Research on Experiment of Islanding Protection Device of Grid-connected Photovoltaic System Based on RTDS

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Abstract. Solar photovoltaic power generation is the power generation using solar cell module converting sunlight into DC electric energy. In the paper an equivalent model of solar photovoltaic power generation system is built in RTDS. The main circuit structure of the two-stage PV grid-connected system consists of the DC-DC, DC-AC circuit. The MPPT (Maximum Power Point Tracking) control of the PV array is controlled by adjusting the duty ratio of the DC-DC circuit. The proposed control strategy of constant voltage/constant reactive power (V/Q) control is successfully implemented grid-connected control of the inverter when grid-connected operation. The closed-loop experiment of islanding protection device of photovoltaic power plant on RTDS, verifies the correctness of the simulation model, and the experimental verification can be applied to this type of device.

1. Introduction
With the continuous growing of power demand, the supply of global energy sources becomes increasingly tight, and the use in solar energy is drawing more and more attentions currently. TO widely use the solar energy in distributed generation can not only cut down the consumption of traditional energy, but also reduce environmental pollution [1-5].

This paper proposes to use V/Q control mode to realize the grid-connected control of inverter, which will not need to use the complicated phase-locked loop control technology, and under the circumstance of constant electric current at the DC side of inverter, just adjusting DC busbar voltage and controlling the steady state reactive value at the side of grid to be 0 can guarantee the grid-connected operation requirement that the power factor of inverter is 1. The MPPT control of photovoltaic array is also one part of the control system in this paper, which adopts the constant voltage tracking method to track the MPP—Maximum Power Point quickly, and through the connection between great inductance and DC side of inverter, it can guarantee that the DC input by inverter is smooth, the simulation results indicate reasonable system structure, and the control system has high performance. Through the experiment of islanding protection device in photovoltaic power station, the photovoltaic grid-connected simulation system is verified to be able to use in the research of grid-connected simulation in large-scale photovoltaic power station and the closed-loop experiments of all kinds of devices.
2. Main topology of photovoltaic power generation system
The photovoltaic grid-connected system usually consists of three parts: photovoltaic array, photovoltaic inverter and power grid. The topological structure of grid-connected is shown in Fig 1.

Among them, the photovoltaic array consists of several photovoltaic modules, and the photovoltaic array output power is equivalent to the power in series-parallel connection of the component photovoltaic modules. The photovoltaic grid-connected inverter is to convert the DC output from solar energy cells into AC meeting power grid requirements and input it into the devices of power grid, which is the core of the energy transformation and control of grid-connected photovoltaic system.

This figure of grid-connected topology structure is the photovoltaic grid-connected inverter system for two-stage conversion. A DC energy-storage capacitor with enough capacity is usually installed between the pre-DC-DC convertor and post-DC-AC convertor, between 10 and 100e3 \( \mu F \) generally. This DC energy-storage capacitor can also have decoupling function in the control of pre-convertor and post-convertor, at the same time of energy change in the pre-convertor and post-convertor when buffering. Therefore, the control strategy on the pre-convertor and post-convertor can generally be researched independently [3].

The photovoltaic array at DC side and DC-DC convertor circuit in this paper adopt the interfacing technology with double controlled source in connection, while at three phase AC side, it is connected between interface transformer and load. In this paper, under the V/Q control mode of inverter, it is supposed that: firstly, the photovoltaic array shall be working under the STC (Standard Test Conditions). STC refers to the input condition with the external temperature 25\(^\circ\)C and the illumination intensity 1000\( \text{W/m}^2 \) [1-2].

3. Design of Control Circuit
The energy-storage capacitor C in Figure 1. Divides DC-DC convertor circuit and DC-AC convertor circuit into two parts, and their control designs can be carried out separately. The photovoltaic system controlled circuit in this paper is divided into two parts, the first part DC-DC convertor mainly realizes the MPPT control in photovoltaic cell array; the second part DC-AC convertor adopts V/Q control mode, and realizes the output voltage and frequency stabilization of inverter. There are two basic control goals in this part: firstly, to keep DC voltage stabilization in the front end; secondly, to realize grid-connected current control, or even need to adjust the reactive power of power grid according to instructions [7-8].

3.1. Controller design in DC-DC convertor circuit (Photovoltaic cell array MPPT control)
In order to increase the utilization efficiency of solar energy, we shall try our best to make the solar energy cell array run at MPP under STC, which is the basic requirement for solar energy cell to run. Thus, we shall carry out MPPT control on photovoltaic array [5][8]. The control block diagram is shown as Fig 2.
Among them: $U_{pv}$ is the voltage value at the end of photovoltaic array; $V_{ref}$ is the set value of the voltage value at the end of photovoltaic array.

The adoption of DC-DC circuit to realize MPPT control in solar energy cell array is a kind of the most common control modes. It uses PI regulator to control the duty ratio of switch tube $D$, and set reasonable PI control parameters. By comparison between the sampled signal of voltage at the end of photovoltaic array and the reference value of voltage, the modulating signal will be obtained after the error is adjusted by PI regulator. The signal is just the duty cycle of DC-DC circuit switching tube, and the carrier signal amplitude is set as 0-1. It is stipulated that, when the modulating signal is greater than or equal to the carrier signal, the switch tube will be connected, and otherwise it will be closed. In this way, it guarantees that the modulating signal amplitude is just the duty ratio $D$ of switching tube. If there is any requirement on the abrupt change in photovoltaic array power, the reference value voltage can be changed to realize power adjustment. This is a easy way in adjustment, and the constant voltage tracking method is easy to use under STC.

3.2. The controller design in DC-AC converter circuit

The single-phase circuit principle in the operation of connected grid for photovoltaic power generation is shown in Fig. 3 as below. The power grid is considered as the voltage source with infinite capacity, and $U$, $I$, $Z$ are respectively the voltage, current and resistance of the power grid, the inverter is equivalent to current supply, the output current is $i_o$, and the voltage, current and resistance in the equivalent load are $U_L$, $I_L$ and $Z_L$ respectively.

Because of the great inductance and smooth current connected at the side of DC busbar, it is set to be $I_0$. If DC busbar voltage $V$ is controlled, it is equivalent to control the active power $P$ input into the inverter.

$$P=U*I$$

(1)
\[ U_G = U_L + Z_G \cdot I_G \]  

(2)

Because the line impedance \( Z_G \) of power grid is little, it can be obtained that:

\[ U_G = U_L \]  

(3)

As can be seen in Formula (3), the output voltage of inverter is decided by the voltage of power grid. The active power \( P \) output from inverter and reactive power \( Q \) can be also expressed as:

\[ P = U_G \cdot I_o \cdot \cos(\angle U_G - \angle I_o) \]  

(4)

\[ Q = U_G \cdot I_o \cdot \sin(\angle U_G - \angle I_o) \]  

(5)

In order to input the high-quality electric energy to the power grid, the reactive power shall be reduced to the greatest extent in the power output from the inverter, and make the power factor be close to 1, namely require \( Q = 0 \). Because \( P \) input into power grid is positive, it can be obtained according to Formula (4) and Formula (5) that, \( \angle U_G = \angle I_o \), which can achieve the goal of the same phase.

According to the above analysis, control the reactive power \( Q = 0 \), which can make the power factor at the side of grid be 1.

The V/Q control mode adopted in this paper uses the principle of SPWM (Sinusoidal Pulse Width Modulation), which can realize the control of power factor at the side of grid well, and guarantee the grid-connected waveform quality. The V/Q control block diagram is shown in the below Fig. 4.

Among them: \( V \) is DC busbar voltage; \( V_{ref} \) is DC the set value of busbar voltage; \( Q \) is the reactive power transmitted into the power grid; \( Q_{ref} \) is the set value of reactive power; \( \text{Angle} \) is the phase position of sinusoidal modulated wave (rad); \( \text{Mag} \) is the amplitude of sinusoidal modulated wave; the carrier frequency is 3kHz, with amplitude range of 1, double polar modulation. SPWM modulated wave frequency adopts the grid frequency \( f \), and guarantees the requirement of the same frequency in grid-connected waveform and power grid.

![Circuit diagram of V/Q control](image)

**Fig.4** Circuit diagram of V/Q control

### 4. The experimental verification of islanding protection device in photovoltaic power station

According to the above discussion, build the islanding protection simulation model in the photovoltaic power station on RTDS/RSCAD, as shown in below Fig.6.
Fig. 5 is the system chart of the experiment of islanding protection device in photovoltaic power station. DC/DC and DC/AC are the two-stage conversion of DC-DC, DC-AC, L1 is 110kV circuit, L2 is 35kV circuit, T35 and T110 are both transformers, S110 is 110kV large power grid system. K1 to K5 in the figure are fault points, BRK1-BRK10 are breakers, and BRK1 is the grid-connected switch of photovoltaic system. This photovoltaic power station can be equivalent to 5 photovoltaic power generation models with the same capacity. The number of modules in series of every photovoltaic array $N_s=200$, the number of modules in parallel $N_p=100$, the number of cells in every module $N_c=36$. The open-circuit voltage value of single module under STC is $V_{oc}=21.7V$, the DC output voltage at MPPT calculated according to the theory of photovoltaic power generation is about 3.4kV, which value is the reference voltage of PI regulator $V_{ref}$. The maximum power of every equivalent photovoltaic array under STC is about 1MW. The power grid connects with LC filter circuit by interface transformer, and the filter capacitor among them uses Δ connection way, the model of interface transformer is Yd11. The major parameters in the system are shown in the below Table 1.

| Parameters                                           | Numerical Valuea |
|------------------------------------------------------|------------------|
| DC capacitance C                                     | $80e3\ \mu F$   |
| Inductance L in DC-DC circuit                        | 0.1H             |
| AC filter inductance L2                              | 0.0005H          |
| Filter capacitor Cf                                  | 10μF             |
| Changes in small-step and large-step interface       | 380V/380V        |
| transformers                                        |                  |

All of the photovoltaic modules shown in the above Fig. 5 adopt the model building proposed in this paper. In this control model, the PI regulator parameters in DC-DC circuit are set as below: proportionality coefficient $K_p=0.5$; integral coefficient $K_i=10$. In DC-AC circuit, proportionality coefficient $K_p=0.2$; integral coefficient $K_i=10$. The simulation waveform of single photovoltaic modules is shown in Fig. 6 as below.
In the above Fig.6, $V_{pv}$ is the actual value of voltage at the end of photovoltaic array; $I_{C, pv}$ is the actual value of current at the end of photovoltaic array; $P_{pv}$ is the actual value of the output power of photovoltaic array. PML is the actual value of the active power of input grid, and QML is the actual value of the reactive power of input grid. NA, NB and NC are 380V busbar grid-connected point voltage of the photovoltaic modules, and IBRKA, IBRKB, IBRKC are the electric current of every photovoltaic modules at the grid-connected location. The total harmonic contents of three-phase current (in consideration of the first seven times of harmonic waves) are respectively: 0.54%, 0.49%, 0.53%, so the harmonic contents are very little. Therefore, in the above-mentioned photovoltaic modeling approach, the output power is stable, which can be used in the application of the simulated engineering of large-scale photovoltaic power station.

This experiment connects the islanding protection device in photovoltaic power station into the three-phase voltages at the side of grid (380V of busbar voltage) and the grid-connected point (the exit of 35kV boosting transformer circuit) of the inverter in the photovoltaic new energy field and the position signals of Switch BRK1 to Switch BRK5 in the system. The actuating signals of switch BRK1 for cutting down or connecting with the grid in the islanding protection device will be connected with oscillograph and simulation system respectively.

According to the judging logic of the islanding protection device in photovoltaic power station, when there is any fault-free switch trip at K1 to K5, interphase in two-phase, two-phase grounding and three-phase fault, the grid-connected switch will all be cut down. The below Fig.7 is the experimental recorded waveform of ABG at K2 in the near-end of 110kV circuit.

In Fig.7, 1-T-BRK1 is the actuating signal of islanding detection device BRK1. When there is any fault in K2, the islanding detection device can detect that the corresponding voltages in 35kV busbar and 380V busbar reduce, and send out the grid-connected switch trip order after the delayed period of 300ms. The simulated grid-connected voltage in photovoltaic power station can output ideal voltage waveform under different operation conditions. The tested device can run reliably under the...
environment of photovoltaic grid connected, and the action of device is in conformity with the theoretical judgement. In the meantime, it also verifies the simulation model of photovoltaic grid connected built on RTDS can apply to the experiment of photovoltaic grid-connected device.

5. Conclusion
The photovoltaic grid-connected system uses RTDS/RSCAD in modeling and simulation, adopts V/Q control mode to realize the control in photovoltaic grid connected, simplifies the design in control system, and can realize the adjustable power factor well with good control effect. Through the verifications of all experiments in the closed loop of islanding protection device, the photovoltaic grid-connected model built by RTDS can apply to engineering practice.

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