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Method of adaptive solar tracking using variable step size

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(12) **United States Patent**
Mikhael et al.

(10) **Patent No.: US 8,552,286 B2**
(45) **Date of Patent: Oct. 8, 2013**

(54) **METHOD OF ADAPTIVE SOLAR TRACKING USING VARIABLE STEP SIZE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **13/674,252**

(22) Filed: **Nov. 12, 2012**

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US 2013/0068283 A1 Mar. 21, 2013

Related U.S. Application Data

(62) Division of application No. 13/217,016, filed on Aug. 24, 2011, now Pat. No. 8,338,695.

(60) Provisional application No. 61/376,480, filed on Aug. 24, 2010.

(51) **Int. Cl.**

G01J 1/20	(2006.01)
G01C 21/02	(2006.01)
G05B 13/02	(2006.01)

(52) **U.S. Cl.**

USPC **136/246**; 136/244; 250/201.1; 250/203.1; 250/203.4; 700/38

(58) **Field of Classification Search**

USPC 136/244, 246; 700/38; 250/200–205

See application file for complete search history.

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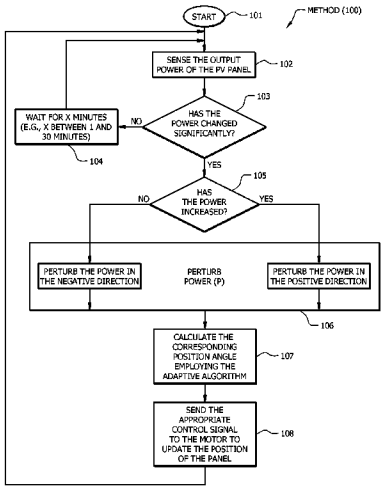
(57) **ABSTRACT**

A method for controlling a photovoltaic (PV) panel in a PV system including a computing device that provides motor control signals and implements an iterative adaptive control (IAC) algorithm for adjusting an angle of the PV panel. The IAC algorithm relates P at a current time k (P(k)), an elevation angle of the PV panel at k (θ_S(k)), P after a next step (P(k+1)) and an elevation angle of the PV panel at k+1 (θ_S(k+1)). The algorithm generates a perturbed power value P(k+1) to provide a power perturbation to P(k), and calculates θ_S (k+1) using P(k+1). The motor control signals cause the motor to position the PV panel to achieve θ_S (k+1). A change in P resulting from the positioning is compared to a predetermined change limit, and only if the change in P is ≥ the change limit, again sensing P, and repeating the generating, calculating and positioning.

8 Claims, 4 Drawing Sheets



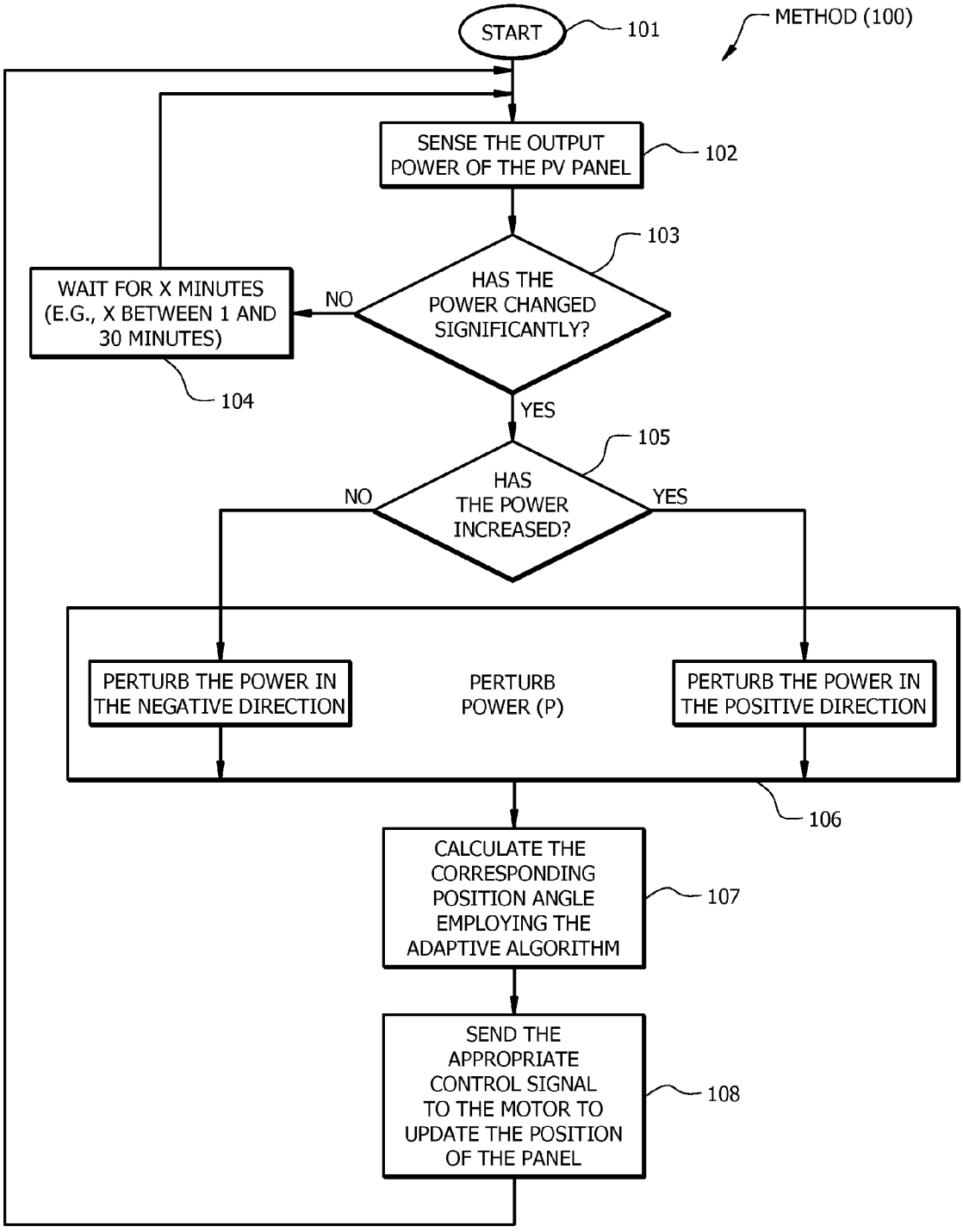

START
101
METHOD (100)
SENSE THE OUTPUT POWER OF THE PV PANEL
102
103
HAS THE POWER CHANGED SIGNIFICANTLY?
NO
WAIT FOR X MINUTES (E.G., X BETWEEN 1 AND 30 MINUTES)
104
YES
105
HAS THE POWER INCREASED?
NO
YES
PERTURB THE POWER IN THE NEGATIVE DIRECTION
PERTURB POWER (P)
PERTURB THE POWER IN THE POSITIVE DIRECTION
106
CALCULATE THE CORRESPONDING POSITION ANGLE EMPLOYING THE ADAPTIVE ALGORITHM
107
SEND THE APPROPRIATE CONTROL SIGNAL TO THE MOTOR TO UPDATE THE POSITION OF THE PANEL
108

FIG. 1

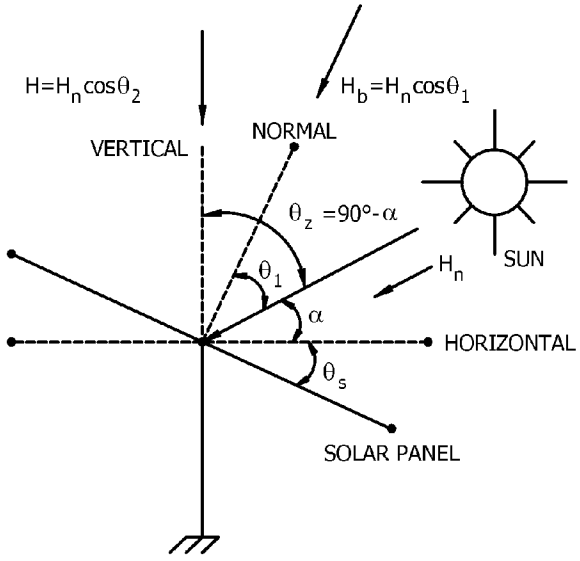

H=Hncosθ2
Hb=Hncosθ1
VERTICAL
NORMAL
θz =90°-α
θ1
Hn
SUN
α
HORIZONTAL
θs
SOLAR PANEL

FIG. 2

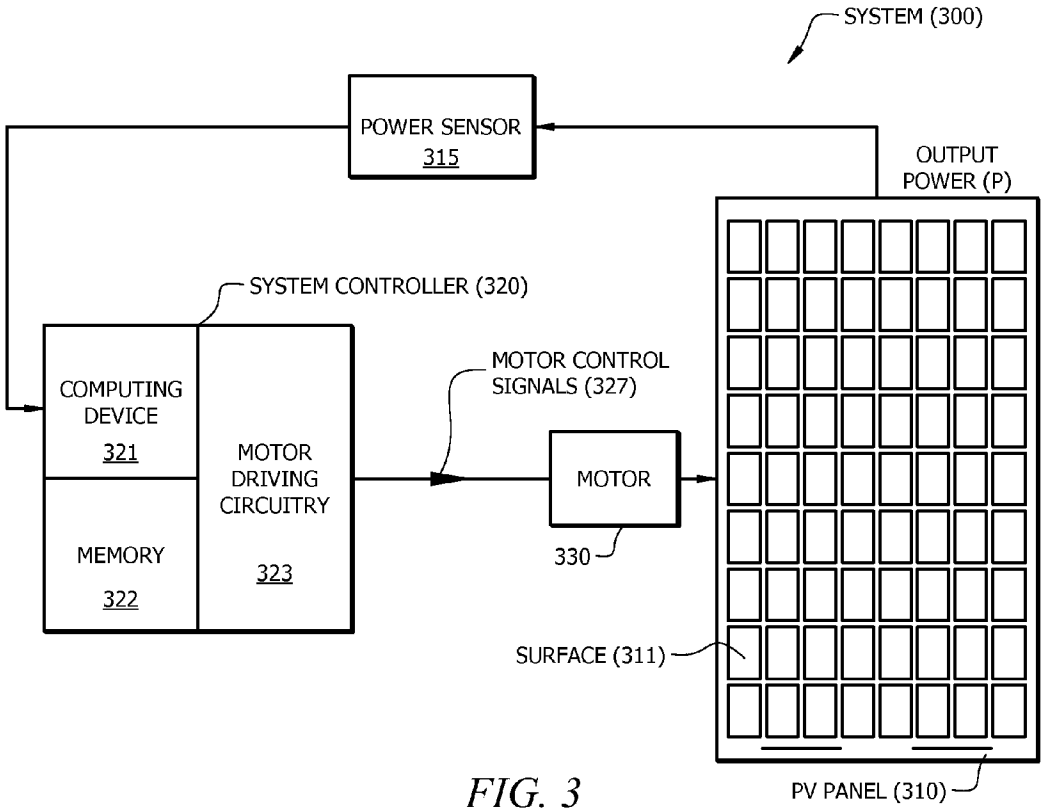
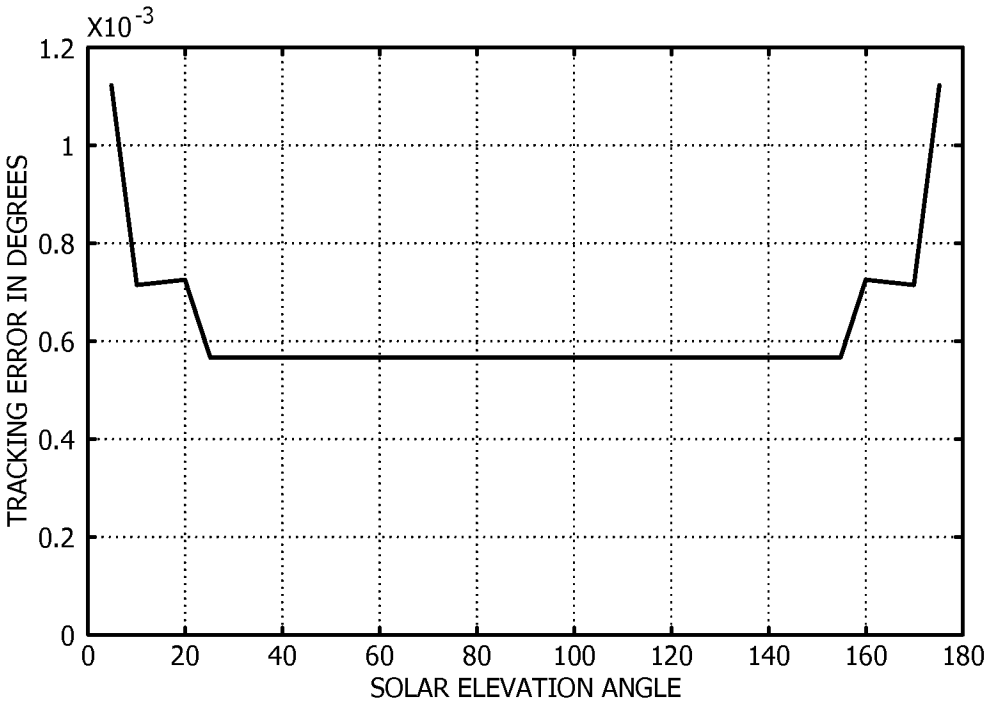
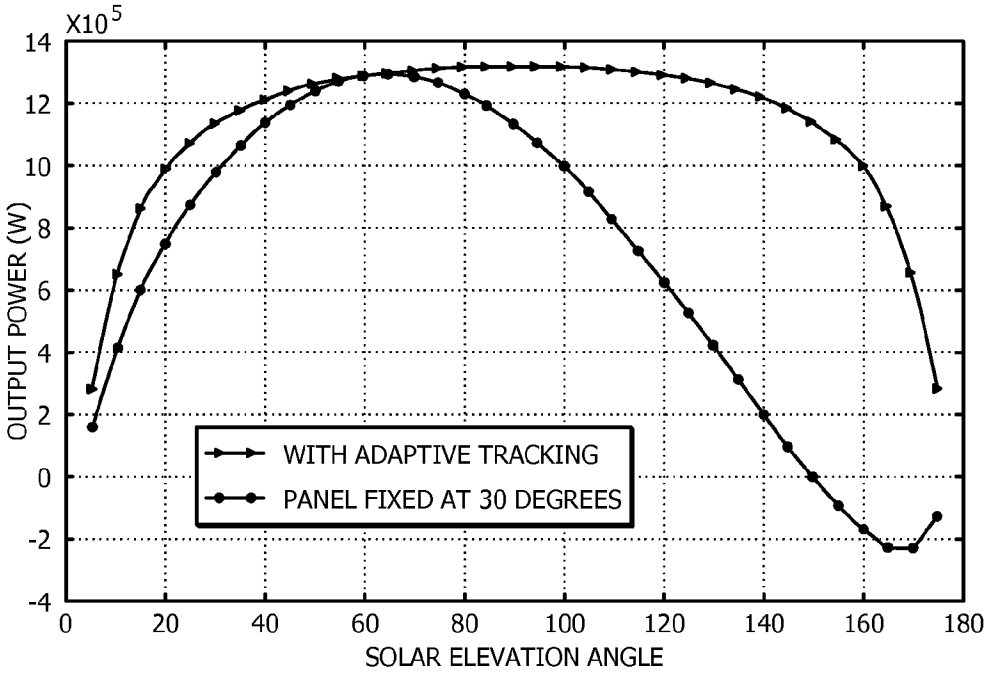

SYSTEM (300)
POWER SENSOR
315
OUTPUT
POWER (P)
SYSTEM CONTROLLER (320)
COMPUTING
DEVICE
321
MEMORY
322
MOTOR
DRIVING
CIRCUITRY
323
MOTOR CONTROL
SIGNALS (327)
MOTOR
330
SURFACE (311)
PV PANEL (310)

FIG. 3



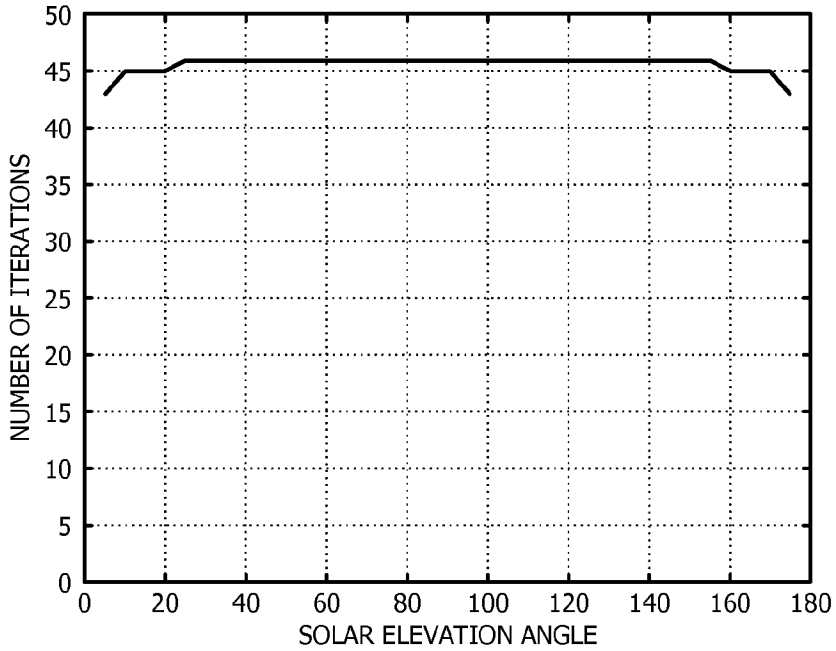
TRACKING ERROR VS. SOLAR ELEVATION ANGLE

FIG. 4



OUTPUT POWER VS. SOLAR ELEVATION ANGLE

FIG. 5



NUMBER OF ITERATIONS VS. SOLAR ELEVATION ANGLE

FIG. 6

METHOD OF ADAPTIVE SOLAR TRACKING USING VARIABLE STEP SIZE

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims is a divisional application of U.S. Non-Provisional patent application Ser. No. 13/217,016 entitled "ITERATIVE ADAPTIVE SOLAR TRACKING HAVING VARIABLE STEP SIZE", filed on Aug. 24, 2011, which is now U.S. Pat. No. 8,338,695, which claims the benefit of U.S. Provisional Patent Application No. 61/376,480 entitled "ITERATIVE ADAPTIVE SOLAR TRACKING HAVING VARIABLE STEP SIZE", filed on Aug. 24, 2010, both of which are incorporated by reference in their entirety into this application.

TECHNICAL FIELD

Disclosed embodiments relate to photovoltaics, and more specifically to photovoltaic systems having iterative solar tracking.

BACKGROUND

In solar technology, the photovoltaic (PV) panel orientation relative to the sun's rays determines power production. On a clear day, power is maximized when the solar panel is oriented normal to the direction sun's rays. During days with dubious weather, the actual maximum point of power production may not be exclusively based on the position of the sun due to atmospheric scattering. Also, because the sun's position in the sky moves throughout the day, the elevation angle for a solar panel needs to be changed several times each hour (e.g., every minute) to provide maximum output power. Over longer periods of time, the azimuth position for maximum power output changes as well, requiring the azimuthal angle of the solar panel to also be changed.

Sun tracking allows a PV panel to follow motion of the sun to help maximize power. Sun tracking and can be performed manually, or automatically. Conventional automation requires sensors to determine the location of the sun, or to have a pre-programmed tracking path to predict the position of the sun to obtain in an attempt to obtain maximum power throughout the day. These systems can be expensive and inaccurate. There is thus a need to create a more efficient system and method for automatic solar tracking.

SUMMARY

Disclosed embodiments describe iterative adaptive solar tracking that uses a variable step size for adjusting the angle of photovoltaic (PV) panel(s) which may be contrasted with known iterative solar tracking that uses a constant step size for angular adjustments of the PV panel. A PV system including solar tracking comprises at least one PV panel for receiving radiation, a power sensor for detecting output power (P) from the PV panel, and a system controller comprising at least one computing device (e.g., microprocessor or microcontroller) that provides motor control signals and implements a disclosed iterative adaptive control (IAC) algorithm.

The IAC algorithm includes an iterative relation that increases the output power P from the PV panel by iteratively adjusting its elevation angle θ_S, and optionally also the azimuthal angle θ_{AZ}, to track the position of the sun. The output power P is used as the performance function in the IAC algorithm which is maximized using an adaptive gradient ascent approach.

The IAC algorithm is based on the Inventors recognizing that the output power P depends on the maximum direct-beam solar radiation intensity H_n and the angle between the normal to the surface of the PV panel and the sun's rays θ_1. Since H_n varies with the time of day and year, and thus cannot be controlled, the IAC algorithm maximizes the output power P by minimizing θ_1. The PV system perturbs the output power P, and the perturbed power value is used in the iterative relation to adaptively estimate the corresponding position angle θ_S (and optionally also θ_{AZ}) for the PV panel(s) to achieve this perturbed power value. The resulting P is then measured. The iterative process can continue until there is no appreciable change in P.

Furthermore, at every iteration of the iterative relation, non-constant step sizes can be generated to update the position angles. This allows superior convergence properties for the IAC algorithm in terms of convergence speed, accuracy, and stability in contrast to known sun tracking methods that employ fixed step size angular position updates.

Also disclosed is a system controller for position controlling a PV panel in a PV system including a power sensor sensing output power (P), and a motor for positioning the PV panel. The system controller includes a computing device having memory that provides motor control signals and implements an IAC algorithm stored in the memory for adjusting an angle of the PV panel. The IAC algorithm includes an iterative relation that relates P at current time k (P(k)), its elevation angle at k (θ_S (k)), P after a next step (P(k+1)) and its elevation angle at k+1 (θ_S (k+1)). The IAC algorithm generates a perturbed power value P(k+1) to provide a power perturbation to P(k), and calculates a position angle θ_S (k+1) of the PV panel using the perturbed power value. The motor control signals from the computing device cause the motor to position the PV panel to achieve θ_S (k+1).

A method for controlling a PV panel in a PV system including a computing device that provides motor control signals and implements a disclosed IAC algorithm for adjusting the angle of the PV panel. The IAC algorithm relates P at a current time k (P(k)), an elevation angle of the PV panel at k (θ_S (k)), P after a next step (P(k+1)) and an elevation angle of the PV panel at k+1 (θ_S (k+1)). The algorithm generates a perturbed power value P(k+1) to provide a power perturbation to P(k), and calculates θ_S (k+1) using P(k+1). The motor control signals cause the motor to position the PV panel to achieve θ_S (k+1). A change in P resulting from the positioning is compared to a change limit, and only if the change in P is ≥ the change limit, again sensing p and then again generating, calculating and positioning.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a flow chart showing steps in an exemplary method of automatic solar tracking using a variable step size for adjusting the angle of a PV panel, according to a disclosed embodiment.

FIG. **2** is a diagram showing general geometric relationships between the sun and a planar PV panel.

FIG. **3** is a block diagram representation of an example PV system including a disclosed system controller that implements a disclosed sun tracking algorithm, according to a disclosed embodiment.

FIG. **4** is simulation data showing tracking error vs. solar elevation angle, according to a disclosed embodiment.

FIG. **5** is simulation data showing output power vs. solar elevation angle, according to a disclosed embodiment.

FIG. **6** is simulation data showing the number of iterations vs. solar elevation angle, according to a disclosed embodiment.

DETAILED DESCRIPTION

Disclosed embodiments in this Disclosure are described with reference to the attached figures, wherein like reference numerals are used throughout the figures to designate similar or equivalent elements. The figures are not drawn to scale and they are provided merely to illustrate the disclosed embodiments. Several aspects are described below with reference to example applications for illustration. It should be understood that numerous specific details, relationships, and methods are set forth to provide a full understanding of the disclosed embodiments. One having ordinary skill in the relevant art, however, will readily recognize that the subject matter disclosed herein can be practiced without one or more of the specific details or with other methods. In other instances, well-known structures or operations are not shown in detail to avoid obscuring structures or operations that are not well-known. This Disclosure is not limited by the illustrated ordering of acts or events, as some acts may occur in different orders and/or concurrently with other acts or events. Furthermore, not all illustrated acts or events are required to implement a methodology in accordance with this Disclosure.

Notwithstanding that the numerical ranges and parameters setting forth the broad scope of this Disclosure are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements. Moreover, all ranges disclosed herein are to be understood to encompass any and all sub-ranges subsumed therein. For example, a range of "less than 10" can include any and all sub-ranges between (and including) the minimum value of zero and the maximum value of 10, that is, any and all sub-ranges having a minimum value of equal to or greater than zero and a maximum value of equal to or less than 10, e.g., 1 to 5.

FIG. **1** is a flow chart showing steps in an example method **100** of automatic solar tracking using a variable step size for adjusting the angle of at least one PV panel, according to a disclosed embodiment. Step **101** shown as start comprises providing at least one PV panel having a panel surface for receiving solar radiation, a power sensor coupled to an output of the PV panel for sensing an output power (P) provided by the PV panel, and a system controller. The system controller includes at least one computing device (e.g., microprocessor) having an associated memory that provides motor control signals and implements an IAC algorithm stored in the memory for adjusting the angle of the PV panel. The IAC algorithm includes an iterative relation that relates the P at a current time k (P(k)), its elevation angle at k (θ_S (k)), P after a next step (P(k+1)) and its elevation angle at time k+1 (Θ_S (k+1)). The IAC algorithm can also adjust θ_{AZ}.

Step **102** comprises sensing the power output of the PV panel. Step **103** comprises calculating a change in P and determining whether P changed significantly (e.g., relative to a predetermined P change limit). Step **104** comprises waiting a predetermined waiting period (e.g., 1 to 30 minutes as shown in FIG. **1**) before returning to step **102** for another power sensor reading. Accordingly, at any point in the day, the method will wait for the predetermined waiting period between power sensor readings, and if there is no significant change in power (step **103**), the method will continue to wait another predetermined waiting period (e.g., 1 to 30 minutes). The predetermined waiting period will not measurably affect the performance of the system controlled by method **100** as the earth moves slowly around the sun.

During startup, the registers or other memory device associated with the power sensor that stores sensed P values for step **102** are generally initialized to 0. Hence, at startup there will be no change in P at step **103** and step **104** will redirect the method **100** at startup after the predetermined waiting period (e.g., 1 to 30 minutes as shown in FIG. **1**) for another P reading. As a result, there will not be an initial power perturbation (step **106**, described below) at startup until the power sensor in step **102** senses a non zero value of P. During daylight the sensed P is always positive, and when the sensed P is determined to be appreciable (step **103**), the method will find an increase in P (step **105**) and the method will reach step **106** (power perturbation).

During operation of method **100** following startup, the change in P determined in step **103** will be the change in P resulting from the updated PV panel position resulting from the positioning step described below (step **108**). As with startup, if the change in P is below a predetermined P change limit, step **104** is triggered which comprises waiting a predetermined waiting period then returning to step **102** for another power sensor reading. However, if the change in power at step **103** is at or above the pre-determined limit that defines an appreciable P change, step **105** is triggered which determines whether the P has increased or decreased to direct step **106** to perturb the power value for use in the iterative relation in the proper direction.

Step **106** comprises generating a perturbed power value P(k+1) to provide a power perturbation to the current P(k) for use in the iterative relation. The power can be perturbed in the positive or negative direction. Perturbing the power in the positive direction means increasing the power to be achieved, not the angle. As noted above, the angle is what is estimated by the IAC corresponding to the perturbed power. Likewise, perturbing power in the negative direction means decreasing the power to be achieved. If the output power P is increasing, the power perturbations continue to add a positive term to the current output power measurement (sensed at step **102**), and if the output power P has decreased, it is known the movement should be in the opposite direction. Therefore, a term is subtracted from the current output power measurement to provide a reduced perturbed power value.

Once step **106** generates a perturbed power value to be achieved, the method moves to step **107** to find the corresponding position angle to achieve this perturbed power value. Step **107** comprises calculating a position angle θ_S (k+1) using the value for perturbed power value in the iterative relation. As described below, the iterative relation uses a variable step size for adjusting θ_S that is based on both P(k+1) and P(k).

Step **108** comprises positioning the PV panel to achieve θ_S (k+1). The positioning can comprise sending a suitable control signal to a stepper motor to update the position of the PV panel to achieve θ_S (k+1). If the motor is a stepper motor, the control signal will be a pulse width modulation (PWM) signal. However, if a different type of motor is used, other signal modes can be used.

The method can optionally also apply a related IAC algorithm to also sun track the azimuthal position angle θ_{AZ} simultaneously with the elevation angle θ_S. It is noted that θ_{AZ} is known to not measurably change unless the change is measured in weeks.

FIG. **2** is a diagram showing general geometric relationships and relevant parameters between the sun and a planar PV panel for an embodiment that iteratively positions the θ_S for a solar panel, that is used in reference to the exemplary sun tracking algorithm described below. H is the power/area and H_b is the incident direct beam (maximum; being normal to the surface of the PV panel) solar radiation.

FIG. **3** is a block diagram representation of an example PV system **300** having a system controller that implements a disclosed sun tracking algorithm, according to a disclosed embodiment. System **300** includes at least one PV panel **310** comprising an interconnected assembly photovoltaic cells having a panel surface **311** for receiving solar radiation and convert the solar radiation to electrical power. Because a single PV panel **310** can produce only a limited amount of power, in a typical application there will be several PV panels.

A power sensor **315** is coupled to an output of the PV panel **310** for sensing the output power (P) provided by the PV panel. System **300** includes a system controller **320** including at least one computing device **321** (e.g., processor) having associated memory **322** and motor driving circuitry **323** that provides motor control signals **327**. System controller **320** implements an iterative adaptive control (IAC) algorithm that is stored in the memory **322** for adjusting an angle of the PV panel **310**. The IAC algorithm includes an iterative relation that relates P at a current time k (P(k)), its elevation angle at k (θs (k)), P after a next step (P(k+1)) and its elevation angle at k+1 (θs (k+1)), wherein the IAC algorithm is operable to generate a perturbed power value P(k+1) to provide a power perturbation to P(k), and calculate a position angle (k+1) of the PV panel **310** using P(k+1) in the iterative relation.

The system **300** also includes a mechanical system comprising a motor (e.g., a DC motor) **330** coupled to receive the motor control signals **327** provided by motor driving circuitry **323**. The motor control signals are configured for positioning the PV panel to achieve θs (k+1). Although shown in FIG. **3** controlling a single motor **330**, motor driving circuitry **323** can control a plurality of motors to allow control of the angular position of a plurality of PV panels.

Mathematical Description of an Exemplary Algorithm

One approach for iteratively adjusting θ_S for solar panels is described below in equation form as follows. Firstly, the following parameters are defined-k: iteration index, μ(k): step size of position angle increment/decrement at k, α: elevation angle of the sun which is an unknown.

The update equation for the position angle is given as:

$$\theta_S(k+1) = \theta_S(k) + \mu(k)\frac{\partial P(k)}{\partial \theta_S(k)} \tag{1}$$

The output power P of the PV panel is directly proportional to the incident direct beam solar radiation (H_b) given by the following relation:

$$P = H_b * A \tag{2}$$

where, A is the area of the PV panel.

Substituting (2) in (1), the following is obtained:

$$\theta_S(k+1) = \theta_S(k) + \mu(k)\frac{\partial H_b * A}{\partial \theta_S(k)} \tag{3}$$

H_b can be expressed as

$$H_b = H_n \cos(\theta_1) \tag{4}$$

where, H_n is the maximum direct-beam solar radiation intensity, and θ_1 is the angle between the normal to the PV panel surface and the sun's rays. As mentioned above, since no sensors are needed to measure the radiation received from the sun, H_n is estimated adaptively. Hence, substituting (4) in (3), the following is obtained:

$$\theta_S(k+1) = \theta_S(k) + \mu(k)\frac{\partial H_n \cos(\theta_1) * A}{\partial \theta_S(k)} \tag{5}$$

However, from FIG. **2**, it can be seen that at any point in time the following relation exists:

$$\theta_1 + \alpha + \theta_S = 90° \tag{6}$$

When the PV panel is tracking the sun, $\theta_1 = 0$, and correspondingly, $\alpha + \theta_S = 90°$.

Hence, substituting for θ_1 in (5), the following is obtained:

$$\theta_S(k+1) = \theta_S(k) + \mu(k)\frac{\partial H_n \cos(90 - \{\alpha + \theta_S\}) * A}{\partial \theta_S(k)} \tag{7}$$

Combining θ_S and α into one angle θ_γ, i.e. $\theta_S + \alpha = \theta_\gamma$, rewriting (1) as an optimization expression with respect to θ_γ as follows

$$\theta_\gamma(k+1) = \theta_\gamma(k) + \mu(k)\frac{\partial P(k)}{\partial \theta_\gamma(k)} \tag{8}$$

Therefore, (8) can be rewritten as

$$\theta_\gamma(k+1) = \theta_\gamma(k) + \mu(k)\frac{\partial H_n \sin(\theta_\gamma) * A}{\partial \theta_\gamma(k)} \tag{9}$$

Equations (10)-(13) described below provide a calculation of the step size. By evaluating (9) the following is obtained:

$$\theta_\gamma(k+1) = \theta_\gamma(k) + \mu(k) H_n \cos(\theta_\gamma) * A \tag{10}$$

Since the measured output power P is a function of θ_γ, P can be expanded in an expansion, such as in a second order Taylor's series expansion with respect to θ_γ as follows:

$$P(k+1) = P(k) + \frac{\partial P(k)}{\partial \theta_\gamma(k)}\Delta\theta_\gamma(k) + \frac{1}{2!}\frac{\partial^2 P(k)}{\partial \theta_\gamma(k)^2}[\Delta\theta_\gamma(k)]^2 \tag{11}$$

It is possible to use a Taylor series of 3rd order, or higher than 3rd order. However, raising the order beyond 2nd order does not generally result in any appreciable increase in accuracy. In addition, it significantly increases the computational complexity of the algorithm. From (10), the following is obtained

$$\Delta\theta_\gamma(k) = \mu(k) H_n \cos(\theta_\gamma) * A \tag{12}$$

Substituting (12) in (11), and performing the following derivative,

$$\frac{\partial P(k+1)}{\partial \mu(k)} = 0 \tag{13}$$

the following expression is obtained:

$$\theta_\gamma(k+1)=\theta_\gamma(k)-\cot(\theta_\gamma)/2 \tag{14}$$

Rewriting (14) as follows:

$$\theta_\gamma(k+1) = \theta_\gamma(k) - \frac{H_n A * \cos(\theta_\gamma)}{2 * H_n A * \sin(\theta_\gamma)} \tag{15}$$

From (2), (4), and (6), it is known that

$$P=H_nA*\cos(\theta_1)=H_nA*\sin(\theta_\gamma) \tag{16}$$

Therefore,

$$H_n A * \cos(\theta_\gamma) = \sqrt{H_n^2 A^2 - P^2} \tag{17}$$

Hence, substituting (16) and (17) in (15), the following is obtained:

$$\theta_\gamma(k+1) = \theta_\gamma(k) - \frac{H_n\sqrt{1-\frac{P(k)^2}{A^2H_n^2}}}{2 * P(k)/A} \tag{18}$$

Simplifying (18), the following position angle update equation results

$$\theta_\gamma(k+1) = \theta_\gamma(k) - \frac{\sqrt{A^2H_n^2 - P(k)^2}}{2 * P(k)} \tag{19}$$

Since the parameter being controlled is the position angle θ_S of the solar panel, (19) can be rewritten as:

$$\theta_S(k+1) = \theta_S(k) - \frac{\sqrt{A^2H_n^2 - P(k)^2}}{2 * P(k)} \tag{20}$$

The adaptive system may continue adjusting θ_S by the optimal amount represented by the ratio term in (20) at each iteration, until $\theta_S+\alpha=90°$, and the panel is directly facing the sun and/or the maximum power position. Since (20) contains H_n which is unknown, the output power P(k) is perturbed to a new value P(k+1) to provide a power perturbation to P(k) and θ_S(k+1) is adaptively derived in each case, until the peak power H_n*A is achieved. Hence, (20) can be rewritten as the following iterative relation:

$$\theta_S(k+1) = \theta_S(k) - \frac{\sqrt{P(k+1)^2 - P(k)^2}}{2 * P(k)} \tag{21}$$

The output power P(k) is perturbed as follows,

$$P(k+1)=P(k)+[\mathrm{sgn}(P(k)-P(k-1))]*(P(k)-P(k-1)) \tag{22}$$

where, sgn is the signum function which as known in mathematics extracts the sign of a real number. Thus the step size for an increment or decrement of θ_S(k+1) is non-constant and generally changes with each step according to the above equations based on P(k) and P(k+1).

Depending on the season and time of the year, an analogous IAC algorithm based on the description above may be followed for adjusting θ_{AZ}. However, as noted above, since θ_{AZ} generally changes much more gradually as compared to θ_S, the adjustment to θ_{AZ} needed is substantially less frequently (e.g., weekly or monthly) as compared to θ_S.

EXAMPLES

Disclosed embodiments of the invention are further illustrated by the following specific Examples, which should not be construed as limiting the scope or content of this Disclosure in any way.

Simulation results were generated using MATLAB software by varying the solar elevation angle from 0 to 180 degrees (sunrise to sunset), and calculating the tracking error and speed of convergence in each case, after a disclosed IAC algorithm converges. For each elevation angle α, the corresponding direct beam intensity H_n in (4) can be calculated according to the equation given by

$$H_n=B*\exp[-C/\sin(\alpha)] \tag{23}$$

where, B and C are site and climate related constants.

Initially, the PV panel was modeled as facing east during sunrise, i.e. α=0, and position angle θ_S=90°. As the day progressed, and a increased from 0 to 180°, the IAC algorithm automatically updated θ_S in optimal steps to align the sun's direct rays with the normal to the PV panel. Thus, the adaptive system was able to track changes in α, and correspondingly H_n, without any prior knowledge or measurement of these parameters. In this manner, peak power H_n*A was produced by the panel throughput the day.

The resulting tracking error vs. the solar elevation angle is plotted in FIG. **4**. The corresponding output power achieved by the IAC algorithm, in comparison to a PV panel fixed at 30° position angle is shown in FIG. **5**. The convergence speed, in terms of number of iterations required to converge in each case, is illustrated in FIG. **6**.

From the simulation results, it is evident that the IAC algorithm yields excellent tracking accuracy of the order of 10^{-3}, with a significant increase in power output as compared to a fixed PV panel. Furthermore, the IAC algorithm consistently converges in less than 50 iterations, demonstrating fast adaptation to the changes in the elevation angle of the sun.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement which is calculated to achieve the same purpose may be substituted for the specific embodiments shown. This application is intended to cover adaptations or variations of the present subject matter. It is to be understood that the above description is intended to be illustrative, and not restrictive. Combinations of the above embodiments, and other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the present subject matter should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

The examples that are described in the above description provide sufficient detail to enable those skilled in the art to practice the subject matter, and serve to illustrate how the subject matter may be applied to various purposes or embodiments. References to "an", "a", "one", or "some" embodi-

ments in this disclosure are not necessarily to the same embodiment, and such references may contemplate more than one embodiment. Other embodiments may be utilized, and structural, logical, and electrical changes may be made without departing from the scope of the present disclosure.

This disclosure is intended to cover any and all adaptations or variations of various embodiments. Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which embodiments belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

We claim:

1. A method for automatic solar tracking for a photovoltaic (PV) system including at least one PV panel having a panel surface for receiving solar radiation, comprising:

providing an iterative adaptive control (IAC) algorithm that includes an iterative relation that relates an output power (P) at a current time k (P(k)), an elevation angle of said PV panel at k (θ_S (k)), said P after a next step (P(k+1)) and an elevation angle of said PV panel at k+1 (θ_S (k+1));

generating, using at least one computing device, a perturbed output power value P(k+1) to provide a power perturbation to said P(k),

calculating, by said computing device, said θ_S (k+1) using said value for said P(k+1) in said iterative relation, and

positioning said PV panel to achieve said θ_S (k+1);

sensing said P with said PV panel positioned at said θ_S (k+1);

wherein said IAC algorithm further implements:

comparing a change in said P resulting from said positioning to a predetermined P change limit, and

if said change in said P is ≥ said predetermined P change limit, repeating said sensing said P and said generating, calculating and said positioning, and

if said change in said P < said predetermined P change limit, waiting a predetermined waiting period before repeating said sensing said P and said generating, calculating and said positioning.

2. The method of claim **1**, wherein said iterative relation comprises:

$$\theta_S(k+1) = \theta_S(k) - \frac{\sqrt{P(k+1)^2 - P(k)^2}}{2 * P(k)}.$$

3. The method of claim **1**, wherein said P(k+1) is generated by the following equation:

$$P(k+1)=P(k)+[\mathrm{sgn}(P(k)-P(k-1))]*(P(k)-P(k-1))$$

wherein said sgn is the signum function.

4. The method of claim **1**, further comprising implementing an iterative adaptive control algorithm for iteratively adjusting an azimuthal angle θ_{AZ} of said PV panel.

5. The method of claim **1**, wherein said method is exclusive of photosensors for sensing said solar radiation received by said PV panel.

6. The method of claim **1**, wherein said predetermined waiting period is 1 to 30 minutes.

7. The method of claim **1**, wherein a stepper motor is used for said positioning, said stepper motor controlled by a pulse width modulation (PWM) signal.

8. The method of claim **1**, wherein said computing device comprises a microprocessor.

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