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Maximum Power Point Tracking for Photovoltaic Grid-Connected Inverter Based on Voltage-Oriented Control

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Abstract

In this paper, an improved maximum power point (MPP) tracking (MPPT) with better performance based on voltage-oriented control (VOC) is proposed to solve a fast changing irradiation problem. In VOC, a cascaded control structure with an outer dc link voltage control loop and an inner current control loop is used. The currents are controlled in a synchronous orthogonal d, q frame using a decoupled feedback control. The reference current of proportional–integral (PI) d-axis controller is extracted from the dc-side voltage regulator by applying the energy-balancing control. Furthermore, in order to achieve a unity power factor, the q-axis reference is set to zero. The MPPT controller is applied to the reference of the outer loop control dc voltage photovoltaic (PV).Without PV array power measurement, the proposed MPPT identifies the correct direction of the MPP by processing the d-axis current reflecting the power grid side and the signal error of the PI outer loop designed to only represent the change in power due to the changing atmospheric conditions. The robust tracking capability under rapidly increasing and decreasing irradiance is verified experimentally with a PV array emulator. Simulations and experimental results demonstrate that the proposed method provides effective, fast, and perfect tracking

Solar Cell Modeling

To properly model a solar cell, it is important to understand how solar cells operate. Solar cells are primarily made of semiconductor material that when exposed to light induces a process of photon reflection and absorption, generation of free carriers and lastly charge separation, which creates an electric field. The semiconductor properties determine how effectively this process occurs. Some of the most important properties include the absorption coefficient, the reflectance of the semiconductor surface, drift-diffusion parameters and surface recombination velocities.

The absorption coefficient depends on the value of the band gap of the semiconductor material and the nature of the band gap. Absorption coefficient values for the most commonly used semiconductor materials are widely available. The reflectance of the semiconductor surface depends on the surface finishing, particularly the shape and antireflection coating. Drift-diffusion parameters control the migration of charge towards the collecting junction; the parameters are carrier lifetimes and mobility's for electron and holes. It is also important to know the surface recombination velocities at the surface of the solar cell where minority carriers recombine. These factors effectively determine how much of the sun's energy a solar cell can capture and successfully convert to electrical energy.

For practical power applications, the voltage produced by one solar cell is usually not sufficient to power most equipment. An array of 20 to 80 solar cells connected in series to form a "Solar Module" is usually necessary to provide the required voltage. Solar cell manufacturers provide some key parameters of a solar module in their Data Sheet. The output power is given in Wp (Watt peak), which means the module is rated at Standard Test Conditions (STC). The STC are illumination levels of 1000 W/m2 (bright sunshine), a spectrum equivalent to Air Mass 1.5 and 25°C module temperature at the test. The manufacturer's data sheet also provides the short circuit current, the current produced when the output voltage is zero and the open circuit voltage, the voltage across the output terminals when there is no current flowing in the cell.

The simplified equivalent circuit of a solar cell consists of a diode and a current source which are switched in parallel. The current source generates the photo current IPh, which is directly proportional to the solar irradiance G. The p-n transition area of the solar cell is equivalent to a diode.
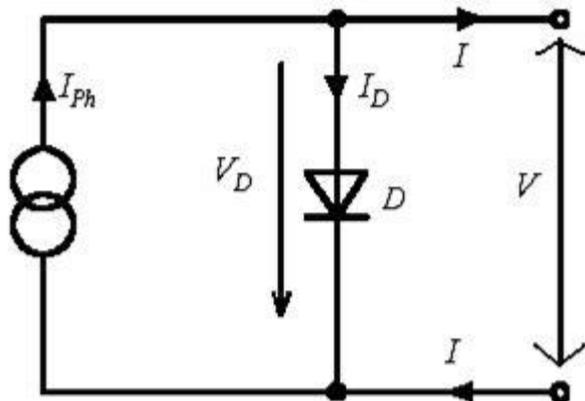
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Fig1 Equivalent circuit of solar cell

Fig 2 equivalent circuit for one diode modal of solar cell

The V-I equation of the simplified equivalent circuit could be derived from Kirchhoff's current law

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot (\exp(\frac{V}{m \cdot V_T}) - 1)$$

where

I_{Ph} --- Photo current

I_D --- Diode current

I_S --- Diode reverse saturation current

m is Diode ideal factor

$V_T = (k*T)/q$ is Thermal voltage (25.7 mV at 25°C)

k = Boltzmann Constant=1.3824*e-23

T = AbsoluteTemperature

q = charge of an electron=1.60*e-19 couloumbs

V = output voltage of the solar cell

I = output current through the solar cells

The simplified equivalent circuit doesn't give an optimal representation of the electrical process at the solar cell. In real solar cells a voltage loss on the way to the external contacts could be observed. This voltage loss could be expressed by a series resistor R_S. Furthermore leakage currents could be observed, which could be described by a parallel resistor RP
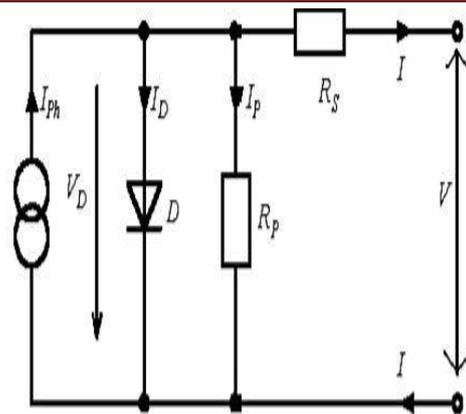
Derived from Kirchhoff´s first law the equation for the extended I-V curve could be achieved.

$$I = I_{Ph} - I_D - I_P$$

$$I_P = \frac{V_D}{R_P} = \left\{ \frac{(V \pm IR_S)}{R_P} \right\}$$

$$I = I_{Ph} - \left\{ I_S \left[\exp\left(\frac{q(V + IR_S)}{mkTN_S} \right) - 1 \right] \right\} - \frac{(V + IR_S)}{R_P}$$

Where

I Ph is the photo current

I D I is the Diode current

R_S is the cell's series resistance

R_P is the shunt resistance

MPPT Requirements

A tracker consists of two basic components as shown in Fig 3 a switch-mode converter and a control section with tracking capability. The switch-mode converter is the core of the entire supply. The main component of the MPPT in this work is the DC-DC buck converter that steps down the solar panel output voltage to the desired load voltage.

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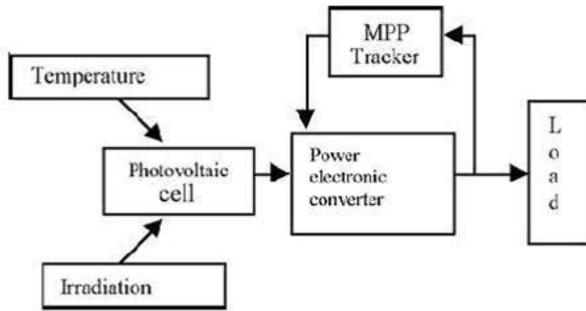*(NCDATES- 09ᵗʰ & 10ᵗʰ January 2015)*

Fig3 Block diagram Requirements of Maximum
power point tracking system

To ensure that the solar module operates at the maximum power point, the input impedance of the DC-DC converter must be adapted to force the solar module to work at its maximum power point.
Depending on the load requirement, different types of DC-DC converters can be employed in the MPPT design. For example, the boost converter is able to output a higher voltage from a nominal input voltage; other types of DC-DC converters include the buck-boost converter, CUK converter and full-bridge converter.

DC-DC Converters

DC –DC Converters acts as an interface between PV Panel and load, allowing the follow up of maximum power point. Its main task is to condition the energy generated by the array of cells following a specific control strategy. The DC-DC Conversion process implies in turn an associated effect of impedance transformation. Converters are impedance adopters similar to the transformers, except that in converters the adaptation parameter is not the turn's ratio between the primary and secondary but the duty cycle Delta, which can be governed electronically.
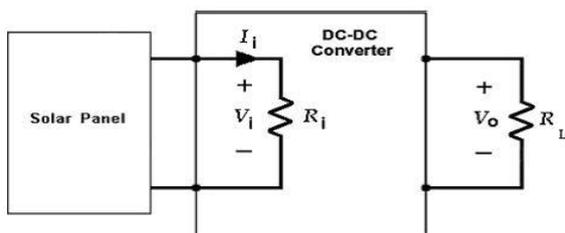

Fig 4 panel converter connection

DC-DC Converters are used in applications where average output value is required which can be higher (or) lower than the input voltage. This is achieved by governing the times in which the converters main switch conducts (or) does not conduct [PWM technique] usually to a constant frequency.
The buck converter uses energy storage components such as inductors and capacitors to control the energy flow from the solar module to the load by

continuously opening and closing a switch. The switch is usually an electronic device that operates in two states: in the conduction mode (on), the output of the solar cell is connected to an inductor while in the cut-off mode (off), the output of the solar module is disconnected from the inductor. The buck converter also contains a forward biased diode that provides a return path for the current in the Cut-off State.
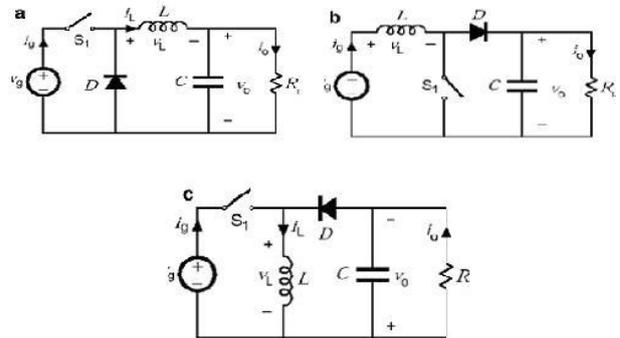

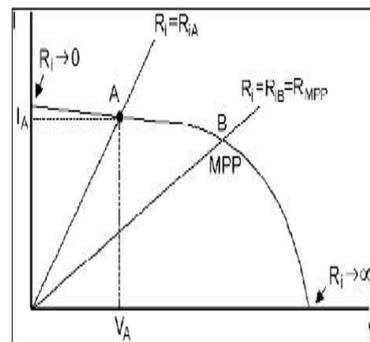Fig 5 DC-DC converters commonly used and their
Resistances

Fig.3.4: Location of the Operating Point of a Photovoltaic Module

Fig6 Location of the operating point of photovoltaic
module

The switch is actually a MOSFET that is controlled by a PWM signal. The switch conducts on and off to control the voltage level at the inductor. The voltage at the inductor has a rectangular waveform that is later filtered by the LC combination to produce a quasi-continuous voltage at the output. The average value of the rectangular waveform can be adjusted to control the length of the conduction and cut-off states of the switch. The on time of the switch is related to its time period such that $t_{on} = DT$, where D is the duty cycle.

In the ON state, current flows from the module through the inductor causing the inductor to store energy. In this state the diode is in reverse bias and no current flows through it. In the OFF state, the off time

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is given by toff = (1 - D)T and the current in the inductor causes the diode to become forward biased. The diode turns ON and provides a path to maintain the continuity of current through the inductor. The duty cycle can be adjusted to set the output voltage of the converter to the desired value. For an ideal DC-DC converter, the duty cycle is the ratio between the output voltage and the input voltage, D = Vo/Vi = Ii/Io. In this thesis, the DC-DC converter is used as a DC power supply, where the input voltage varies with temperature and Insulation conditions, but the output voltage is maintained at a desired value. This allows the duty cycle to be set such that the input voltage to the DC-DC converter is always set at the solar module's maximum power point voltage.

3.3 Control Section

The control section is designed to determine if the input is actually at the maximum power point by reading voltage/current back from the switching converter or from the array terminal and adjust the switch-mode section. Depending on the application, different feedback control parameters are needed to perform maximum power tracking. Most commonly voltage and power feedback controls are employed to control the system and hence to find the MPP of the array.

Implementation Of Perturb & Observe Algorithm

P&O is based on sensing two parameters at the terminal of the PV array: voltage and current. The operation of the algorithm is rather simple. It checks for output power of the PV array and compares its increase or decrease to the direction of increment of the operating voltage of the array itself.

If the PV array is operating in the left region of the graph, then any increment in the voltage would shift the power closer to the MPP and any decrement in the voltage would shift the power away from the MPP. Similarly, if the PV array is operating in the right region, then any increment (decrement) in the operating voltage would cause the power to decrease (increase). Table.4.1 shows a summary of the P&O algorithm.

Increment	Change in Power	Next Increment
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

Table 1 Summary of P&O Algorithm

Characteristics of P&O Technique

Although the Perturb and Observe algorithm is the most widely used for finding the maximum power point, it has a few drawbacks. The P&O technique is slow in finding the MPP and consequently it can fail to produce accurate results in rapidly changing conditions such as rapid changes in weather conditions, which results in greater oscillation around the ideal operating voltage. The error in the measurements is further increased by noise introduced by the high frequency DC-DC converters.

The most basic form of the P&O algorithm operates as follows. Table.4.1 describes about summary of P&O algorithm. Here it is assumed that PV module is operating at a point which is away from the MPP. In this algorithm the operating voltage of the PV module is incremented by a small value and the resulting change of power, $\Box$ P, is observed. If $\Box$ P is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage increment in the same direction should move the operating point towards the MPP. If $\Box$ P is negative, the operating point has moved away from the MPP and the direction of increment should be reversed to move back towards the MPP. Figure 7 shows the flowchart of this algorithm.
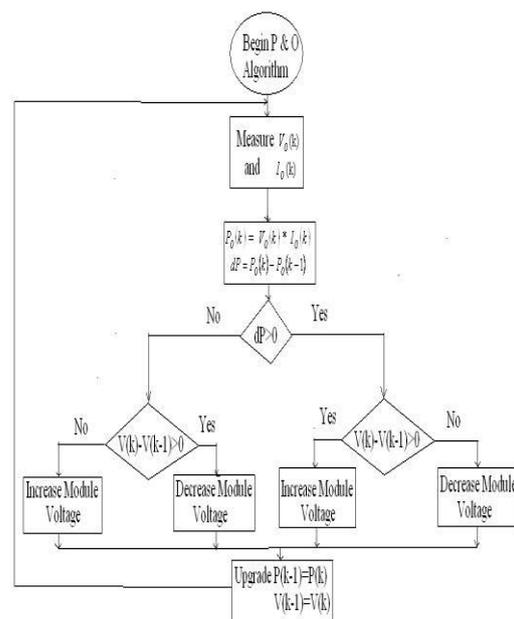

Fig. 7 Flow chart of P&O Algorithm

PROPOSED MPPT

The dc voltage controller is used to produce the reference current value for the id current controller. Its aim is to keep the voltage constant on the dc side in normal condition or during rapidly changing

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atmospheric conditions. The MPPT algorithm modulates the reference voltage V ∗ dc according to the environmental conditions in order to keep the operating point of the PV panels close to the MPP. In the conventional P&O method, the MPP is obtained from the PV array power by multiplying the voltage and current of PV arrays and comparing it with the previously measured power. In the case of a sudden increase in irradiance, the P&O algorithm reacts as if the increase occurred as a result of the previous perturbation of the array operating voltage.

The next perturbation, therefore, will be in the same direction as the previous one. Assuming that the system has been initially oscillating around the MPP, the path of this behavior is drawn in Fig. 6. It can be seen that a continuous perturbation in one direction will lead to an operating point far away from the actual MPP. This process continues until the increase in irradiance slows down or ends. To overcome the limitations of the P&O method, the proposed MPPT enables us to decouple the change in power caused by the simultaneous increment perturbation and irradiation variation. The irradiation variation is estimated by using the signal error of the PI controller of the dc voltage control. The PI regulator is designed to assure zero signal error if the atmospheric conditions are constant and a constant signal error in the opposite case. Hence, the signal error reflects only the change in power caused by the irradiation variation. After that ,in order to calculate the total change in the PV array power, 1the d-axis grid current component is used. Finally, the change in power caused by the previous perturbation is obtained by a simple subtraction; therefore, the correct direction of the MPP can be identified.

A. PV Power Calculation
In the synchronous rotating frame d, q, the active and reactive powers of a three-phase grid-connected VSI are given by

$$\begin{cases} P = \frac{3}{2}(\nu_d i_d + \nu_q i_q) \\ Q = \frac{3}{2}(\nu_d i_d - \nu_q i_d). \end{cases}$$

If the three-phase grid voltage is ideally sinusoidal without any harmonics, then in the d, q frame, the grid voltage vector is given by

$$\begin{cases} V_d = V \\ V_q = 0. \end{cases}$$

In practice, the grid voltage is non sinusoidal due to harmonics. Therefore, both Vd and

Vq will not be constant but have slight ripples whose frequencies and magnitudes depend on the harmonic components. However, in steady state, the average value of Vq is still equal to zero. Consequently, (5.1) can be re written as (5.3). Its active power depends on the d-axis current, and there active power depends on the q-axis current. Furthermore, in order to achieve unity power factor fundamental current flow, the q component of the command current vector is set to zero

$$\begin{cases} P = \frac{3}{2}(\nu_d i_d) \\ Q = \frac{3}{2}(\nu_d i_q). \end{cases}$$

Assuming lossless power transmission between solar array and grid line, the relationship of instantaneous active power exchanged between the PV array and the grid is given by

$$P_{pv} = P = \frac{3}{2}(\nu_d i_d).$$

This allows one to obtain the relation

$$i_d = \frac{2}{3V_d} P_{pv}.$$

Therefore, the PV power information can be obtained from thed-axis grid current component by the relation (5.5).

B. Signal Error of Outer Voltage Regulator
The change of d-axis current in one period sampling Te under irradiation variation is expressed by the following:

$$\Delta i_d(k) = \Delta i_V(k) + \Delta i_G(k).$$

iv(k) is the change of d-axis current component caused by the tracker perturbation, and∆iG(k) is the change of d-axis current component caused by the change in irradiation Fig 8 Thus, the dc bus-voltage control loop under changing irradiation can be modeled with the block diagram of Fig.9 where the current of PV array is an input disturbance. In this case, the error between voltage reference V ∗ dc and voltage measurement Vdcis the following:
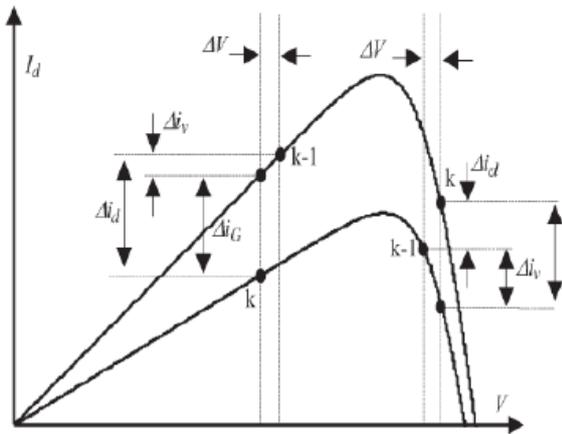
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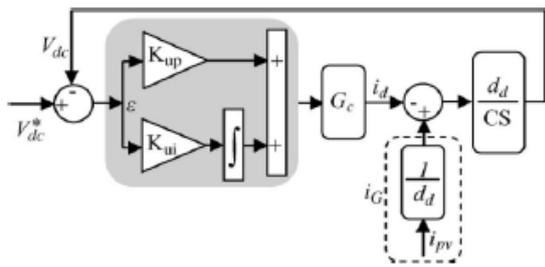Fig.8 Id–V characteristic under variable irradiation

Fig.9 Voltage loop diagram under variable irradiation

$$\varepsilon(s) = A(s)V_{dc}^{*}(s) + B(s)i_{G}(s)$$

$$A(s) = \frac{CS^2}{CS^2 + d_d k_{up}S + d_d k_{ui}}$$

$$B(s) = \frac{d_d}{C} \frac{S}{S^2 + \frac{d_d k_{up}}{C}S + \frac{d_d k_{ui}}{C}}.$$

If we consider only the impact of perturbation iG, we can write

$$\varepsilon(s) = \frac{d_d}{C} \frac{S}{S^2 + \frac{d_d k_{up}}{C}S + \frac{d_d k_{ui}}{C}} i_{G}(s).$$

Assuming that the rate of change in the irradiation is constant over one sampling period Teof the MPPT ($\Delta iG= \alpha.T$ e), theiG(s) expression can be written
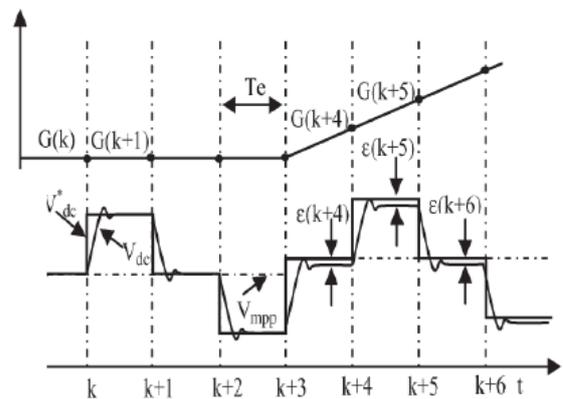
$$i_{G}(s)\frac{\alpha}{S^2}.$$

By inserting (5.8) into (5.9), the error is defined as

$$\varepsilon(s) = \frac{d_d}{C} \frac{\alpha}{S^3 + \frac{d_d k_{up}}{C}S^2 + \frac{d_d k_{ui}}{C}S}.$$

To calculate the signal error, we use the final value theorem for Laplace transforms. According to this theorem, as long as ε(s)

Fig 10 Voltage loop diagram under variable irradiation

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Fig.11 Flowchart of the proposed MPPT algorithm

The flowchart of the proposed MPPT is shown in Fig.10 The first step is to set up a fixed voltage whose value is about 0.8times of the PV array open-circuit voltage. Then, the instantaneous voltage of the PV array and the d-axis grid current component are measured using the saved previous voltage and current in order to calculate the differential values of id and

Vdc. After that, the iG and iV are calculated by using (5.13)and (5.3), respectively. With this information, two increments are calculated. The first IncV will be used when the PV array voltage is far away from the MPP voltage and the second IncG when irradiance change is present and the PV array voltageis initially equal to the voltage of the MPP. In the next test, if abs(ΔiV) is more than zero (the power change caused by the previous tracker perturbation is different from zero), the reference voltage of the PV array is given by adding IncVto the previous reference voltage (IncV can be positive or negative, depending on the sign of Vdc and iV). In the opposite case, the reference voltage is incremented with IncG (IncG can be positive or negative in function of the sign of iG) if abs(ΔiG)is more than zero (irradiance change is present), when

iG is equal to zero; the reference voltage increment is set to zero.

does not have any poles in the right half of the complex plane, except maybe $s = 0$, then

$$\varepsilon = \lim_{S \to 0} \left[\frac{d_d}{C} \frac{\alpha}{S^2 + \frac{d_d k_{up}}{C}S + \frac{d_d k}{C}} \right.$$

Hence, the signal error has the following form

$$\varepsilon = \frac{\alpha}{k_{ui}}.$$

Finally, the iG(k) that reflects only the change in power caused by the irradiation variation is defined as in

$$\Delta i_G = T_e.\varepsilon.k_{ui} = T_e k_{ui}.\left(V_{dc}^*(k-1) - V_{dc}(k) \right).$$