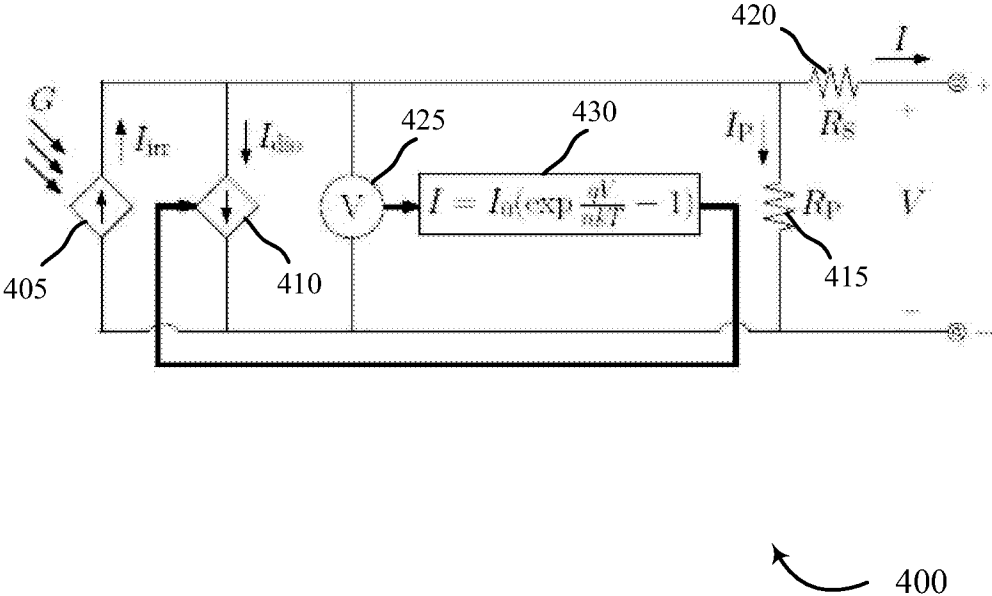
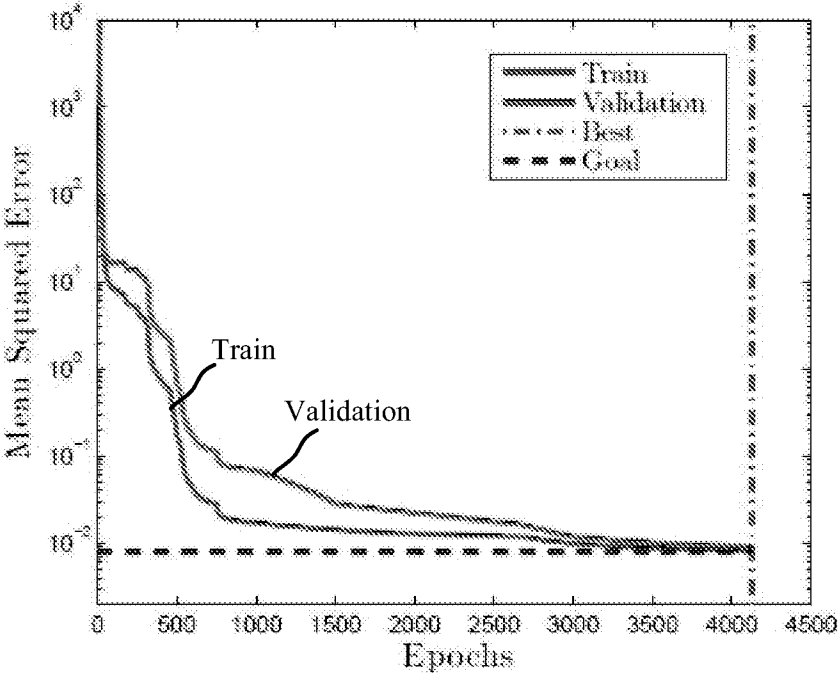


FIG. 4



500

FIG. 5

6/11

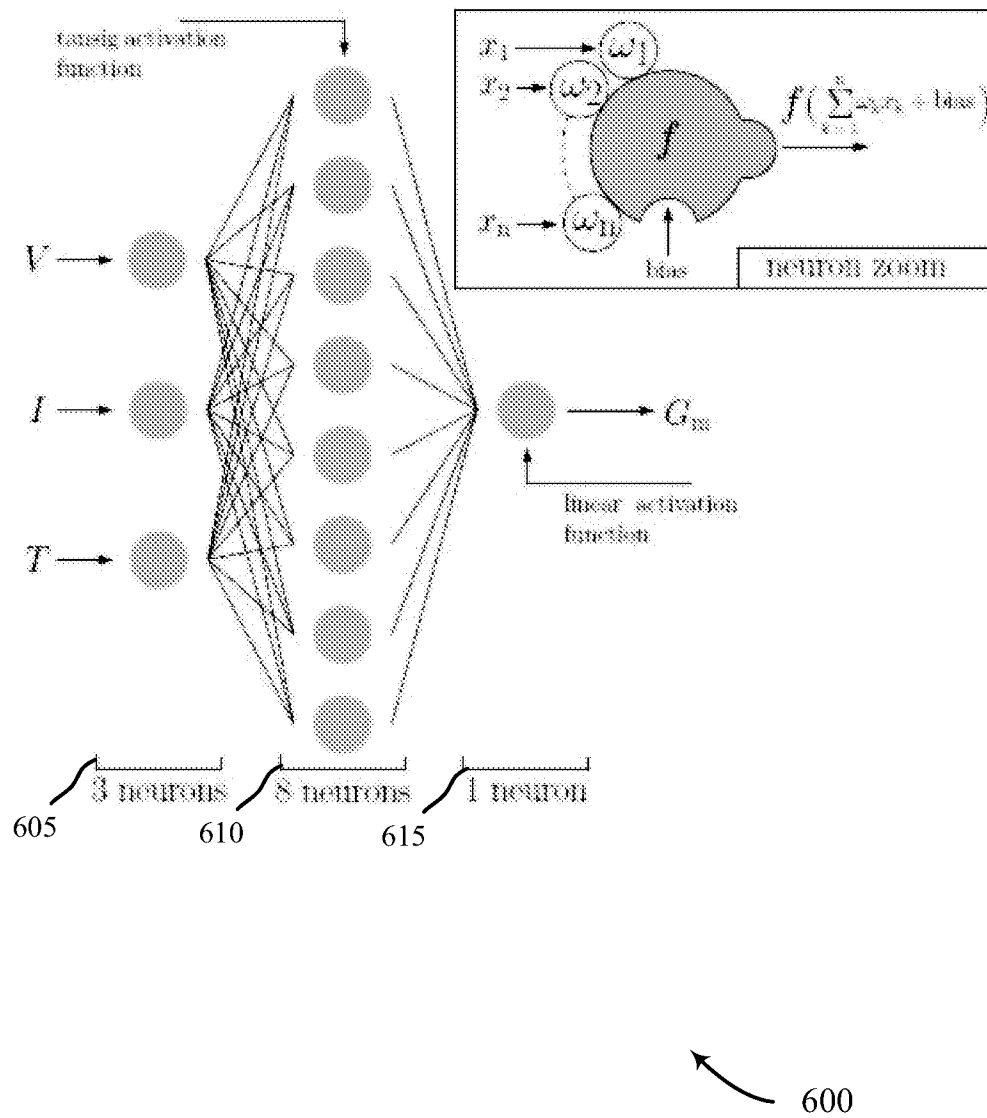


FIG. 6

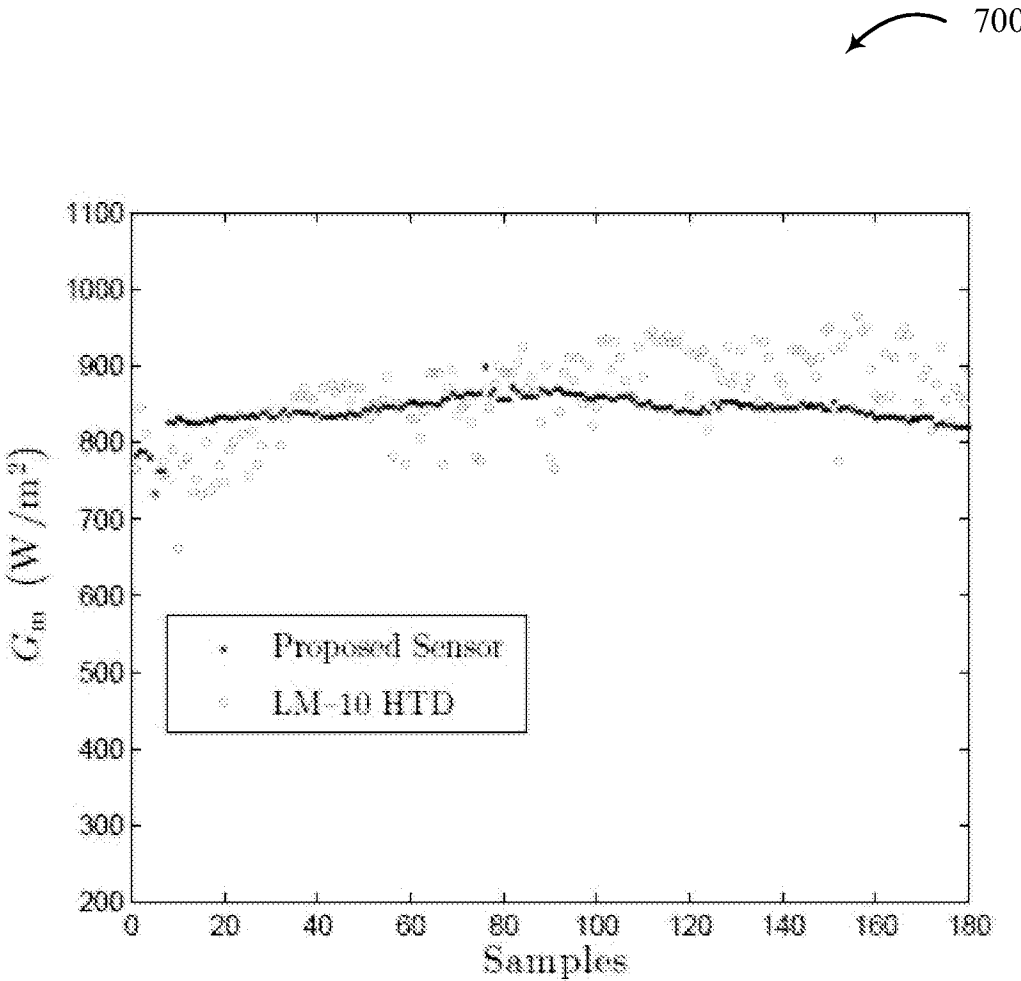
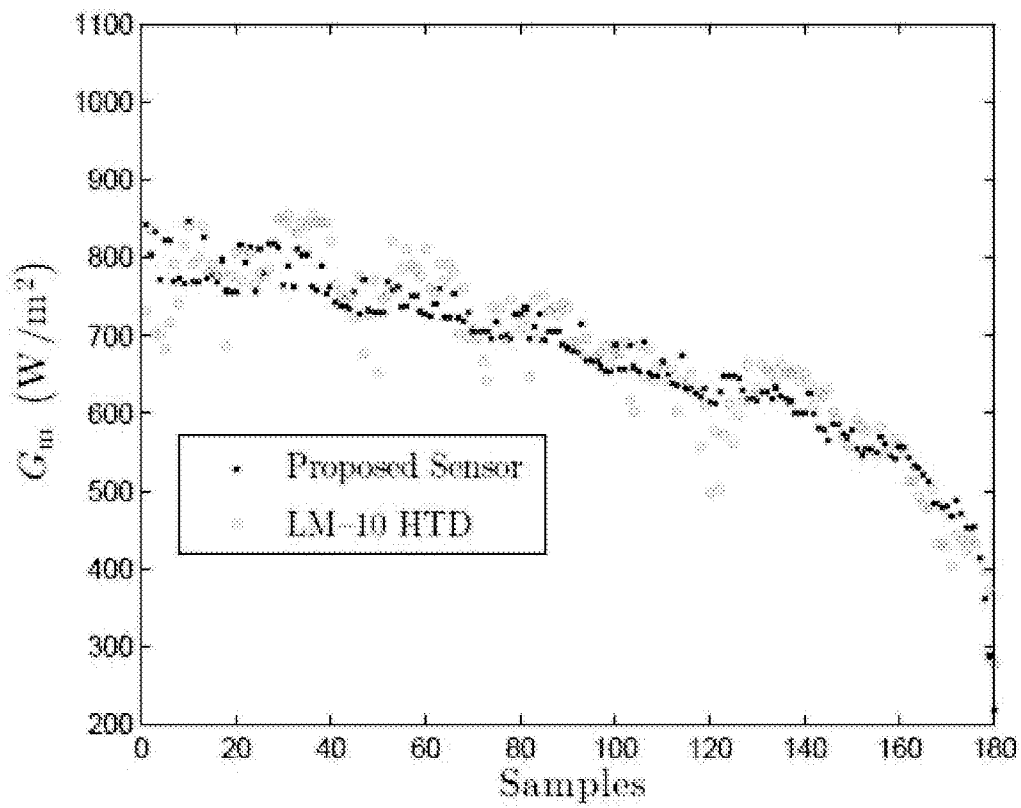
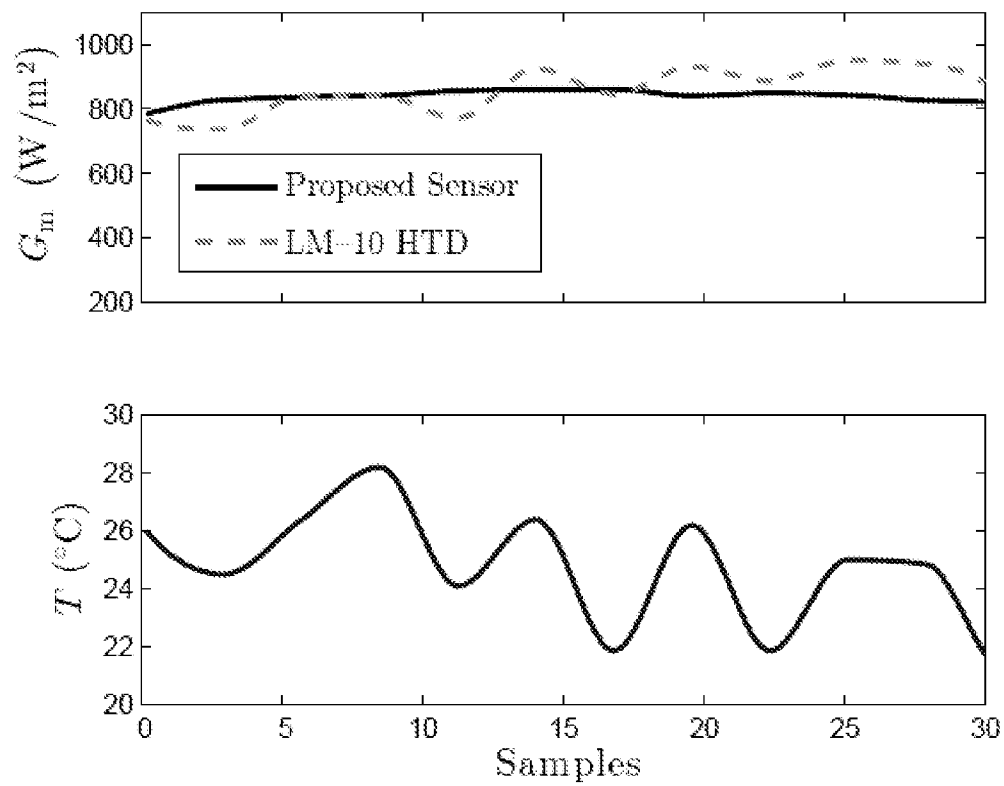


FIG. 7



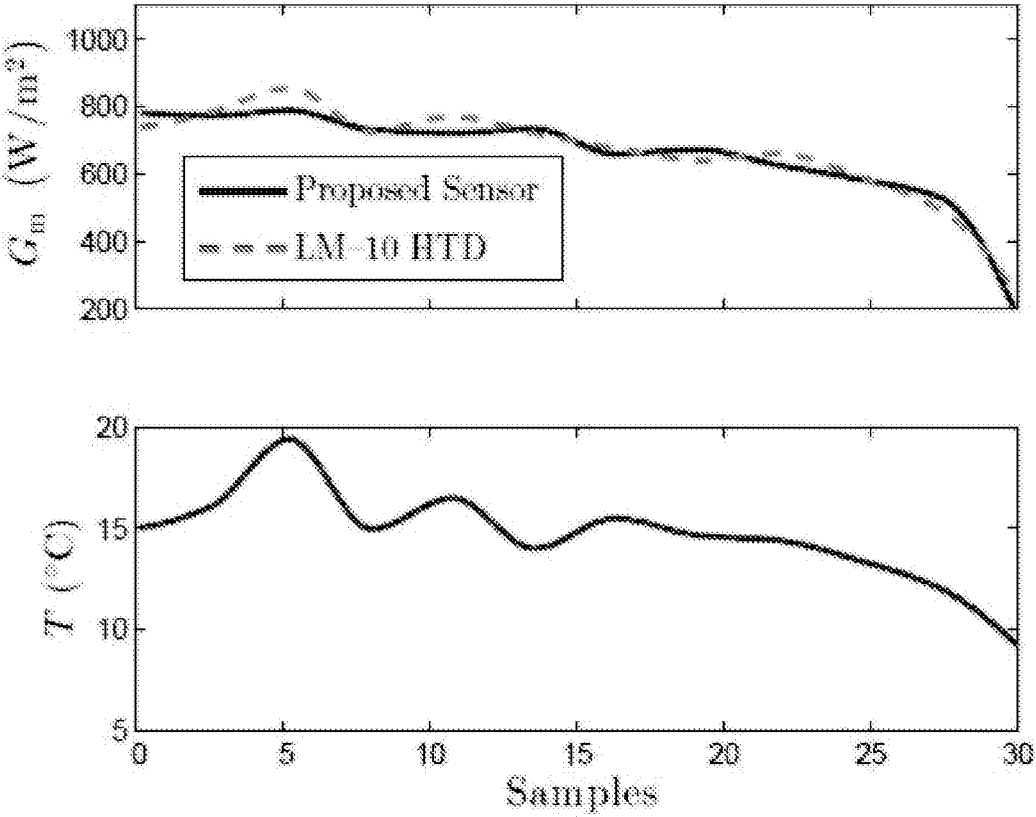
800

FIG. 8



900

FIG. 9



1000

FIG. 10

11/11

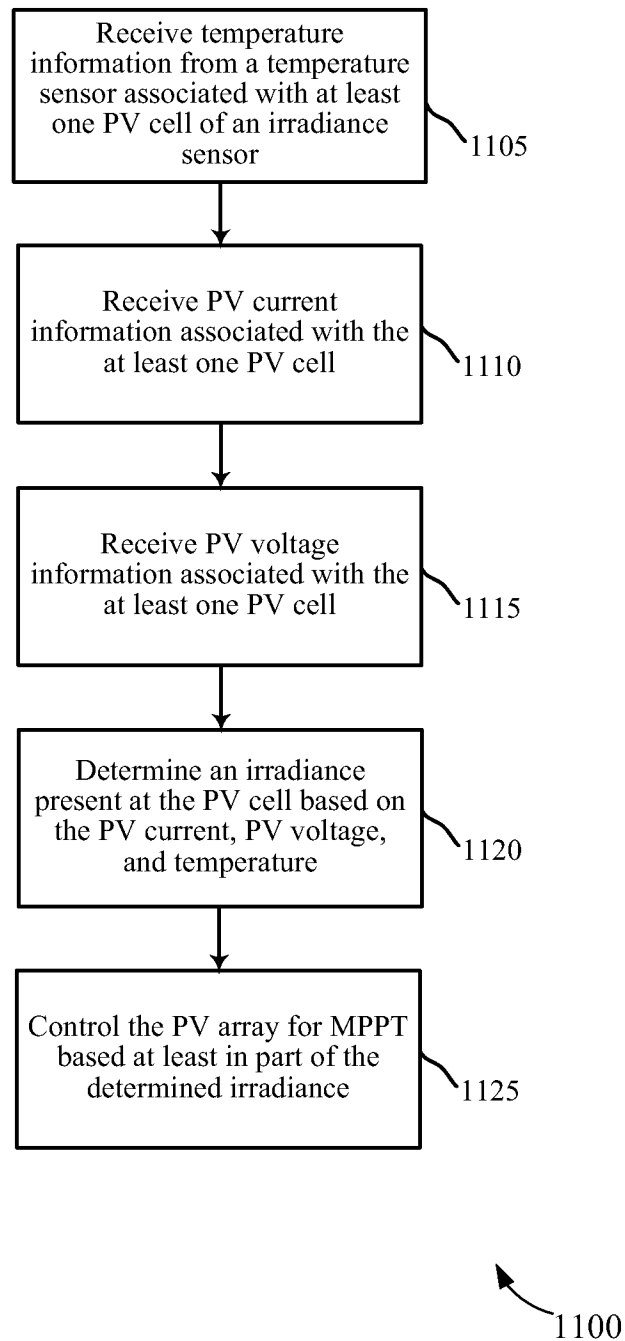


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/028702**A. CLASSIFICATION OF SUBJECT MATTER****G01J 1/02(2006.01)i, H02S 50/00(2014.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01J 1/02; G05B 13/04; G06F 1/28; H02J 1/00; G06F 19/00; G01W 1/00; G01R 33/02; H01L 31/042; H02S 50/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: photovoltaic cell, temperature sensor, PV current, PV voltage, irradiance, Maximum Power Point tracking**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2011-0178641 A1 (ZACHARY JUDKINS) 21 July 2011 See abstract, paragraph [0018] and claims 1, 7, 21, 22.	1-19
Y	WO 2012-074808 A2 (DOW GLOBAL TECHNOLOGIES LLC.) 07 June 2012 See abstract, paragraph [0022], claims 1, 4, 16, 18 and figures 1A, 2B.	1-19
Y	US 2012-0068543 A1 (ALESSANDRO CARAGLIO et al.) 22 March 2012 See abstract, paragraph [0080] and claims 17-19, 26.	2-6, 15-19
A		1, 7-14
A	US 2011-0224839 A1 (CHRISTOPHER THOMPSON) 15 September 2011 See abstract, paragraph [0013] and claims 1-9.	1-19
A	US 2010-0318297 A1 (MICHAEL HERZIG et al.) 16 December 2010 See abstract, paragraphs [0058], [0063]-[0068], [0074] and claims 1, 4-9.	1-19
A	WO 2010-042533 A2 (ATONOMETRICS, INC.) 15 April 2010 See abstract, paragraphs [0070]-[0074] and claims 1, 2.	1-19



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

18 July 2014 (18.07.2014)

Date of mailing of the international search report

18 July 2014 (18.07.2014)

Name and mailing address of the ISA/KR

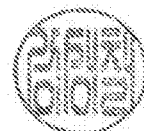
International Application Division
Korean Intellectual Property Office
189 Cheongsu-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
Republic of Korea

Facsimile No. +82-42-472-7140

Authorized officer

KANG, Sung Chul

Telephone No. +82-42-481-8405



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2014/028702

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2011-0178641 A1	21/07/2011	US 2013-269754 A1 US 8455806 B2	17/10/2013 04/06/2013
WO 2012-074808 A2	07/06/2012	CN 103250260 A EP 2647055 A2 US 2013-0321013 A1 WO 2012-074808 A3	14/08/2013 09/10/2013 05/12/2013 28/02/2013
US 2012-0068543 A1	22/03/2012	EP 2436094 A1 IT PI20090067 A1 WO 2010-136968 A1	04/04/2012 28/11/2010 02/12/2010
US 2011-0224839 A1	15/09/2011	CN 102893264 A WO 2011-112780 A1	23/01/2013 15/09/2011
US 2010-0318297 A1	16/12/2010	US 2008-0195561 A1 US 2009-0144000 A1 US 2010-0219983 A1 US 2010-0271222 A1 US 7742897 B2 US 8190395 B2 US 8725459 B2	14/08/2008 04/06/2009 02/09/2010 28/10/2010 22/06/2010 29/05/2012 13/05/2014
WO 2010-042533 A2	15/04/2010	WO 2010-042533 A3	05/08/2010