Modeling and Simulation of Photovoltaic Grid-Connected System

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Abstract. Based on the mathematical model of the photovoltaic array, we can construct a model of a three-phase photovoltaic grid-connected system consisted of a Photovoltaic Array, boost circuit, Maximum Power Point Tracking and photovoltaic inverter. Through the model of PSCAD/EMTDC simulation software, we can understand the principle of Maximum Power Point Tracking, comprehend the working principle of the photovoltaic inverter controller, analysis the influence of harmonics on power quality of power grid, and verify the correctness of the three-phase photovoltaic grid-connected system model.

Keywords: Photovoltaic power generation · Photovoltaic system modeling · Grid-connected control strategy · Compensation measures · Power quality

1 Introduction

With global warming and energy depletion, solar energy, as a clean, renewable energy source, has become the focus of many countries. The solar photovoltaic industry is one of the fastest growing and most stable fields in the world. Due to the subsidy policies of various countries, the cost of photovoltaic power generation has gradually decreased. In China, the number of grid-connected photovoltaic power stations is increasing, so the integral modeling and grid-connected characteristic analysis of photovoltaic system are particularly important. The analysis of the power grid characteristics caused by the connection of solar energy needs to be further improved. This paper is divided into four parts, based on PSCAD/EMTDC to study the three-phase photovoltaic grid-connected system.

2 Main Equipment of Photovoltaic Power Station

Primary equipment of photovoltaic power station is mainly composed of photovoltaic array, bus box, photovoltaic inverter, and other common electrical primary equipment. Photovoltaic cells are the most important components in photovoltaic power stations. Their role is to convert solar energy into electric energy. The output voltage and energy of a single photovoltaic cell is very low, so dozens of photovoltaic cells are usually

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encapsulated to form a photovoltaic module [1]. Then the photovoltaic modules connected in series and parallel to a photovoltaic array through the junction box and dc distribution cabinet. Inverter is the most important component of photovoltaic power station. Its function is to convert the direct current generated by the photovoltaic power station into the alternating current needed by the grid [2]. Photovoltaic inverters are usually three - phase full - bridge structures. The grid-connected control of the inverter and the self-protection function of the inverter are all included in the controller of the inverter. We can construct a model of a three-phase photovoltaic grid-connected system consisted of a Photovoltaic Array, boost circuit, Maximum Power Point Tracking and photovoltaic inverter [3, 4].

3 Maximum Power Point Tracking Technology

MPPT can keep the photovoltaic cell in the best working state constantly, that is, the maximum output power. The goal of MPPT is to control the output voltage of the photovoltaic array to track the MPP voltage, so that the photovoltaic array has the maximum photoelectric conversion efficiency [5]. The current Maximum Power Point Tracking technology includes constant voltage tracking method, short circuit current method, disturbance observation method, incremental conductance method, based on fuzzy control theory and artificial neural network intelligent theory and so on [6]. This paper will be based on the incremental conductance method of Maximum Power Point Tracking theory.

The output power of the photovoltaic cell is $P = UI$

Derivative U on both sides of the equation:

$$\frac{dP}{dU} = I + U\frac{dI}{dU} = 0$$

$$\frac{dI}{dU} = -\frac{I}{U}$$

$$dU = U(k) - U(k-1)$$

When:

$$\frac{dI}{dU} < -\frac{I}{U} \quad U > \text{maximum power point voltage}$$

$$\frac{dI}{dU} > -\frac{I}{U} \quad U < \text{maximum power point voltage}$$

$$\frac{dI}{dU} = -\frac{I}{U} \quad U = \text{maximum power point voltage}$$

In this way, we can obtain the voltage of maximum power point, and realize the power tracking. Generally, the photovoltaic cell's output voltage in the DC side is relatively low. Therefore, it is necessary to use the Boost circuit to increase the photovoltaic cell's

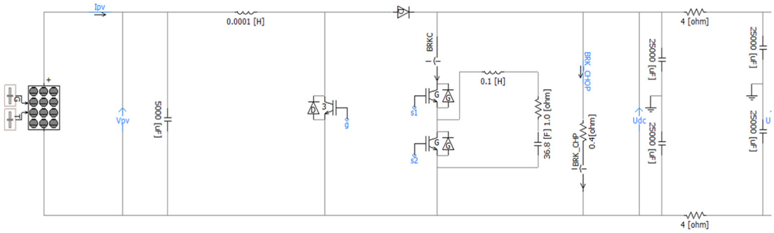

Fig. 1. Boost module of MPPT controlled

output voltage in the DC side and obtain the voltage needed by the power grid. The schematic diagram of Boost circuit in PSCAD is shown in Fig. 1.

First the instantaneous voltage V_{PV} and current I_{PV} of the photovoltaic cell are fed into the MPPT control module, then calculated the working voltage V_{MPPT} at the maximum power point. Compared with V_{MPPT}, the instantaneous voltage V_{PV} is controlled by PI control,V_{PV} outputs PWM drives signal "g" to control the switching of IGBT. When the duty cycle increases, appears in $V_{PV} > V_{MPPT}$; By adjusting duty cycle can obtain the expected PV output voltage.

The function of BRK-CHP is to prevent the damage caused by excessive current on the left side when the right side is empty. The part controlled by S1 and S2 is the crowbar protecting, which can play a role in accelerating and attenuating the rotor winding current, and the value of resistance seriously affects the effectiveness of the crowbar protection circuit (Fig. 2).

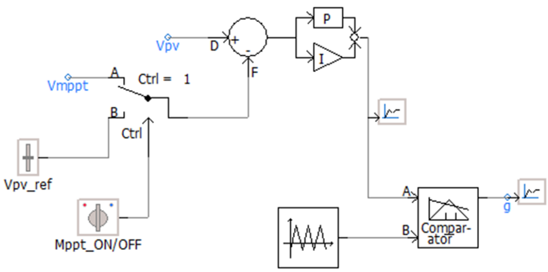

Fig. 2. PI closed loop control module

4 Grid-Connected Control Strategy Based on Rotating Coordinate System

Since the grid-connected terminal is a three-phase AC system, the research cannot be carried out in the static coordinate system [7]. All the existing methods require Park transformation and Clark transformation to realize the transformation from three-phase stationary coordinate system to two-phase rotating coordinate system. The following is the derivation of the formula: firstly, through the Park transformation, converted the coordinate quantity of ABC into the coordinate quantity of dq0:

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \sin\theta & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{1}$$

Make:

$$T_{abc-dq0} = \begin{bmatrix} \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \sin\theta & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \mathbf{u}_d \\ \mathbf{u}_q \end{bmatrix} = \mathbf{T}_{abc-dq}\begin{bmatrix} \mathbf{u}_a \\ \mathbf{u}_b \\ \mathbf{u}_c \end{bmatrix} = \begin{bmatrix} \mathbf{u}_M \\ \mathbf{0} \end{bmatrix} \tag{3}$$

Under the rotating coordinate system, $U_d = U_M$, $U_q = 0$

Generally speaking, if the grid does not have special requirements for reactive power, the inverter does not output reactive power, so make Q = 0, to achieve three-phase photovoltaic grid-connected system [8].

Similarly, the current of the photovoltaic system is transformed by parker, namely:

$$\begin{bmatrix} \mathbf{i}_d \\ \mathbf{i}_q \end{bmatrix} = \mathbf{T}_{abc-dq}\begin{bmatrix} \mathbf{i}_a \\ \mathbf{i}_b \\ \mathbf{i}_c \end{bmatrix} \tag{4}$$

Have:

$$\begin{cases} P = \mathbf{u}_d\mathbf{i}_d \\ Q = -\mathbf{u}_d\mathbf{i}_q \end{cases} \tag{5}$$

According to (5), power control can be converted into current control, where i_d controls active power and i_q controls reactive power (Fig. 3).

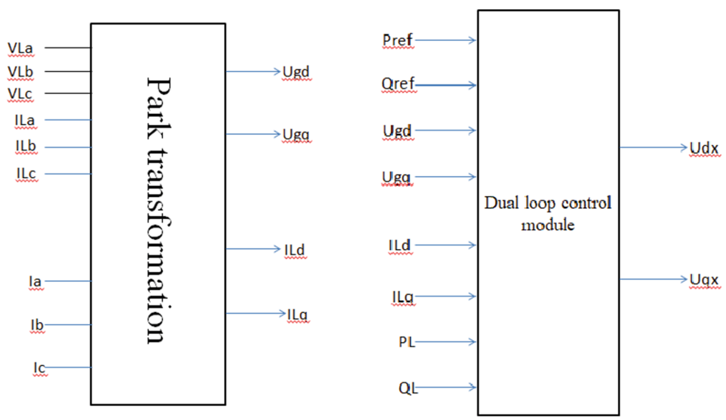

Fig. 3. Photovoltaic system inverter control part

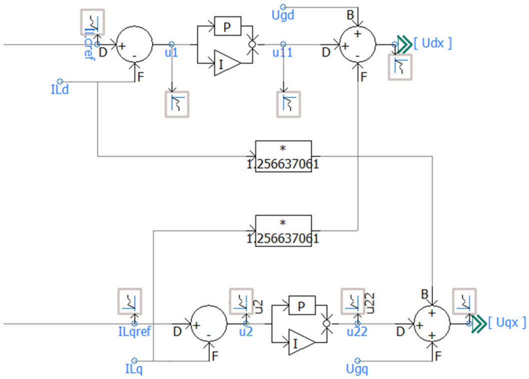

Fig. 4. Current loop control principle

The three-phase static state is changed into two-phase rotation [9]. The calculated DQ axis is used as the input of the current loop, and then the current loop is controlled, as shown in Fig. 4

To achieve the independence of the current decoupling control, we can introduce the current state feedback and grid voltage feed-forward compensation $i_{L\omega L}$, it eliminated the coupling voltage power grid voltage u of d and q axis current, the influence of the formula is as follows:

$$Udref = (idref - iLd)(K3 + \frac{K4}{S}) - iLq\omega L + Ud$$

$$Uqref = (iqref - iLq)(K3 + \frac{K4}{S}) + iLd\omega L + Uq$$

The PI controller can adjust the current according to the difference to ensure that the current output voltage can follow the grid voltage. The d, q axis voltage is converted into the sinusoidal modulation signal after inverse transformation, and the PWM controlled the switching of the three-phase inverter, so that the direct current of the photovoltaic power source is changed into three-phase alternating current with the same frequency and phase as the grid, and finally merged into the grid (Fig. 5).

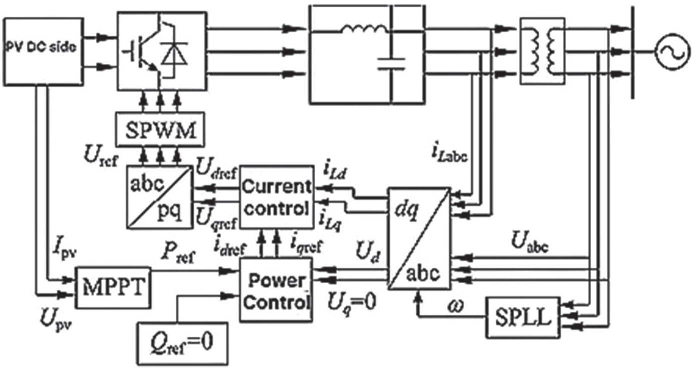

Fig. 5. Photovoltaic system PQ double loop control structure

I_{PV} and U_{PV} on the DC side of the photovoltaic array are sent to MPPT, and obtained the stable maximum power P_{ref} by using Maximum Power Point Tracking, at the same time the Q_{ref} is set to 0. The current and voltage in the three-phase power grid are converted into two-phase rotating d and q coordinates by a rotating coordinate system, and they are sent to PI power control together. I_{dref} is the reference value of the DC capacitor voltage U_{dcref} subtracts the actual value of the DC capacitor voltage U_{dc}, and then obtained by PI control. The reference value of I_{qref} is directly set to zero. The goal of outer loop power control is to make the active power sent by the inverter to the grid equal to the power emitted by the photovoltaic array, while the reactive power sent to the grid is equal to zero. U_{dref} and U_{qref} are obtained by current loop control, and finally they are applied to control the switch of the inverter through SPWM [10].

5 Simulation Analysis

5.1 Simulation Model

The photovoltaic array, combiner box, three-phase inverter, step-up transformer components, and inverter control module are used to build a grid-connected PSCAD simulation model of a photovoltaic power station, as shown in Fig. 6.

The photovoltaic modules connected in series and parallel to a photovoltaic array through the junction box and dc distribution cabinet. Inverter is the most important component of photovoltaic power station. Its function is to convert the direct current generated by the photovoltaic power station into the alternating current needed by the grid.

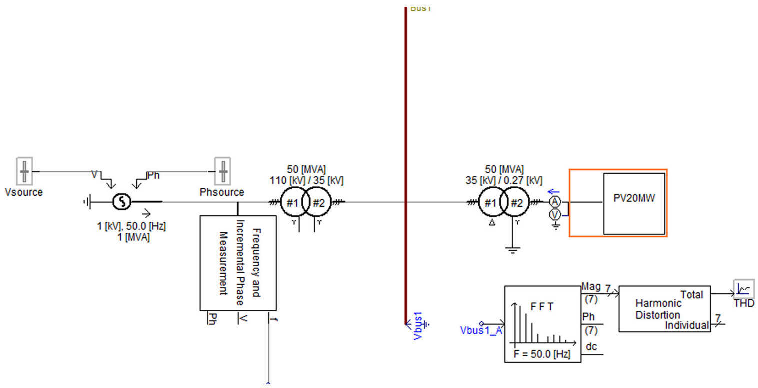

Fig. 6. Photovoltaic power station grid connected simulation module

5.2 Analysis of Simulation Results

Figure 7 is the power diagram of the photovoltaic power station after grid connection. It can be seen from the figure that the maximum power output after grid connection can reach 2.5 MW, meeting the power transmission requirements.

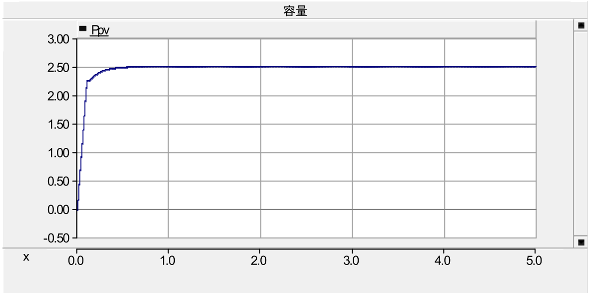

Fig. 7. Power diagram of 2.5 MW PV power grid after grid connection

According to the requirements, we adopted the 0.33 kV/110 kV boost technical scheme,and finally realize block power generation and centralized grid connection. It can be seen that the grid-connected side voltage can reach about 0.32 kV in a short time (Fig. 8), and the voltage deviation is $\frac{0.33-0.32}{0.33} \times 100\% = 3.03\%$, it can maintain stability, but the voltage has jitter.

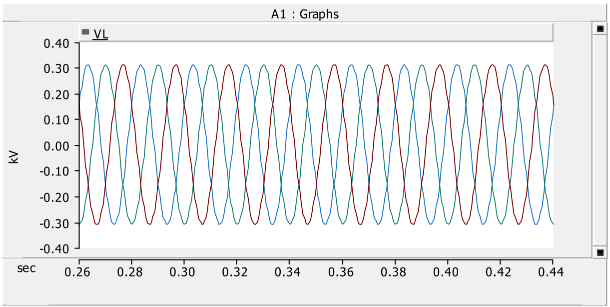

Fig. 8. Voltage waveform diagram of grid-connected slid after grid connection

In order to eliminate harmonics in the power grid as much as possible to obtain the best filtering effect, it is necessary to combine the parameters of the capacitor and the inductor. The LCL filter can be used as the first choice of grid-connected photovoltaic filter because of its compensation effect and low cost.

Add LCL filter in DC-AC inverter unit, the simulation is conducted again, and the total harmonic distortion rate after compensation is shown in Fig. 9.

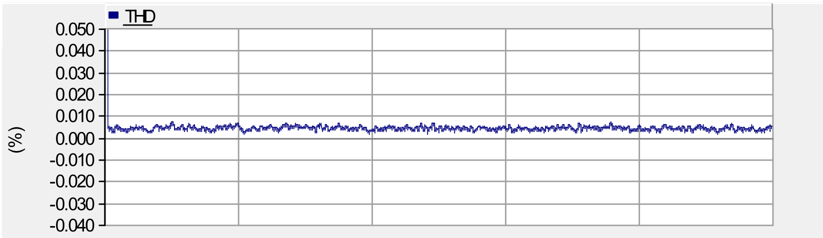

Fig. 9. Total harmonic distortion rate of grid-connected voltage after compensation

After the LCL filter is added to compensate, the total harmonic distortion rate of the a-phase voltage on the power grid side is reduced to about 0.08%. It can be concluded that the LCL filter has achieved a relatively good effect.

6 Conclusion

This paper introduces the photovoltaic array model based on engineering calculation, the Boost circuit with maximum power tracking function, and the inverter control with PQ decoupling, and realizes the overall modeling of the grid connection system of three-phase solar photovoltaic power generation. Finally, we analyzed the simulation model. Based on PSCAD/EMTDC, this paper studied the characteristics of three-phase grid connection of photovoltaic power generation. We built the model of photovoltaic power station and verified by simulation, which the result is correct. This paper analyzes the factors that affect the power quality of power grid, puts forward a feasible solution, and carries out simulation and verification, which provides a convenient method for the subsequent construction and research of photovoltaic power generation models.

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