Research on New Energy Power Generation Technology under Smart Grid

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Abstract. The paper introduces the new energy solar photovoltaic grid-connected power generation technology and system composition in the smart grid, and describes the basic working principles and functions of photoelectric conversion components and inverters. The article introduces the single-phase photovoltaic grid-connected inverter system and its control system design, tests and analyzes the harmonics generated by the inverter system after grid-connected, and proposes some further improvements and research and development work for the system in the future view.

1. Introduction
The large-scale application of renewable energy such as solar and wind energy will be an important symbol of human society's development in the 21st century. To achieve this goal, we must make renewable energy an indispensable and essential supplementary energy as soon as possible, making renewable energy development from the independent power supply mode in remote areas without electricity to the conventional grid-connected power generation in areas with electricity [1]. Significantly increase the utilization rate of renewable energy and improve the environment for sustainable social and economic development.

Since the application of solar photovoltaic power generation technology in the civil field in the 1970s, many photovoltaic power generation systems have been installed worldwide. These systems are mainly concentrated in communications, pipe network protection, traffic signals, and power supply for residents in remote areas. Most of these systems are applications of independent photovoltaic power generation systems. Due to the high timeliness of solar energy utilization, independent photovoltaic power generation systems must be equipped with complex energy storage systems, which much restrict their application; grid-connected photovoltaic power generation systems do not need to be equipped with complex energy storage systems, which saves investment and improves the reliability of power supply, surplus energy can also be fed into the grid [2]. More importantly, the grid-connected photovoltaic power generation system will break the power grid's unified mode from high-voltage to the low-voltage centralized power supply, and the emergence of a decentralized power supply mode (low voltage) will improve the reliability of the grid and the utilization rate of renewable power.

With the improvement of photovoltaic power generation systems' cost performance in recent years, its application range has become broader and broader. It has begun to develop from special occasion applications to commercial applications [3]. At present, dozens of MW-level solar photovoltaic power generation systems have been built in the world. In the 1990s, solar photovoltaic power generation...
technology, like other renewable energy technologies, has become a necessary technical means to reduce the global greenhouse effect. Many developed countries have begun to implement grid-connected solar photovoltaic power generation roof plans. This is a brand-new A photovoltaic grid-connected power generation system that combines solar energy technology with architectural design.

2. Composition of the solar photovoltaic grid-connected power generation system

The schematic diagram of the 10kW rooftop photovoltaic grid-connected power generation system is shown in Figure 1, including photovoltaic array and integrated frame, DC power distribution unit, inverter unit VSR, AC power distribution unit and metering unit, safety and protection system [4]. Lightning protection devices are installed at the output end of the photovoltaic array and the input end of the three-phase four-wire system on the grid side to ensure the system's safe and reliable operation.

![Diagram of 10kW solar photovoltaic grid-connected power generation system](image)

**Figure 1.** Composition of 10kW solar photovoltaic grid-connected power generation system.

The system design uses 13 strings and nine parallels, a total of 117 solar cell module array combinations, to finally form 3 independent single-phase (A, B, C) grid-connected inverter systems connected to the three-phase grid, and the rated value of each solar cell module Power PW(Wp)=85W. The advantage of this design is that the system is highly reliable and easy to maintain. Even if one phase fails, the other two phases can continue to generate electricity.

The photovoltaic array's orientation and elevation angles are 45° and 15° to the south and west, respectively. It is necessary to consider the ability to absorb as much solar energy as possible and the requirements of the house structure. The layout of the photovoltaic array of the grid-connected photovoltaic power generation system on the roof in the future will be restricted by the structure of the building [5]. The roof system's A system is similar to the 10kW system, but the A system divides the three-phase inverter vertical cabinet into three wall-mounted A, B, C single-phase inverter controllers; the B system is a wall-mounted single-phase inverter Converter controller.

The power generation system of the photovoltaic power station contains 20 sub-systems of 1MW; each sub-system of 1MW contains two 500kW photovoltaic units; each 500kW photovoltaic unit
includes one 500kW cell array and one 500kW photovoltaic inverter, project a total of 40 500kW photovoltaic units. In a photovoltaic unit, after the photovoltaic cell components are installed and connected, DC will be generated and collected in the current box, after passing through each corresponding DC switch cabinet, and finally flowing to the inverter to convert the DC to AC.

The AC low voltage (270~400 volts) converted by 2 inverters in every 2 photovoltaic units is stepped up to a high voltage of 35kV through a step-up transformer. After 20 photovoltaic sub-systems are connected in parallel, 4 cycles the 35kV collecting line is connected to the newly built 35kV power distribution room bus. The 35kV bus is connected by a single bus, and one 35kV overhead line from the power station is sent to the nearby 35kV voltage level public system.

Among them, the photovoltaic array also has components such as solar cell modules, photovoltaic combiner boxes, DC cabinets, and connecting cables. The grid-connected inverter also includes grid-connected inverters, AC cabinets, cables, etc. The photovoltaic power station monitoring system monitors the various components of the photovoltaic power station in real time, collects and processes various required data and the operating status of the equipment, has equipment failure alarm prompts, records and stores important information and data, and can also control the power station the equipment is remotely controlled.

Photovoltaic power generation, which represents a high level of typical daily solar radiation in a year, generally occurs from 12 noon to 14:00 in the afternoon. The maximum solar radiation of each month usually occurs at about 13:00 at noon, but according to the radiation intensity of each month the difference in level is slightly different when the solar radiation intensity is maximum. From 18:30 in the evening to 6 in the morning of the next day, the solar radiation is basically zero. From 6 to 13:00, the solar radiation gradually increases, and from 13:00 to 18:30 in the afternoon, the radiation gradually changes from the peak. Attenuate until it is zero.

3. Solar Photoelectric Conversion Module
At present, the varieties of solar photoelectric conversion modules that have entered commercial applications include monocrystalline silicon, polycrystalline silicon, and thin-film circuits. The photoelectric conversion efficiency of monocrystalline silicon photoelectric conversion modules is the highest, reaching 14% and 17%, and its manufacturing cost is high, with high stability and long service life. Generally, an area of 7080m² is required to set a 10kV square matrix. This system uses monocrystalline silicon photoelectric conversion components, provided by Solar Technology Co., Ltd.

The working principle of the solar photoelectric conversion module is the photovoltaic effect. When sunlight or other light sources illuminate the solar panel, the panel absorbs light energy and produces photogenerated electron-hole pairs. Under the electric field's action inside the battery, the photogenerated electrons and holes are separated. The three systems all use SEC-85C solar cell components, and their main electrical parameters are nominal power: 85W±2W; best working point voltage: 17.8V±0.5V; best working point current: 4.75A; open circuit voltage: 22.5V±0.5V; short-circuit current: 5.20A±0.3A. The above parameters' test conditions are measured under the standard conditions of solar irradiance 1kW/m², AM1.5, and single-chip temperature 25°C.

4. Working principle of inverter
4.1. Function of the inverter
(1) Realize high-quality electric energy conversion, convert the direct current generated by the solar photoelectric conversion module array into 220V, 50Hz single-phase, sine wave alternating current; its current and voltage distortion rates are less than 5%. (2) Realize the system's safety protection requirements, such as output overload protection, output short circuit protection, input reverse protection, DC overvoltage protection, AC overvoltage and under-voltage protection, "islanding" protection, and device self-protection; self-protection has power Module protection and overheating protection. "Islanding" protection means that when the inverter power supply is connected to the grid if the grid is suddenly disconnected, the inverter output will self-oscillate under an absolute load-
"islanding effect" occurs, the inverter power supply will be automatically shut down and related accident details. (3) To achieve the maximum power point tracking control, the solar cell's output power is related to the intensity of the sun shining on the surface of the cell and it’s matching with the load.

Figure 2 shows a set of output characteristics of solar cells under different illuminances. To make full use of solar cells, it is necessary to ensure that the voltage and current product is maximized under a certain degree of sunlight so that the output power of solar cells tends to be maximized. Find the maximum power point of the solar cell under each illuminance value from Figure 2, and connect the maximum power point with a smooth curve AB. The AB line is the maximum power line under different illuminance. It is easy to see from Figure 2 that the voltage value on the AB line is approximately constant above an absolute illuminance. Therefore, the current compensation control strategy based on the constant voltage is adopted in the 10kW system, which approximates the solar cell's maximum power point tracking control (MPPT). This approximate control scheme simplifies the MPPT algorithm while effectively solving the conventional oscillation caused by the MPPT algorithm enhances the system stability. This approximate MPPT algorithm is a constant voltage control (CVT) based on current compensation. The array voltage is changed because of the current compensation, as shown in the line segment A'B' in Figure 2. In the roof system, the control system is improved from the two-loop control (current and voltage) of the 10kW system to the three-loop control (maximum power, current, and voltage), and the outer loop control loop realizes the accurate maximum power point tracking according to the AB line control.

![Figure 2. Schematic diagram of maximum power point tracking.](image)

According to the characteristics of the solar cell modules used in the system, each cell module's operating voltage is 17V. This system uses 13 modules to work in series, and the DC voltage at the approximate maximum power point is set at 221V.

4.2. Single-phase grid-connected inverter and control strategy

4.2.1. Calculation of reducing voltage switch stress. (1) The composition of a 10kW single-phase photovoltaic grid-connected inverter system is shown in Figure 3. The system consists of a photovoltaic
array, a voltage-type reversible pulse width modulation (PWM) rectifier, an approximate maximum power point tracking unit (CVT with current compensation), and a reversible current control system based on 80C196MC. A single-phase VSR current predictive control algorithm with zero vector is discussed below.

![Single-phase photovoltaic grid-connected inverter system composition.](image)

In Figure 3, the power switch can quickly obtain the loop voltage equation from the AC side:

\[ e_s - R_i - L \frac{di}{dn} = V_n \]  

In the formula, \( e_s \) represents the grid voltage; \( i \) represents the grid-side current. \( R \) represents the loop's equivalent resistance, \( V_L \) represents the inductor terminal voltage, \( V_n \) represents the H-bridge AC terminal voltage, \( V_d \) represents the DC side voltage. So, we define the switch function

\[ S=1 \quad V_1, V_4 \]
\[ S=-1 \quad V_2, V_3 \]
\[ S=0 \quad V_1, V_3, V_2, V_4 \]  

When PWM control is performed by the switching function of formula (2), the AC terminal voltage of the H Bridge can be described as:

\[ V_n = \begin{cases} 
0 & S=0 \\
V_{dc} & S=1 \\
-V_{dc} & S=-1 
\end{cases} \]  

\[ V_n = SV_{dc} \]
In the formula, \( T \) represents the PWM switching period. To suppress the current rate of change and reduce the switching stress of the power tube in PWM control, we can symmetrically add a "zero vector" mode in a PWM carrier cycle to smooth the current waveform shown in Figure 4.

![Diagram](image)

**Figure 4.** Current tracking diagram with "zero vector" modulation added.

4.2.2. Design of voltage regulator. The key to the voltage outer loop control system's design is the voltage regulator, whose control performance will directly affect the operation of the single-phase PFC. Since single-phase PFC operation mainly completes AC/DC conversion and hopes to obtain a stable AC voltage, it is necessary to consider excellent anti-interference performance. A variable-speed integral PID adjustment algorithm can be used.

In the general PID digital algorithm, because the integral constant \( K_I \) does not change, the integral gain does not change during the entire adjustment process. However, the requirements of the control system for the integral term in the dynamic process are: when the system deviation is large, the integral action is weakened, and when the deviation is small, the integral action should be strengthened; otherwise, the output of the control system will be an overshoot, and the base will be saturated.

It can be seen that the value of \( f[\epsilon(n)] \) varies from 0 to 1. When the deviation is greater than the given separation interval \( A+B \), \( f[\epsilon(n)] \) is integrated. When the deviation is less than \( A+B \), the smaller the deviation, the greater the \( f[\epsilon(n)] \); the faster the cumulative acceleration; when the deviation is less than \( B \), the cumulative acceleration reaches the maximum, and the best values of \( A \) and \( B \) are finally determined through debugging.

(2) Different from integral separation PID algorithm

The variable-speed integral PID algorithm does not use the "switch" of the integral speed to switch. Still, it continuously changes its integral speed, so its regulation quality is further improved than the integral separation PID algorithm. The voltage and current control loop ensure that the system automatically tracks the grid side's voltage and frequency. Even when there is no sunlight on the solar panel, the "automatic tracking" is always maintained; when sunlight, the solar panel, the generated DC is converted into AC by an inverter and then input to the low-voltage power grid (single-phase 220V or three-phase 380V). After the grid-connected operation is completed, the system is automatically put into operation.
5. Harmonic test after grid connection

To further understand the influence of the grid-connected system on the harmonic current sent by the grid and the voltage waveform at the 380V grid-connected point, experts from the East China Electric Power Test and Research Institute are specifically invited to use the DZ-4E power quality analyzer to determine the harmonic voltage distortion rate and the 10kW grid-connected system. The second frequency spectrum analyzed the harmonic current content, and the results of the second measurement were the same.

Tests on various working conditions show that the harmonic current injected into the grid by the grid-connected system is below 1.0A, and the total voltage distortion rate THD is less than 1.0%; compared with the grid background voltage harmonic test, it does not make 380V the voltage waveform tends to deteriorate significantly. It can be seen from the spectrogram that the 5th harmonic voltage distortion rate is the largest. The total current distortion rate THD is mostly less than 10%, and the distortion degree of the three-phase current is different. The B-phase current has the most severe distortion. The highest is 11.07%; the second is the A-phase current, and the C-phase current has the smallest distortion, about 4.28% - 4.44%. The preliminary analysis believes that it is caused by the inconsistent nonlinear characteristics of the output isolation transformer. From the current waveform spectrum analysis, the current waveform contains 211 odd and even harmonic components, but the 2, 3, and 5 harmonic voltages are the main ones.

Due to the limitation of the local sunshine intensity, the grid-connected system's output power during the test is only 50% - 60% of the rated power, resulting in the A and B two-phase grid-side current distortion rate THD exceeding the allowable value IEEE-519 stipulates 5%). The factory inspection proved that, at rated power, the current distortion rate of A, B, C three-phase grid side is about 5%. Therefore, it is still worth discussing how to define the distortion rate of the harmonic current output when the load is not rated.

From the beginning of 2015 to the end of October 2019, a total of 3 sets of solar photovoltaic grid-connected power generation systems have been developed. From 10kW system to roof system, the main improvements are as follows:

1. At rated power, the inverter conversion efficiency is increased from 90% to 92%, the current distortion coefficient is decreased from 5% to 4%, and the voltage distortion coefficient is decreased from 1.8% to 0.9%; the power factor is increased from 0.96 to 0.997. Close to the required 1.0. (2) The control loop is changed from two-loop control (voltage control is an outer loop, current control is an inner loop) to three-loop control (maximum power point control is an outer loop, voltage control is a middle loop control is an inner loop). It is realized True maximum power point tracking. (3) The display operating system is changed from the conventional meter display and switch operation to the computer man-machine interface system displayed on the LCD screen. The inverter cabinet's size is reduced, the display accuracy is improved, and the operation is more convenient.

6. Conclusion

To make the solar photovoltaic grid-connected power generation system practical, we need to do a lot of research and development work: (1) to improve the cost performance of solar cell modules, from the current cost of 30 yuan/W to 1020 yuan/W, the photoelectric conversion efficiency increased by another 23%. (2) To improve the inverter's performance index, further improve the conversion efficiency and reduce the distortion coefficient. (3) Diversify solar cell modules to meet the requirements of building design. (4) To make the roof system a part of the architectural design, can it be beautiful and economical.

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