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Maximum Power Point charge Controller for DC-DC Power Conversion in Solar PV System

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1. INTRODUCTION

Photovoltaic production becomes double every two years, increasing by an average of 48 percent each year since 2002. For this reason it becomes the world's fastest-growing energy technology [1]. Photovoltaic efficiency is very important for solar application. Photo-voltaic (PV) panels (sometimes referred to as photovoltaic modules) produce current at a specific voltage depending on the amount of solar radiation hitting the cells of the panel. The theoretical maximum amount of power from the sun at the earth's surface is about 1 KW per square meter at the equator on a clear day. To make the electrical power useful when the sun is not available, it must be stored, typically in batteries. The nature of the PV panels is that they have a specific Voltage × Current curve that changes with the temperature and on the amount of sunlight or the angle at which the sun strikes the panel. Higher temperatures lower the voltage and more sunlight increases the output current. Distributed photovoltaic generation, in the form of roof-top domestic systems, is being installed at an increasing scale [2-4]. Significant power quality issues, especially voltage rise and voltage unbalance have been widely studied [5, 6]. Higher penetrations or renewable generation within the distribution network can be achieved by the addition of intelligent control, storage or regulatory devices, [7].

In this case charge controller plays a vital role to protect the battery [8]. A series charge controller disables further current flow into batteries when they are full. A shunt charge controller diverts excess electricity to an auxiliary or "shunt" load, such as an electric water heater, when batteries are full [8, 9]. For increased

system efficiency, it is desirable to operate PV panels at the voltage and current levels that produce the peak power, which is referred to as the Maximum Power Point [8, 10]. The Proposed charge controller performs DC-DC power conversion typically utilizing Pulse Width Modulation (PWM) control of the electrical energy produced by the PV panels in order to transform such energy into a suitable form [11].

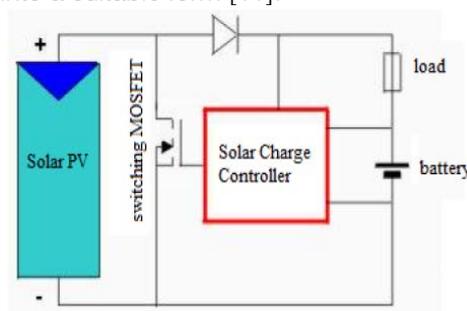


Figure 1A : SHS with series controller [8]

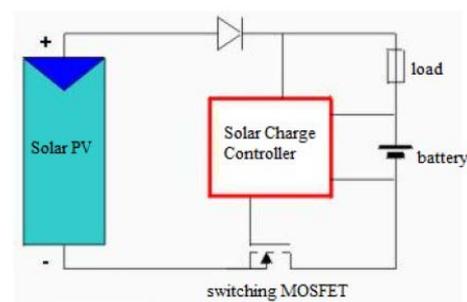


Figure 1B : SHS with shunt controller Charge [8]

A charge controller is needed in photovoltaic system to safely charge sealed lead acid battery [12]. The most basic function of a charge controller is to prevent battery overcharging. If battery is allowed to routinely overcharge, their life expectancy will be dramatically reduced [13]. A charge controller will sense the battery voltage, and reduce or stop the charging current when the voltage gets high enough [14]. This is especially important with sealed lead acid battery where we cannot replace the water that is lost during overcharging. Unlike Wind or Hydro System charge controller, PV charge controller can open the circuit when the battery is full without any harm to the modules [15]. Most PV charge controller simply opens or restricts the circuit between the battery and PV array when the voltage rises to a set point [16]. Then, as the battery

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absorbs the excess electrons and voltage begins dropping, the controller will turn back on [17].



Figure 1C : Basic image of controller and battery wiring [18]

Charge controller has been regarded as one of the important devices in stand-alone photovoltaic systems to prevent the battery from damage due to over-charging and over-discharging [20]. Besides that, the unstable voltage from photovoltaic systems may spoil the load [19]. Studies show that the life time of the battery is degraded without using charge controller [21]. Therefore, a charge controller should be designed to prolong the battery's life time and stabilize the voltage from photovoltaic panel [22].

II. BACKGROUND OF THE INVENTION

a) Field of the Invention

This invention relates broadly to charge controllers that perform DC-DC power conversion. More particularly, this invention relates to charge controllers for solar applications, including converting DC electrical energy provided by photo-voltaic means for charging electrochemical batteries and for direct output [23-29].

b) State of the Art

Photo-voltaic (PV) panels (sometimes referred to as photovoltaic modules) produce current at a specific voltage depending on the amount of solar radiation hitting the cells of the panel. The theoretical maximum amount of power from the sun at the earth's surface is about 1 KW per square meter at the equator on a clear day. To make the electrical power useful when the sun is not available, it must be stored, typically in batteries. The nature of the PV panels is that they have a specific Voltage \times Current curve that changes with the temperature and on the amount of sunlight or the angle at which the sun strikes the panel [30-36]. Higher temperatures lower the voltage and more sunlight increases the output current.

For increased system efficiency, it is desirable to operate PV panels at the voltage and current levels

that produce the peak power, which is referred to as the Maximum Power Point. Loads such as batteries, on the other hand, have a need for voltage and current which is independent and often different from what the PV panel is producing. A charge controller (which can also be referred to as a charge regulator or regulator) is connected between the PV panel(s) and the batteries or load in order to deal with this miss-match. The charge controller performs DC-DC power conversion typically utilizing Pulse Width Modulation (PWM) control of the electrical energy produced by the PV panels in order to transform such energy into a suitable form. For example, for battery charging applications, the PWM control is used to adjust the voltage levels and current levels output the battery [37-42]. More particularly, as the battery reaches full charge, the PWM control is used to limit the voltage level supplied to the battery such a not to the harm the battery (i.e., inhibiting the boiling of the electrolyte of the battery, which can destroy the battery). Early charge controllers were only able to reduce the amount of voltage from the PV panels if too high for the batteries. Since the voltage from the PV panels would be lower at high temperatures, the PV panels had to be over sized to ensure that the minimum voltage at high temperatures would be at least as high as the battery to be charged plus voltage headroom enough to force current into the battery [43-48]. At any temperature lower than the maximum, the excess voltage from the PV panels would have to be discarded by the charge controllers. Because PV panels are the most expensive component of the system, the need for extra (or larger) PV panels negatively impacted the cost-effectiveness of such PV power systems [49-55].

Newer and more efficient charger controllers have emerged that provide a better match between the PV panels and their load. Their goal is to use all the power from the PV panel(s) regardless of the voltage and current at any amount of insolation or at any temperature. The newer charge controllers employ a DC to DC converter section that is adapted to dynamically charge the battery (or to directly power a load) at the exact voltage and current that is most appropriate for that battery (or load). Although the newer charge controllers provide improved system efficiencies relative to the older models, they too often suffer from several shortcomings. More particularly, the charge controllers are slow to adapt to changing conditions of the PV panel(s) over the course of any given day, including low light conditions in the morning, evening and during cloud cover and also temperature changes sometimes associated with the changes in insolation. The edges of clouds create particularly issues because they cause a rapid change in lighting which may be followed by a relatively rapid change in temperature. Because they do not quickly adapt to changing conditions, the charge controllers have limited efficiency, which results in the

need for extra (or larger) PV panels to be used for a given power output and high costs.

III. SUMMARY OF THE INVENTION

It is therefore an object of the invention to provide a charge controller that quickly adapts to changing conditions and thus affords improved energy conversion efficiencies. It is another object of the invention to provide such a charge controller which can be adapted for use with a wide range of PV panels. It is a further object of the invention to provide such a charge controller which can be adapted for use with a wide range of DC loads including batteries for energy storage and DC-AC inverters for direct output. In accord with these objects, which will be discussed in detail below, a charge controller is provided that includes an input interface that receives input DC electrical signals. A converter section converts the input DC electrical signals to output DC electrical signals. Control means is operably coupled to the converter section. The control means includes means for operating the converter section at an estimated maximum power point of the input DC electrical signals [56-62]. The estimated maximum power point is derived by a control scheme that includes the following operations:

- i) storing an input voltage level corresponding to the estimated maximum power point;
- ii) varying the input voltage of the input DC electrical signals over a sequence of sample points from a first voltage level to a second voltage level, and deriving and storing an output current value of the output DC electrical signals at each sample point;
- iii) selecting the maximum output current value from the output current values stored in ii), and identifying the particular input voltage level corresponding thereto; and
- iv) varying the input voltage of the input DC electrical signals over a sequence of sample points from the second voltage level to the particular input voltage level identified in iii); and
- v) updating the stored input voltage level corresponding to the estimated maximum power point to the particular input voltage level identified in iv).

In the preferred embodiment, for each given sample point in ii), the output current value for the sample point is derived by averaging a plurality of output current measurements at the given sample point, and the first and second voltage levels of ii) are derived from the measured open circuit voltage.

In another aspect of the invention, the control scheme carried out by the charge controller derives the estimated maximum power point by the following operations:

- a) storing an input voltage level corresponding to the estimated maximum power point;

- b) varying the input voltage of the input DC electrical signals over a number of sample points around the input voltage level stored in a), and deriving and storing an
- c) output current value of the output DC electrical signals at each sample point;
- d) selecting the maximum output current value from the output current values stored in b) and identifying the particular input voltage level corresponding thereto; and
- e) updating the stored input voltage level corresponding to the estimated maximum power point to the particular input voltage identified in c).
- f) The number of sample points in b) include a first plurality of sample points at input voltage values less than the input voltage level stored in a) and a second plurality of sample points at input voltage values greater than the input voltage level stored in a).

In the preferred embodiment, for each given sample point in b), the output current value for the sample point is derived by averaging a plurality of output current measurements at the given sample point, and the voltage differences between the sample points of b) is on the order of 100 millivolts [63-69].

In yet another aspect of the present invention, the control scheme carried out by the charge controller updates an input voltage level corresponding to an estimated maximum power point at a frequency of at least 500 Hz. It will be appreciated that the maximum power point control operations of the present invention quickly adapt to changing conditions and thus afford improved energy conversion efficiencies.

In the illustrative embodiment, the converter section comprises a buck converter topology having input reservoir capacitance, at least one series switching element (e.g. an FET field effect transistor or IGBT insulated gate bipolar transistor), at least one synchronous rectifier switching element, at least one inductor, and gate drive circuitry that selectively switches the at least one series field effect transistor and the at least one synchronous rectifier field effect transistor between ON and OFF states in response to pulse width modulation control signals supplied thereto.

The control means (e.g., a microcontroller, microprocessor, digital signal processor or other control logic) is operably coupled to the gate drive circuitry for varying the duty cycle of the pulse width modulation control signals supplied to the gate drive circuitry in order to vary the input voltage level of the input DC electrical signals. In the preferred embodiment, the control scheme carried out by the control means includes an MPPT (Maximum Power Point Tracking) charging mode as well as a bulk charging mode, an absorption charging mode, and a float charging mode.

In the MPPT charging mode, the control means regulates the input voltage of the input DC electrical

signals such that it is maintained at the input voltage level corresponding to the estimated maximum power point as determined and stored by the control scheme. In the bulk charging mode, the control means regulates the output current of the output DC electrical signals such that it is limited to a predetermined maximum current limit.

In the absorption charging mode, the control means regulates the output voltage of the output DC electrical signals such that it is maintained at a

predetermined absorption charging mode voltage level. In the float charging mode, the control means regulates the output voltage of the output DC electrical signals such that it is maintained at a predetermined float charging mode voltage level [70-72].

Additional objects and advantages of the invention will become apparent to those skilled in the art upon reference to the detailed description taken in conjunction with the provided figures.

IV. DESCRIPTION OF THE DRAWINGS

FIG. 1

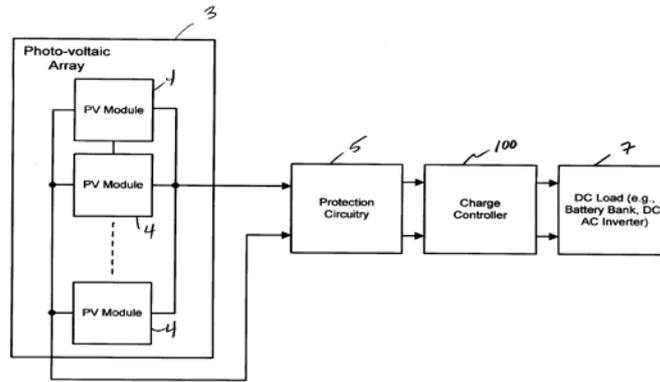


Fig. 1 : is a block diagram of a solar electric generator system in which the present invention can be embodied.

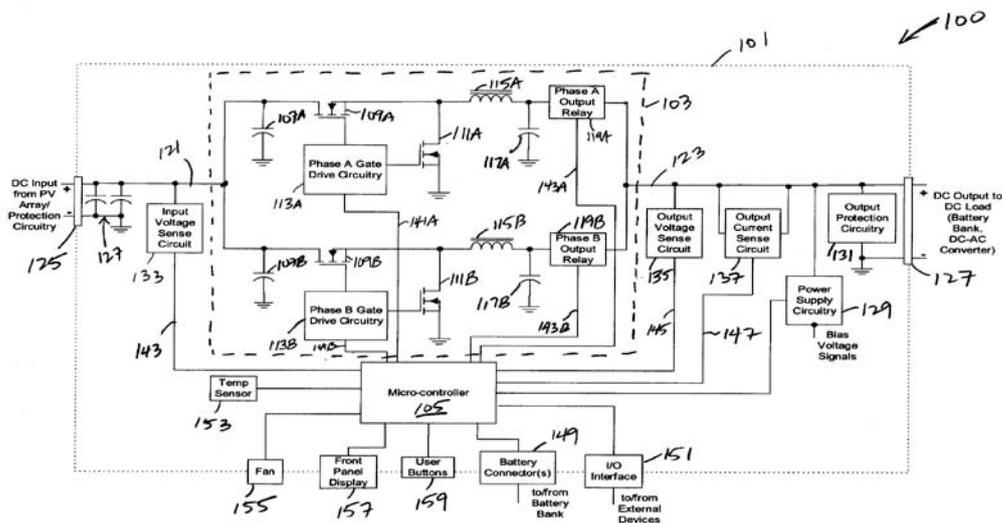
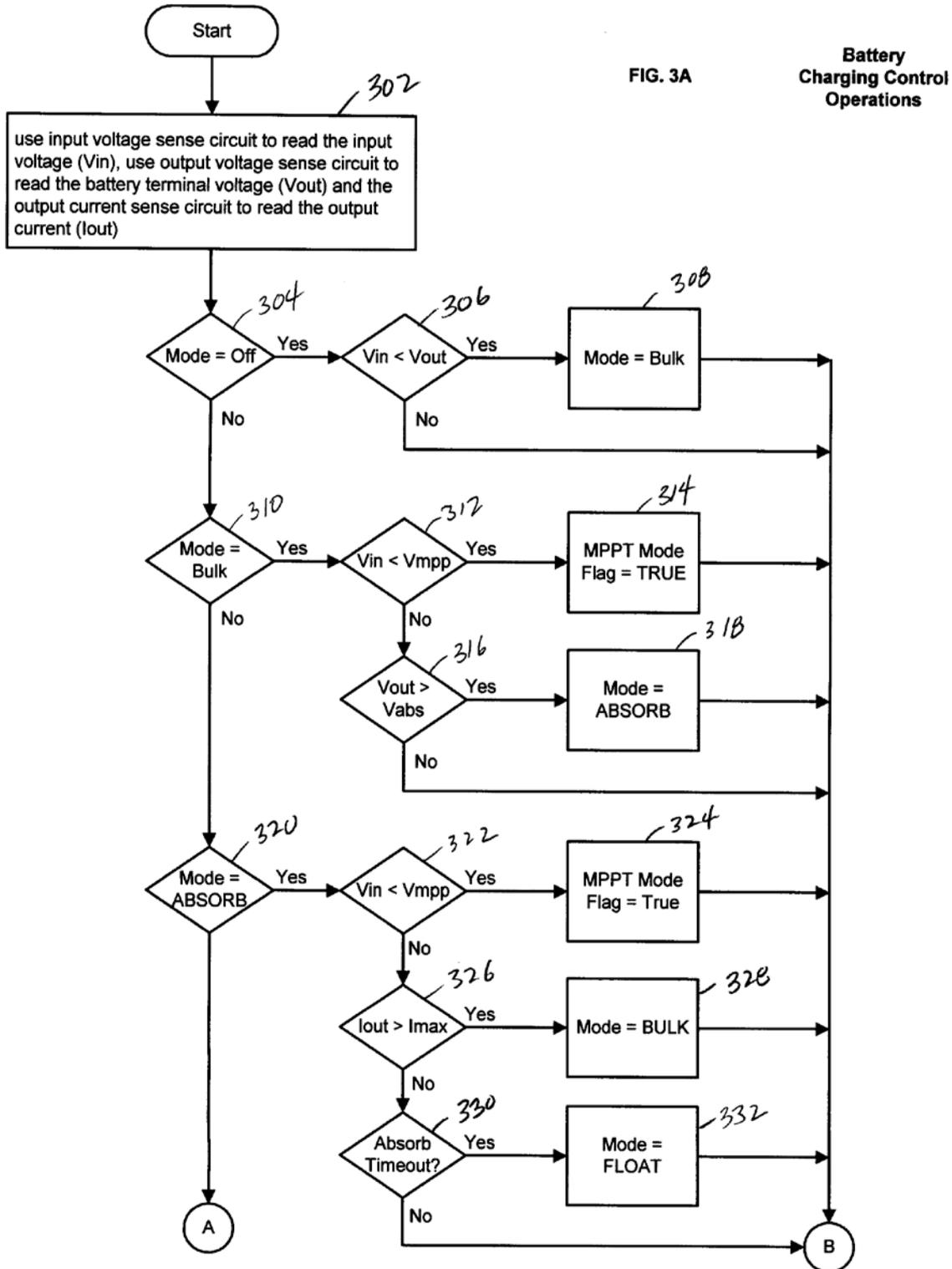


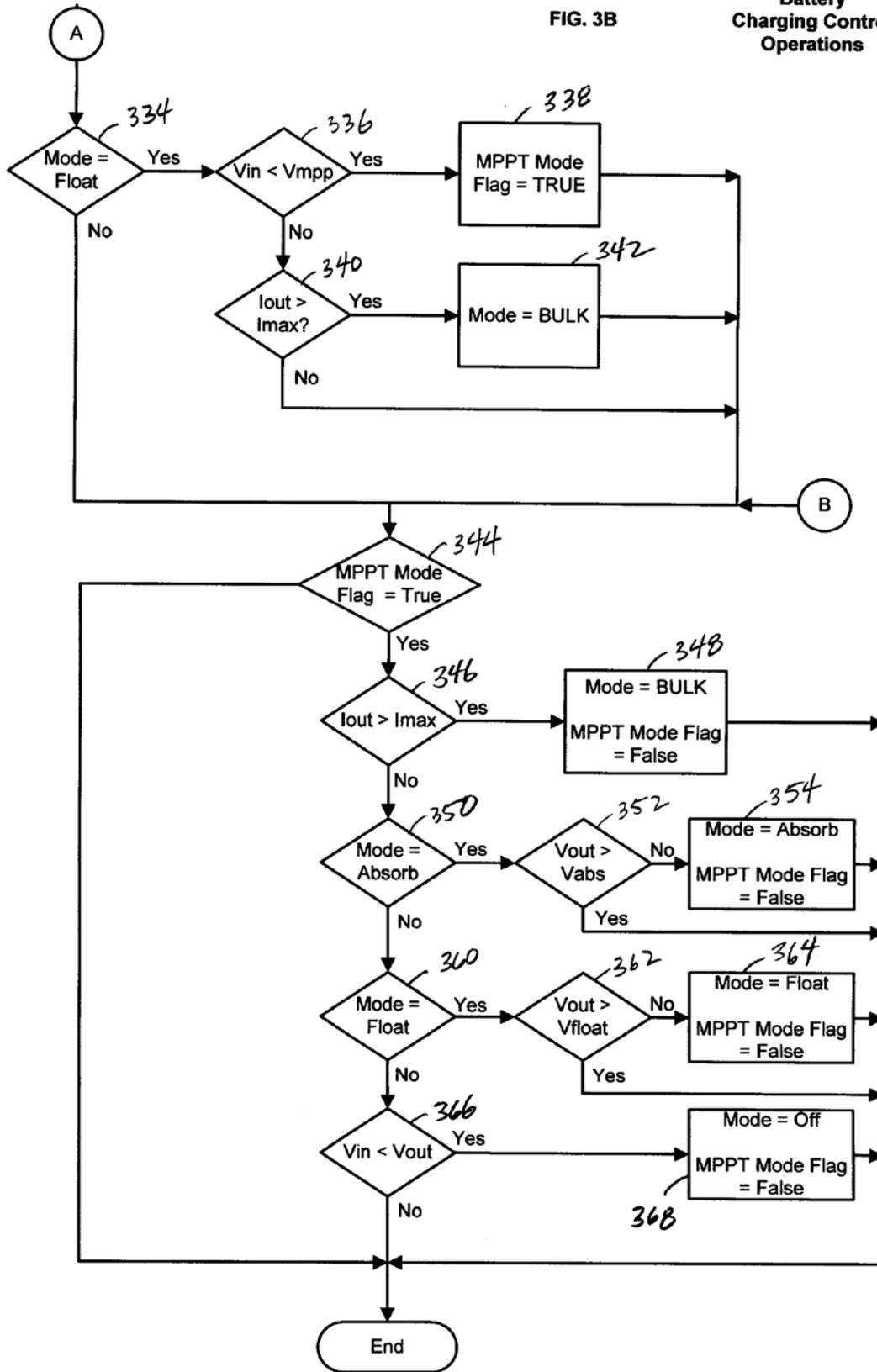
Fig. 2 : is a high-level schematic diagram of a charge controller in accordance with the present invention, which can be used as part of the solar electric generator system of FIG. 1 to convert the DC electrical signals generated by the photovoltaic array into a DC form suitable for supply to the DC load.



Figs. 3A and 3B : collectively, is a flow chart illustrating automatic battery charging operations carried out by the charge controller of FIG. 2 in accordance with the present invention;

FIG. 3B

Battery Charging Control Operations



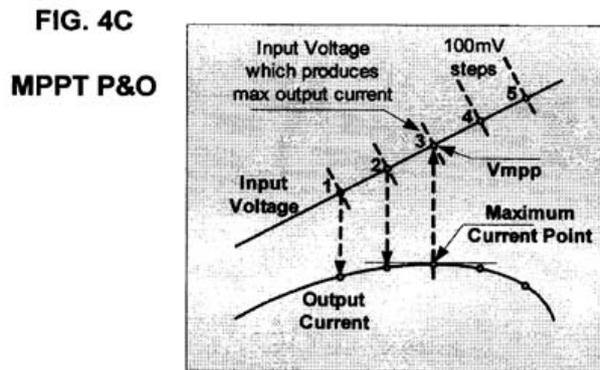
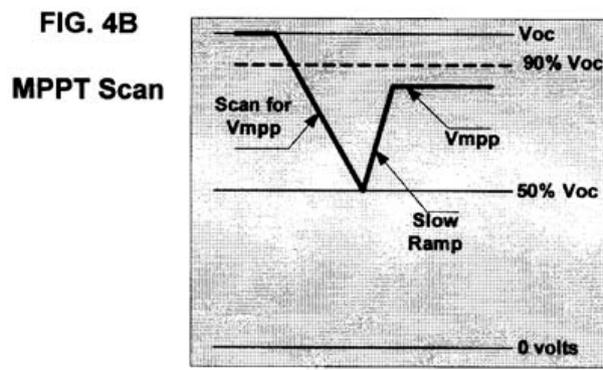
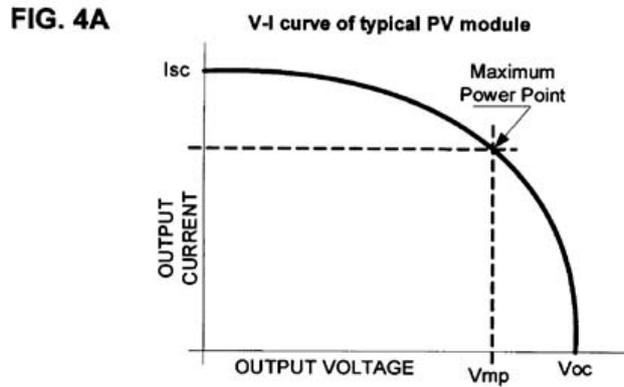


Fig 4a : is a pictorial illustration of the I-V curve of a typical photovoltaic module;

Fig 4b : is a pictorial illustration of exemplary scanning operations that are carried out by the charge controller of FIG. 2 for deriving an input voltage for estimated maximum power point conversion operations in accordance with the present invention;

Fig 4c : is a pictorial illustration of exemplary perturbation and observation operations that carried out by the charge controller of FIG. 2 for deriving the input voltage for estimated maximum power point conversion operations in accordance with the present invention;

FIG. 5 MPPT Mode Control

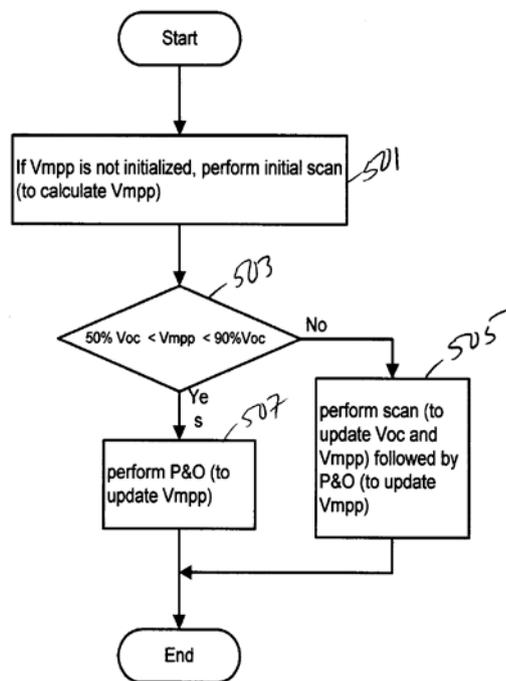


Fig. 5: is a flow chart illustrating operations carried out by the charge controller of FIG. 2 for deriving the input voltage for estimated maximum power point conversion operations in accordance with the present invention.

V. DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Turning now to FIG. 1, there is shown a functional block diagram of a solar power conversion system **1** which includes a photo-voltaic (PV) array **3** capable of generating direct current electricity from incident solar radiation. The photo-voltaic array **3** typically includes a number of PV modules **4** each comprising a number of series-connected solar cells. The PV modules **4** can be connected in a parallel configuration as shown so that sufficient power can be generated under minimum radiation conditions. The DC electrical signals generated by the PV array **3** are supplied to a number of series-connected components including protection circuitry **5**, a charge controller **100** and a DC load **7**. The protection circuitry **5** provides for protection against lightning strikes and other faults (typically by shunting fault current to ground through MOVs and the like) and can also provide protection for reverse-polarity faults. The protection circuitry **5** may also be responsible for limiting the maximum voltage which can otherwise be higher than the maximum allowable voltage for the components in the next stage.

The open-circuit voltage (V_{oc}) of the PV array **3** is about 20% to 30% higher than the operating voltage of the same array and the increased voltages at low temperatures represent the worst case. The charge controller **100** converts the DC electrical signals generated by the PV array **3** into DC electrical signal suitable for output to the DC load **7**. The DC load **7** can be a bank of one or more batteries for energy storage and/or a DC-AC inverter for direct output.

As shown in FIG. 2, the charge controller **100** includes a system housing **101** supports a synchronous buck converter section **103** interfaced to a microcontroller **105**. The synchronous buck converter section **103** utilizes two switching elements (a series field effect transistor (FET) and a synchronous rectifier FET) to store energy into (and extract energy from) an inductor. The series FET and the synchronous rectifier FET are driven by gate drive circuitry to alternate between two states, a charging state and a discharging state. In the charging state, the series FET is turned ON and the synchronous rectifier FET is turned OFF such that the inductor is connected to a DC source voltage to store energy in the inductor. In the discharging state, the series FET is turned OFF and the synchronous rectifier FET is turned ON in order to discharge the energy stored in the inductor to the load. The gate drive circuitry that controls the operation of the series FET and the synchronous FET must prevent both switches from being turned on at the same time, which is a fault known as "shoot-through". During operation, the cooperation of the switching action of the series FET, synchronous rectifier FET and the inductor reduce the DC source voltage level by a factor which is controlled by the duty cycle for the charging state of both FETs. This duty cycle is controlled by pulse width modulation (PWM) control signals supplied to the gate drive circuitry as is well known.

A multiphase synchronous buck converter is a topology whereby multiple buck converter circuits as described above are placed in parallel between the source voltage and the load and controlled to out of phase with each other. For example, two parallel circuits are set to switch such that one circuit is ON while the other is OFF. In other words, the two circuits are 180 degrees out of phase with one another. The primary advantage of this multiphase topology is that the load current can be split among the circuits or phases, thus allowing for increased load currents. Another equally important advantage is that the output ripple is reduced by the number of phases, thus allowing for easier filtering and lower output ripple. Each of these "phases" is turned ON at predetermined intervals over the switching period.

In the illustrative embodiment shown, the buck converter section **103** employs a two phase topology with two high current paths (phases A and B) each having input capacitance **107**, a series FET **109**, a

synchronous rectifier FET **111**, gate drive circuitry **113**, an inductor **115**, output capacitance **117**, and an output relay **119**. The input capacitance **107** and the series FET **109** of the two phases are connected to an input path **121** as shown. The output relays **119** of the two phases are connected to an output path **123** as shown. The input capacitance **107** filters unwanted high frequency noise components. The output capacitance **117** filters the current flowing from the inductor in the discharge state with the series FET **109** turned OFF and the synchronous rectifier FET **111** turned ON. The output capacitance **117** also provides low impedance for transient load current changes, thus reducing steady-state output ripple.

An input connector **125** provides for supply of the positive (+) and negative (-) DC voltage signals generated by the PV array **3** of FIG. 1. Input reservoir capacitors **127** are connected between these two DC voltage signals via the input connector **125**. The positive (+) terminal of the connector **125** and the positive terminal of the input reservoir capacitors **127** are connected to the input path **121** of the buck converter section **103** as shown. The input reservoir capacitors **127** are charged in the charging state (when the series FET **109** for the two phases is OFF) and discharged in the discharging state (when the series FET **109** for the two phases is OFF and the synchronous rectifier FET **111** for the two phases is ON). The input reservoir capacitors **127** witness pulsed current with an amplitude equal to the load current. It is common practice to select the input reservoir capacitance with an RMS current rating more than half the maximum current load. If multiple capacitors are paralleled, the RMS current for each input reservoir capacitor should be total current divided by the number of input reservoir capacitors.

The output path **123** of the buck converter section **103** is connected to the positive (+) terminal of an output connector **127**. The negative (-) terminal of the output connector **127** is grounded as shown. The output connector **127** provides for supply of positive (+) and negative (-) DC voltage signals generated by the buck converter section **103** to the DC load of FIG. 1, which can be battery bank and/or an DC-AC Inverter or other DC load.

Power supply circuitry **129** can be connected to the positive (+) terminal of the output connector **127** as shown. The power supply terminal transforms the DC voltage signal carried by the positive (+) terminal of the output connector **127** to internal bias voltage levels for supply to electrical components of the converter **100** as needed. Output protection circuitry **129** can also be provided between the positive (+) and negative (-) terminals of the output connector **127** to provide for overvoltage protection and possibly backflow current protection.

The microcontroller **105** supplies PWM control signals to the gate drive circuitry **113A**, **113B** of the two

phases via control lines **141A**, **141B**. These PWM control signals effectuate desired control over the duty cycle of the charging state of the series FETs **109A**, **109B** for the two phases. The gate drive circuitry **113A**, **113B** for the two phases also controls the operation of the synchronous rectifier FETS **111A**, **111B** for the two phases based upon the PWM control signals supplied thereto. In the preferred embodiment, the series FETs **109A**, **109B** and the synchronous rectifier FETs **111A**, **111B** of the two phases are switched at a frequency of 30 KHz or greater when combined in order to keep noise above human hearing

For battery charging operations (e.g., Bulk Charging, Absorption Charging, Float Charging), the microcontroller **105** controls duty cycle of the PWM control signals supplied to the gate drive circuitry **113A**, **113B** (and thus controls the duty cycle of the charging state of the series FETs **109A**, **109B** for the two phases) based upon the input voltage provided by the PV array, the output voltage level and the output current level supplied to the DC load (i.e., the battery bank), and the battery current produced by the battery bank. The input voltage is measured by the input voltage sense circuit **133**, which supplies a signal representative of the input voltage to the microcontroller **105** via path **143** for conversion into digital form therein. The output voltage is measured by the output voltage sense circuit **135**, which supplies a signal representative of the output voltage to the microcontroller **105** via path **145** for conversion into digital form therein. The output current is measured by the output current sense circuit **137**, which supplies a signal representative of the output current to the microcontroller via path **147** for conversion into digital form therein. The battery current is measured either by an internal current sensing device such as a shunt resistor or hall effect device, or alternatively by an external shunt at the battery bank (not shown), which supplies a signal representative of the battery current to the microcontroller via connector **149** for conversion into digital form therein.

The microcontroller **105** can also measure and/or maintain information regarding other characteristics of the battery bank, such as temperature of the battery bank and the battery terminal voltage measured by Kelvin connections. In the exemplary embodiment, a temperature sensor at the battery bank supplies a signal representative of the battery bank temperature to the microcontroller **105** via connector **149** for conversion into digital form therein. Similarly, a Kelvin connection at the battery bank supplies a signal representative of the terminal voltage of the battery bank to the microcontroller **105** via connector **149** for conversion into digital form therein. The Kelvin connection allows for more accurate monitoring of the terminal voltage of the battery bank, especially during high current charging operations. In such high current charging operations, there can be a significant voltage

drop across the output of the converter, which causes the output voltage sense circuit **135** to underestimate of the true battery voltage. The Kelvin bridge circuit eliminates these inaccuracies as it provides an accurate measurement of the terminal voltage of the battery bank during such high current charging operations. The high accuracy battery voltage measurements are used in the preferred embodiment to provide more accurate battery charging.

The microcontroller **105** also interfaces to a temperature sensor **153** internal to the system housing **101** to measure the internal temperature of the system housing **101**. This temperature can be used to activate, deactivate and control the speed of a fan **155** that blows air from outside the system housing to the interior space of the system housing for cooling as is well known. The microcontroller **105** can also interface to a temperature sensor (not shown) to measure the temperature on the interior or of the heat sink. This temperature too can be used to control the speed of the fan **155** (or additional fans) for cooling as needed.

The microprocessor **105** also interfaces to a front panel display and/or LED **157** and user input buttons **159** for presenting status information to the user as well as carrying out user interaction and control. The front panel display and/or LED **157** preferably presents status indications of a multiplicity of parameters including PV voltage, PV current, battery voltage, charging current, charging status, energy harvest history, battery energy status, energy used, etc.

In accordance with the present invention, the charge controller **100** of FIG. 2 can be adapted for use in a wide range of applications, including the charging of a battery bank for the storage of electrical energy therein and/or the direct output of electrical energy to a DC-AC inverter and the like. FIGS. 3A and 3B, collectively, is a flow chart illustrating exemplary control operations carried out by the microcontroller **105** for automatic charging of a battery bank. The control operations employ five charging modes: Off, Bulk Charging Mode (for a highly discharged battery), Absorption Charging Mode, Float Charging Mode, and Maximum Power Point Tracking (MPPT) mode.

a) Off Mode

In the Off mode, the microcontroller **105** opens the output relays **119** such that no current is passed through to the battery bank.

b) Bulk Charging Mode

In the bulk charging mode, the microcontroller **105** regulates the output current (as measured by the output current sense circuit **137**) such that it is at the maximum current limit of the converter (which is referred to herein as I_{max} and is designed to prevent overload). The maximum current I_{max} is preferably a parameter that is set and possibly updated by user input; alternatively, it can be stored as a constant value. The

microcontroller **105** regulates the output current by controlling the duty cycle of the PMW control signals supplied to the gate drive circuitry **113A**, **113B**. The Bulk charging mode is used to charge a battery that is in a relatively low charge state.

c) Absorption Charging Mode

In the absorption charging mode, the microcontroller **105** regulates the output voltage level (as measured by the output voltage sense circuit **135** or by the Kelvin connection), such that it is maintained at a predetermined absorption voltage level (referred to herein as V_{abs}). The predetermined absorption voltage level is preferably a parameter that is set and possibly updated by user input; alternatively, it can be stored as a constant value. The microcontroller **105** regulates the output voltage by controlling the duty cycle of the PMW control signals supplied to the gate drive circuitry **113A**, **113B**. The Absorption charging mode is used to charge a battery at a relatively high charge state.

d) Float Charging Mode

In the float charging mode, the microcontroller **105** regulates the output voltage level (as measured by the output voltage sense circuit **135** or by the Kelvin connection), such that it is maintained at the predetermined float voltage level (referred to herein a V_{float}). The predetermined float voltage level is preferably a parameter that is set and possibly updated by user input; alternatively, it can be stored as a constant value. The microcontroller **105** regulates the output voltage by controlling the duty cycle of the PMW control signals supplied to the gate drive circuitry **113A**, **113B**. The float charging mode is used to charge a battery at a full or substantially full charge state

e) MPPT Mode

In the MPPT mode, the microcontroller **105** regulates the input voltage level such that it is maintained at or near the peak power point on the current-voltage curve for the PV array **3** connected thereto. This voltage level is referred to herein as " V_{mpp} ". The microcontroller **105** regulates the input voltage by controlling the duty cycle of the PMW control signals supplied to the gate drive circuitry **113A**, **113B**.

The automatic battery charging operations of FIGS. 3A and 3B are performed on a periodic basis, preferably at least every 2 milliseconds or shorter. Such timing can be controlled by an interrupt timer or other timing circuitry. The operations are carried out using a state variable "Mode" that is set to correspond to the given operational mode, which can be either a predetermined value for the Off mode, a predetermined value for Bulk Charging, a predetermined value for Absorption Charging or a predetermined value for Float Charging. Because the MPPT mode can be used in conjunction with any one of the Bulk, Absorption and Float charging modes, a status flag ("MPPT mode

FLAG”) is also used. The MPPT mode flag is set to true when the MPPT mode is active and set to false when the MPPT mode is inactive.

When the Mode variable is set, the microcontroller **105** automatically transitions to carry out the corresponding control operations for the particular mode as described above. In the Off mode, the microcontroller **105** opens the output relays **119** such that no current passes through from the input path **121** to the output path **123** and to the battery bank. In the Bulk charging mode, the microcontroller **105** regulates the output current such that it is at the maximum current limit I_{max} . In the Absorption charging mode, the microcontroller **105** regulates the output voltage level such that it is maintained at a predetermined absorption voltage level V_{abs} . In the Float charging mode, the microcontroller **105** regulates the output voltage level such that it is maintained at the predetermined float voltage level V_{float} .

When the MPPT mode flag is set to true, the MPPT mode operations override the charging mode operations (Bulk, Absorption or Float charging operations) as dictated by the Mode variable. Such override processing causes the microcontroller **105** to regulate the input voltage level such that it is maintained at or near the V_{mpp} value as described herein. When the MPPT mode flag is set to false, the override processing is avoided such that the charging mode operations dictated by the Mode variable are performed.

The operations begin in step **302** where the microcontroller **105** uses the input voltage sense circuit **133** to measure the input voltage (V_{in}), uses the output voltage sense circuit **135** to measure the output voltage (V_{out}), and uses the output current sense circuit **137** to measure the output current (I_{out}). For reverse current protection, the output relays **119** are switched OFF in the event that the output current I_{out} is less than a minimal threshold current, for example 2 amperes. The output relays **119** are switched ON for power conversion in the Bulk Charging, Absorption Charging, Float Charging and MPPT modes.

In step **304**, the microcontroller **105** determines if the Mode variable is set to the “Off” value. If the determination of step **304** is false, the operations continue to step **310**. If the determination of step **304** is true, the operations continue to step **306** where the microcontroller **105** checks whether the input voltage V_{in} is less than the output voltage V_{out} . If the decision of step **306** is true, the microcontroller **105** in step **308** sets the Mode variable to the “Bulk” value and the operations continue to step **344**. If the decision of step **304** is false, the microcontroller **105** continues to step **344**.

In step **310**, the microcontroller **105** determines if the Mode variable is set to the “Bulk” value. If the determination of step **310** is false, the operations continue to step **320**. If the determination of step **310** is true, the operations continue to step **312** where the

microcontroller **105** checks whether the input voltage V_{in} is less than the maximum power point voltage V_{mpp} . If the decision of step **312** is true, the microcontroller **105** in step **314** sets the MPPT Mode flag to true and the operations continue to step **344**. If the decision of step **312** is false, the microcontroller **105** continues to step **316** to check whether the output voltage V_{out} is greater than the absorption voltage V_{abs} . If the decision of step **316** is true, the microcontroller **105** in step **318** sets the Mode variable to the “Absorb” value and the operations continue to step **344**. If the decision of step **316** is false, the operations continue to step **344**.

In step **320**, the microcontroller **105** determines if the Mode variable is set to the “Absorb” value. If the determination of step **320** is false, the operations continue to step **334**. If the determination of step **320** is true, the operations continue to step **322** where the microcontroller **105** checks whether the input voltage V_{in} is less than the maximum power point voltage V_{mpp} . If the decision of step **322** is true, the microcontroller **105** in step **324** sets the MPPT Mode flag to true and the operations continue to step **344**. If the decision of step **322** is false, the microcontroller **105** continues to step **326** to check whether the output current I_{out} is greater than the maximum output current I_{max} . If the decision of step **326** is true, the microcontroller **105** in step **328** sets the Mode variable to the “Bulk” value and the operations continue to step **344**. If the decision of step **326** is false, the operations continue to step **330** to check if an absorption timer has expired. The absorption timer is automatically set when the microcontroller **105** transitions from the Bulk mode to the Absorption mode. The initial absorption timer value is preferably a parameter that is set and possibly updated by user input; alternatively, it can be stored as a constant value. If the test of step **330** is true, the microcontroller **105** in step **332** sets the Mode variable to the “Float” value and the operations continue to step **344**.

In step **334**, the microcontroller **105** determines if the Mode variable is set to the “Float” value. If the determination of step **334** is false, the operations continue to step **344**. If the determination of step **334** is true, the operations continue to step **336** where the microcontroller **105** checks whether the input voltage V_{in} is less than the maximum power point voltage V_{mpp} . If the decision of step **336** is true, the microcontroller **105** in step **338** sets the MPPT Mode flag to true and the operations continue to step **344**. If the decision of step **336** is false, the microcontroller **105** continues to step **346** to check whether the output current I_{out} is greater than the maximum output current I_{max} . If the decision of step **346** is true, the microcontroller **105** in step **342** sets the Mode variable to the “Bulk” value and the operations continue to step **344**.

In step **344**, the microcontroller **105** checks whether the MPPT status flag is set to true. If the test of step **344** fails, the operations end. If the test of step **344**

is true, the operations continue in step **346** to check whether the output current I_{out} is greater than the maximum output current I_{max} . If the decision of step **346** is true, the microcontroller **105** in step **348** sets the Mode variable to the "Bulk" value and clears the MPPT Mode flag to false and the operations end. If the decision of step **346** is false, the operations continue to step **350**.

In step **350**, the microcontroller **105** checks whether the Mode variable is set to the "Absorb" value. If the test of step **350** is false, the operations continue to step **360**. If the test of step **350** is true, the microcontroller **105** continues to step **352** to check whether the output voltage is greater than the V_{abs} . If so, the operations continue to step **354** to set the Mode variable to the "Absorb" value and clears the MPPT Mode flag to false and the operations end. If not, the operations end.

In step **360**, the microcontroller **105** checks whether the Mode variable is set to the "Float" value. If the test of step **360** is false, the operations continue to step **366**. If the test of step **360** is true, the microcontroller **105** continues to step **362** to check whether the output voltage is greater than V_{float} . If so, the operations continue to step **364** to set the Mode variable to the "Float" value and clears the MPPT Mode flag to false and the operations end. If not, the operations end.

In step **366**, the microcontroller **105** checks whether the input voltage is greater than the output voltage. If so, the Mode variable is set to the "Off" value and clears the MPPT Mode flag to false and the operations end. If not, the operations end.

In each one of the Bulk Charging Mode, Absorption Charging Mode and the Float Charging mode, the PV array may not be able to supply the required power to achieve the desired voltage or current limits set by the charging operations. Under these conditions, the microcontroller **105** transitions to the MPPT mode. For example, for the Bulk Charging Mode, the microcontroller **105** automatically transitions to the MPPT mode in steps **312** and **314**. In the Absorption Charging Mode, the microcontroller **105** automatically transitions to the MPPT mode in steps **322** and **324**. In the Float Charging Mode, the microcontroller **105** automatically transitions to the MPPT mode in steps **336** and **338**.

For the MPPT mode, the microcontroller **105** regulates the input voltage level such that it is maintained at or near the peak power point on the current-voltage curve for the PV array as shown graphically in FIG. 4A. This voltage level is referred to herein as "V_{mpp}". In the preferred embodiment, the V_{mpp} voltage level is derived from a scanning step as well as perturbation and observation steps. The scanning step is graphically illustrated in FIG. 4B and

the perturbation and observation steps are graphically illustrated in FIG. 4C.

The scanning step establishes the open circuit voltage of the PV array together with an initial value for V_{mpp}. The perturbation and observation steps vary the input voltage to multiple sample points about the initial "V_{mpp}" value established by scanning and measures the output current at each sample point. The sample point with maximum output current is selected as the new "V_{mpp}" value.

In the illustrative embodiment, the scanning steps include the following sequence of operations:

the duty cycle of the converter section **103** is reduced to zero such that the switching devices remain OFF for a predetermined sampling period such that the input voltage sense circuit measures the open circuit voltage V_{oc} of the PV panel. The microcontroller **105** reads this measurement via input path **143**.

- i) the microcontroller **105** sweeps the input voltage over sample points within a predetermined voltage range based on the V_{oc} measured in i); for example, the predetermined voltage range can be from V_{oc} to 50% to 60% V_{oc} (or to 130% of the battery terminal voltage, whichever is greater); in the preferred embodiment, the microcontroller **105** ramps down the input voltage on 1 volt steps every 400 milliseconds.
- ii) at each one of the sample points in ii), the microcontroller **105** measures and stores the output current; and
- iii) the microcontroller **105** analyzes the stored output current values over the sample points of the scan to identify the sample point with the maximum output current value. This highest output current value, denoted I_{mpp} establishes the initial voltage level "V_{mpp}" that provides peak power; and
- iv) the microcontroller **105** then slowly increases the input voltage level from the floor (low point) of the scan to the "V_{mpp}" level. The slow adjustment to the input voltage level (which is preferably on the order of 1 volt every 200 milliseconds) prevents rapid changes in current which can cause overshoot and errors in the control routine.

In alternative embodiments, it is contemplated that the scanning operations can start at the bottom of the range and sweep the input voltage by ramping up the input voltage. At the top of the range, the microcontroller can then ramp down the input voltage to the V_{mpp} voltage level.

In the illustrative embodiment, the perturbation and observation steps include the following sequence of operations:

- i) the output current is measured a number of times (for example, 128 times in one embodiment) to reduce any inaccuracies due to noise and the average is stored as the maximum current point

- I_{mpp} (which is labeled **P3** for purposes of illustration in FIG. 4C);
- ii) the input voltage is reduced by 200 mV by adjusting the duty cycle of the PWM control signals supplied to the gate driver circuitry **113** and the output current is again measured many times, averaged and recorded (this point is labeled **P1** for purposes of illustration in FIG. 4C);
 - iii) the input voltage is increased by 100 mV by adjusting the duty cycle of the PWM control signals supplied to the gate driver circuitry **113** and the output current is again measured many times, averaged and recorded (this point is labeled **P2** for purposes of illustration in FIG. 4C);
 - iv) the input voltage is increased to 100 mV above the voltage value for the I_{mpp} point in i) by adjusting the duty cycle of the PWM control signals supplied to the gate driver circuitry **113** and the current is again measured many times, averaged and recorded (this point is labeled **P4** for purposes of illustration in FIG. 4C);
 - v) the input voltage is increased to 100 mV by adjusting the duty cycle of the PWM control signals supplied to the gate driver circuitry **113** and the current is measured again many times, averaged and recorded (this point is labeled **P5** for purposes of illustration in FIG. 4C); and
 - vi) The stored output current values for the steps i)-v) above are processed to select the highest output current value and the voltage value for that selected sample point is stored as the new V_{mpp} value.

Note that for the perturbation and observation step described above, the number of sample points, the voltage difference between the sample points, and the order in which the sample points are measured can be changed as desired and are proved for illustrative purposes.

Also note that for the perturbation and observation step described above, one of the sample points is the V_{mpp} point itself, multiple sample points are provided at voltage levels above the V_{mpp} point, and multiple sample points are provided at voltage levels below the V_{mpp} point. Such sampling quickly locates the maximum power point and thus reduces the processing time and delays associated therewith. Such reduction in processing time improves the efficiency of the power conversion process, especially in dynamic conditions (e.g., changing sunlight due to moving cloud cover and the like).

FIG. 5 is a flow chart illustrating exemplary control operations that are carried out by the microcontroller **105** in order to calculate and update the V_{mpp} value as described herein. Such operations are preferably performed on a periodic basis when the MPPT mode flag is activated in accordance with the operations of FIG. 3 as described above. Such timing

can be controlled by an interrupt timer or other timing circuitry. In the illustrative embodiment, the operations of FIG. 5 are performed on a period basis every 2 milliseconds or shorter, which corresponds to a frequency of 500 Hz or greater. In this manner, the V_{mpp} values are updated at least every 2 milliseconds or less (or at a frequency of 500 Hz or greater), which enhances the efficiency of the conversion process especially during dynamic conditions.

In step **501**, the microcontroller **105** checks whether the V_{mpp} has been initialized. If no, the microcontroller **105** performs as initial scanning step as described above with respect to FIG. 5B. This scanning step calculates the initial V_{mpp} value for the MPPT mode processing.

In step **503**, the microcontroller **105** checks whether the input voltage V_{in} is within a predetermined voltage range (for example between 50% V_{oc} and 90% V_{oc}). If not, the operations continue to step **505** to perform a scanning step as described above with respect to FIG. 5B followed by a perturbation and observation step as described above with respect to FIG. 5C. The scanning of step **505** updates the open circuit voltage V_{oc} and the V_{mpp} value, and the perturbation and observation of step **505** updates the V_{mpp} value. From step **505**, the operations end.

If the results of step **503** indicate that the input voltage V_{in} is within the predetermined voltage range, the operations continue to step **507** to perform a perturbation and observation step as described above with respect to FIG. 5C. The perturbation and observation of step **507** updates the V_{mpp} value. From step **507**, the operations end.

There have been described and illustrated herein an embodiment of charge controller for solar applications and methods of operating same. While a particular embodiment of the invention have been described, it is not intended that the invention be limited thereto, as it is intended that the invention be as broad in scope as the art will allow and that the specification be read likewise. Thus, while particular control operations (including particular control states and transitions between control states) have been disclosed, it will be appreciated that other control operations can be used as well. In addition, while particular buck-type converter topologies have been disclosed, it will be understood that the general control operations described herein can be used with other PWM-controlled converter topologies or other non-PWM converter topologies.

Also, while it is preferred that the control operations of the charge controller be carried out by a microcontroller element, it will be recognized that other control elements and control systems can be used (such as a microprocessor, a digital signal processor, an ASIC, a CPLD, an FPGA, or other digital logic device).

VI. CONCLUSION

It is preferably that the control operations be realized as a program of instructions that are loaded into the firmware of the microcontroller or other programmed logic device. Furthermore, while the embodiments described above utilize field effect transistors as switching devices, it will be understood that other switching devices such as IGBT insulated gate bipolar transistors can be similarly used. In addition, while particular solar applications have been disclosed, it will be understood that the charge controller described herein can be adapted for other energy conversion applications such as wind energy harvesting, wave-energy harvesting, hydroelectric energy harvesting, thermoelectric energy harvesting, etc. It will therefore be appreciated by those skilled in the art that yet other modifications could be made to the provided invention without deviating from its spirit and scope as claimed.

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