MAXIMUM POWER POINT TRACKING CONTROL USING BOOST CONVERTER FOR A GRID-CONNECTED PV SYSTEM

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ABSTRACT

This paper presents a solution to design a control scheme for a grid-connected photovoltaic (PV) system to solve maximum power point tracking (MPPT) problem. The designed control structure solves the nonlinear problems in the model of the inverters. Simulation results demonstrate that the implemented control scheme can accurately control the grid-connected PV system as required when an amount of radiation changes.

KEYWORDS: PV System, MPPT, P&O algorithm, DC-DC converter, DC-AC converters.

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1. INTRODUCTION

Grid-connected PV systems have become popular in life. There are two commonly used converter types: On-Grid and Off-Grid. For off-grid converters, the system needs an energy accumulator, usually batteries. During the daytime, excess energy will be accumulated into the storage. At night time, the system will take energy from the storage to use. For On-Grid converters, the system does not need an energy accumulator but converts energy directly onto the grid. This system needs to perform a grid-tie requirement. A typical structure is depicted in Figure 1. The system structure includes a solar panel connected to a DC-DC converter, an inverter converting the received power to the grid, and a DC bus to pair these two components.

Figure 1: Structure of a PV On-Grid System

2. MATHEMATICAL MODEL OF THE SYSTEM

2.1. Mathematical Model of the Solar Cell

Solar cells operate according to the I-V and P-V nonlinear characteristics, which vary linearly with solar radiation and the operating temperature of the photovoltaic cell. General modeling of photovoltaic cells was presented in [1-5]. The equivalent diagram of the system is depicted in Figure 2a. The V- I equation for a photoelectric cell is determined as below:

$$I = I_{PH} - I_S \left[\exp \left(\frac{q(V + IR_S)}{kT_c A} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \quad (1)$$

$$I_{PH} = I_{SC}^{STC} + K_i (T_{PV} + T_{PV}^{STC}) \frac{\lambda}{\lambda^{STC}} \quad (2)$$

The saturated current varies with the temperature of the photovoltaic cell, as determined by the following equation:

$$I_S = I_{RS} \left(\frac{T_C}{T_{PV}^{STC}} \right)^3 \left[\exp \frac{qE_\lambda \left(\frac{1}{T_{PV}^{STC}} - \frac{1}{T_C} \right)}{kA} \right] \quad (3)$$

Figure 2: a) Equivalent diagram of Photovoltaic Cells; b) Working Characteristics of Solar Cell

The P-V characteristic of solar cells shows that it is necessary to use adjustment methods so that the working point of the panel reaches a maximum [6-8] to maximize the capacity of the system.

2.2 Mathematical Models of the Boost

Several structures of boost-typed DC-DC converter have been implemented for PV systems [9-11]. Various control methods have been introduced. However, the algorithms implemented in [9-11] are quite complex, requiring the system to perform a lot of calculations. In this paper, the DC / DC converter shown in Figure 1 is used as a boost [12].

Figure 3: The Structure and Working State of the Boost Converter

- a) Boost converter structure
- b) Working state when the valve is closed
- c) Working state when the valve is open

The working states of the boost converter are shown in Figure 3. The boosters work with two states of the valve Q: ON or OFF. When valve Q is on, the inductor is connected to the source E, we have:

$$L \frac{di}{dt} = E \quad (4)$$

The current variation of the inductor when the valve is closed (ON):

$$\Delta I_{L_on} = \frac{1}{L} \int_0^{DT} E dt = \frac{DT}{L} E \quad (5)$$

When valve Q is opened (OFF), the coil is connected to the load, an equation describing the circuit is obtained as below:

$$E - v = L \frac{dI_L}{dt} \quad (6)$$

The current variation of the inductor during valve opening is described as follows:

$$\Delta I_{off} = \int_{DT}^T \frac{E-v}{L} dt = \frac{(E-v)(1-D)T}{L} \quad (7)$$

When the converter operates in a steady-state, the energy stored in the inductor at the beginning and the end of each cycle must be equal. Therefore $\Delta I_{L_on} = \Delta I_{L_off}$. From (5) and (7), we have:

$$\frac{DT}{L} E = \frac{(E-v)(1-D)T}{L} \Leftrightarrow E = v(1-D) \quad (8)$$

Equation (8) describes the input voltage of boosters with the change of duty D, in which $v = U_{DC}$ is the DC bus voltage; $E = V_{pv}$ is the PV voltage. From (8) we have:

$$V_{pv} = U_{DC} (1-D) \quad (9)$$

Equation (9) describes the dependence of PV voltage on the duty D of the boost converter in a grid-connected PV system.

2.3 Mathematical Model of Grid-Connected Inverters

The grid-connected inverter has the schematic diagram shown in Figure 1.

$$\bar{U}_L = R\bar{I}_L + L\frac{d\bar{I}_L}{dt} + \bar{U}_s \quad (10)$$

Equation of voltage across DC bus capacitors

$$C\frac{du_{dc}}{dt} = i_o - i_{dc} \quad (11)$$

Project (10) on the dq rotation coordinate with the rotation angle of the voltage vector u_d

$$\begin{cases} \frac{di_d}{dt} = -\frac{R}{L}i_d + \omega i_q - \frac{E_d}{L} + \frac{u_d}{L} \\ \frac{di_q}{dt} = -\frac{R}{L}i_q - \omega i_d - \frac{E_q}{L} + \frac{u_q}{L} \end{cases} \quad (12)$$

On the other hand, the DC power is the AC consumption. Therefore,

$$u_{dc}i_0 = \frac{3}{2}(u_{sd}i_d + u_{sq}i_q) \quad (13)$$

Applying i_o from (13) into (14) yields:

$$u_{dc}\left(C\frac{du_{dc}}{dt} + i_{dc}\right) = \frac{3}{2}(u_{sd}i_d + u_{sq}i_q) \quad (14)$$

From (12) and (14) we obtain:

$$\begin{cases} \frac{du_{dc}}{dt} = \frac{3}{2}\frac{(E_d i_d + E_q i_q)}{Cu_{dc}} - \frac{i_{dc}}{C} \\ \frac{di_d}{dt} = -\frac{R}{L}i_d + \omega i_q - \frac{E_d}{L} + \frac{u_d}{L} \\ \frac{di_q}{dt} = -\frac{R}{L}i_q - \omega i_d - \frac{E_q}{L} + \frac{u_q}{L} \end{cases} \quad (15)$$

The set of equations (15) describes the grid-connected converter on the dq coordinate system. In this model, we see a coupling between two dq axes. In order to implement system control, this coupling must be eliminated.

3. DESIGN AND CONTROLS

3.1. DC-DC Converter Controller

Two independent DC-DC and DC-AC converters are connected via the DC-Link bus. Therefore, the tuning of each converter can be considered independent. The output of the DC-DC converter is the input of the DC-AC converter, U_{DC} is the output of the DC-DC converter, and i_o is the input to the DC-AC converter.

The algorithm to find the maximum power point of a solar cell is based on the principle of output impedance adjustment to find the maximum power point of the panel. The most common algorithms are the P&O algorithm, incremental conductance, and fractional open-circuit voltage, in which the P&O algorithm is easily programmable. This algorithm can be implemented simply on microcontroller systems. Besides, assume that $U_{DC} = \text{constant}$. From (9), we find that the boost

converter input voltage V_{pv} is inversely proportional to duty D .

Combined with the P&O algorithm [15-17], we propose an algorithm summarized in Table 1 and Figure 4a

Table 1: The Operating Principle of the P&O Algorithm

Variation of Working Power (ΔP)	Variation of Working Voltage (ΔV)	Working Tendency of the System	Control Tendency
$\Delta P < 0$	$\Delta V < 0$	Position 1	Increase V_{ref}
$\Delta P < 0$	$\Delta V > 0$	Position 2	Decrease V_{ref}
$\Delta P > 0$	$\Delta V < 0$	Position 3	Decrease V_{ref}
$\Delta P > 0$	$\Delta V > 0$	Position 4	Increase V_{ref}

The P&O algorithm is depicted in Figure 5b. Initialize the system with initial values $P = 0$, $V = 0$; Solar panel voltage and current measurements are updated at the beginning of each calculation loop.

Figure 4: a) P-V characteristic; b) The P&O algorithm

Values used for control are voltage variation ΔV and power variation ΔP . If the voltage variation and the power variation are the same sign, duty D of the converter must decrease and vice versa. However, the increase or decrease of duty is not effective because the speed of change is slow. Even when the output voltage is less than the input voltage, the system cannot transmit the power. An added PI controller to speed up the convergence of the system is the solution to this problem.

3.2 Grid-Connected Controller

A method implemented for the grid-connected controller is the cascade controller [18-21], where the inner loop controls the current, and the outer loop controls the voltage. The goal of the grid-connected controller for the solar-cell system is to convert the PV power into the power consumed on the grid. Equation (14) shows that the power consumption P is related to two quantities U_{DC} and i_{dc} . Therefore, the outer loop controller aims to keep the U_{DC} stable.

Current Controller

Select control variables as follows

$$\begin{cases} \Delta u_{Ld} = Ri_{Ld} + L \frac{di_{Ld}}{dt} \\ \Delta u_{Lq} = Ri_{Lq} + L \frac{di_{Lq}}{dt} \end{cases} \quad (16)$$

Accordingly, (12) becomes

$$\begin{aligned} u_{sd} &= -\Delta u_d + \omega Li_q + u_d \\ u_{sq} &= -\Delta u_q - \omega Li_d + u_q \end{aligned} \quad (17)$$

By adding quantities containing components i_d and i_q that the system can suppress coupling, the control structure for the current loop is designed as shown in Figure 5

Figure 5: Structure of the Current Controller

where

$$A = \begin{bmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{bmatrix}; H_{dq} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}; G = \begin{bmatrix} 0 & \omega L \\ -\omega L & 0 \end{bmatrix}$$

Consider the time constant of the converter $T_{sw} = 1/f_{sw}$, where f_{sw} is the carrier frequency. The transfer function of the inner current loop is:

$$G_{io}(s) = \frac{1}{(1 + T_{sw}s)(R + Ls)} \quad (18)$$

Accordingly, we can apply the module optimization standard to find the parameters of the PI controller as follows:

$$k_{pi} = \frac{L}{2T_{sw}}; T_{ii} = \frac{L}{R}$$

The grid-connected inverter does not require the transmission of reactive power. Therefore the reference $i_{qref} = 0$. Accordingly, the control problem becomes voltage control, i.e. $U_{dc} = \text{constant}$.

Voltage Controller

Elimination of the coupling effect has been performed at the current regulator. The U_{DC} voltage regulator will provide the desired current value, i_d . The transfer function of the voltage loop becomes:

$$G_{uo}(s) = \frac{m}{Cs} \frac{1}{1 + 2T_t s} \quad (19)$$

where T_t is the sum of the time constants of the inner loop converter, m is the amplification factor of the power electronic converter.

Synthesize the controller according to the symmetric optimization method, we can select parameters of the a PI controller as follows:

$$k_{pu} = \frac{1}{kT_1\sqrt{a}}; T_{iu} = aT_1$$

4. SIMULATION RESULTS

Simulation parameters are provided in Table 2 and Table 3.

**Table 2: Parameters of the Solar Panels
1Soltech 1STH-215-P**

**Table 3: Parameters of the Grid-
Connected Converter**

Parameter	Unit	Value	MPPT
Rated power	P_{max}	213.15W	$dV = 1V, T_s = 10^{-4}s$
Open-circuit voltage	U_{oc}	36.3V	<i>Boost Converter</i>
Short-circuit current	I_{sc}	7.84A	$L = 0.1H, C1 = 0.1\mu F$
Voltage at maximum point	V_{mp}	29V	$k_p = 0.35; k_i = 10$
Current at maximum point	I_{mp}	7.35A	<i>Inverter</i>
Number of serial panels	N_s	10	$U_{dc} = 700VDC; C = 6000\mu F$
Number of parallel panels	N_p	5	$L = 10mH;$
			$k_{pi} = 25; k_{ii} = 100;$
			$k_{pu} = 0.2372; k_{iu} = 62.5$

Figure 6: Simulation diagram

The simulation scenario is as follows: First, the solar radiation varies from 0W/m^2 to 1000W/m^2 in 0.1s , stands at this value for 0.5s . Then, the solar radiation changes from 1000W/m^2 to 600W/m^2 in 0.1s , stands at this value for 0.4s .

Figure 7: Change in the Radiation Intensity

Figure 8: Panel Capacity

Figure 9: DC Voltage on DC-Link

Figure 10: The Converter Output Current on the dq axis

Figure 11: The Output Current of the Converter

Figure 12: Current and Voltage of the PV

Comments

The power of the panels depends on the variation of the light intensity impacting the panel, as shown in Figures 7 and Figure 8. The ability to track to the maximum power point of the P&O algorithm used in the paper ensures stability and impact time of the system, as depicted in Figure 8. Oscillation with step-change $dV = 1V$ is acceptable. The MPPT unit works correctly under conditions of varying radiation intensity. The current component i_q characterizing the reactive power is kept steady around zero. Therefore, a grid-connected PV system is introduced without causing any adverse effects to the grid, such as voltage distortion or phase shift. The current component i_d representing the power consumption transmitted into the grid varies depending on the input panel capacity.

Figure 10 shows that the current controller virtually eliminates the coupling effect. The standard sinusoidal three-phase current is provided by the SVM PWM modulation method at 5kHz, as shown in Figure 11. At this frequency, the power circuit can use various inexpensive popular switches, providing high practical applicability. The variation of the panel current and voltage is shown in Figure 12.

5. CONCLUSIONS

This paper uses P&O algorithm to control the boost converter to track the maximum power point of solar panels. The control method on the dq coordinate system for the grid-connected inverter has achieved the separation of the control channel separately from two current components, characteristic of power consumption and reactive power. The simulation results have proven the functional ability of the system.

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NOTATION LIST

I_{PH} : Photoelectric current

I_S : Saturated current

$q = 1.6 \times 10^{-19}C$: Atomic charge

$k = 1.38 \times 10^{-23} \text{J/K}$: Boltzmann's constant

T_C : Working temperature of the photovoltaic cell

A : Ideal constant of semiconductor materials

R_{SH} : Parallel resistance (shunt)

R_S : Serial resistance

I_{SC}^{STC} : Short-circuit current of the photoelectric cells at 25°C and 1kW/m^2

T_{PV} : The working temperature of the photovoltaic cells ($^\circ\text{C}$)

K_i : Short-circuit current temperature coefficient of photovoltaic cells

λ^{STC} : Solar radiation 1kW/m^2

I_{RS} : Current flows through the internal parallel resistance R_{SH}

E_λ : Distance energy of semiconductors of photovoltaic cells

T_{PV}^{STC} : Standard temperature of the photovoltaic cell $^\circ\text{C}$.

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