Research on Single-phase Photovoltaic Grid-connected Inverter

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Abstract
Grid-connected photovoltaic power generation is one of the main forms of utilizing solar energy and grid-connected inverter is the core part of the whole grid-connected photovoltaic power generation system, which shoulders the important task of AC and DC energy conversion. To guarantee the stability and reliability of grid-connected photovoltaic power generation, research on photovoltaic grid-connected inverter becomes extremely important. In recent years, two-stage single-phase photovoltaic grid-connected inverter has been applied more and more extensively in low power (within 5kW) single-phase photovoltaic grid-connected power generation system with its advantages of small volume and high power conversion efficiency etc.

Key words: grid-connected photovoltaic, inverter, energy conversion

1. Introduction

Energy is an important basic resource for the development of human society. With the continuous expansion of world economic scale, the world energy consumption keeps on increasing continuously. According to “2014 BP Energy Statistics”, the world primary energy consumption in 1973 was only 5.73 billion tons of oil equivalents; it has reached 9.47 billion tons of oil equivalents in 2003. In the past 30 years, the average annual growth rate of world energy consumption is about 1.8%. In 2007, the global energy consumption was 15.8 billion tons of standard coal, which has increased by 2.4% on the basis of that in 2006. According to the prediction results of Energy Information Administration (EIA), with the development of world economy and society, the world energy demand in the future will continue to increase. It is estimated that in 2010, the world energy demand will reach 10.599 billion tons of oil equivalents, 12.898 billion tons of oil equivalents in 2020 and 13.65 billion tons of oil equivalents in 2025, with average annual increase rate of 1.2%.

Solar power generation is with the broadest development prospect and is one of the renewable energy technologies that each country strives to develop. Joint Research Center (JRC) of Europe has made following predictions for the development of solar power generation in the future: in 2020, the power generated by world solar power generation will account for 1% of the total world energy demand; in 2050, it will account for 20% and in 2100, it will exceed 50%.

After 1980s, the categories of solar batteries increase continuously. Their application range is becoming broader and the market scale has been expanded gradually. After 1990s, photovoltaic power generation technology develops rapidly. In 2006, there are over 10 MW-level photovoltaic power generation stations have been set up in the world. America is the earliest country that made development plan of photovoltaic power generation, who proposed “million roofs plan” in 1997. Japan started up new sunshine plan in 1992. In late 1990s, photovoltaic power generation developed more rapidly. Between 1990 and 2005, the average annual increase rate of world photovoltaic module is about 15% and the photovoltaic module production in 1999 has reached 200MW. The efficiency of commercialized solar cell has increased from 10%-13% to 13%-15%. The production scale has expanded from 1~5MW/a to 5~25MW/a, which is expanding to 50MW/a and even 100MW/a.

2. Classification of photovoltaic power generation system

Classify the photovoltaic power generation system based on its relationship with power system; it can be divided into isolated photovoltaic power generation system and grid-connected photovoltaic power generation system, in which the isolated photovoltaic power generation system is a power generation system, which is not connected with conventional power system, operates independently, is usually established in remote areas far from the grid or is taken as mobile portable power supply in the field, while grid-connected photovoltaic power generation system is a photovoltaic power generation system that is connected with power system. It is the same as other power stations, which can provide active and reactive power to power system.

2.1. Independent photovoltaic power generation system

Independent photovoltaic power generation system is for grid-connected power generation system, which forms circuit within its closed circuit system, converts the solar radiation energy received to power supply load directly through solar cell and stores the excess energy into battery in the form of chemical energy through charge controller. Independent photovoltaic power generation system is composed of solar cell array, battery
pack, charge controller, inverter device and electric load. The structure of independent photovoltaic power generation system is as shown in figure 1.

![Structure of solar independent power generation system](image)

**Figure 1. Structure of solar independent power generation system**

The energy storage device of independent power generation system usually focuses on lead acid battery. The cost of battery accounts for 25% of initial equipment of solar photovoltaic power generation system. If the charge and discharge control for battery is relatively simple, it will cause advanced expiration of battery easily and increase the operation cost of the system. Battery accounts for 43% of investment cost in the 20 years of operation cycle. Most of batteries can’t reach the designed service life; in addition to the shortages of the battery itself as well as the poor maintenance, unreasonable battery operation management is the main reason for the advanced expiration of battery. Therefore, for independent solar photovoltaic power generation system, the investment cost for independent photovoltaic power generation system can be decreased by improving energy utilization rate and studying scientific control strategy for system energy.

### 2.2. Grid-connected photovoltaic power generation system

Different from the independently operated solar photovoltaic power generation system, grid-connected solar photovoltaic power generation system does not need to store the energy through battery and it can input power into public grid directly through grid-connected inverter. As it can input power into public grid directly, it can save the energy storage and release process of battery, decrease energy loss, save its occupation space as well as system investment and maintenance and decrease cost; the power generation capacity can be great and the reliability of power supply of electric equipment can be ensured. However, as inverter is connected with grid in parallel, so it has to keep the consistency of two groups of power supply voltage, phase, frequency and other electric characteristics, or else it will cause mutual charging and discharging between two groups of power supply and arouse internal consumption and instability of the whole power system.

The main component of grid-connected solar power generation system is inverter or power regulator. The inverter device converts the direct current produced by solar photovoltaic power generation system to standard alternating current that meets the requirements of power department. When the power department stops power supply, the inverter device needs to cut off the power automatically. When the power output by solar photovoltaic power generation system exceeds the actual demand of system load, transfer the surplus power to public grid. In rainy days or in the evening, when the output of solar photovoltaic power generation system is less than the actual demand of system load, it can supplement the requested power of system load through public grid. At the same time, it also needs to guarantee that during the failure or maintenance of public grid, the solar photovoltaic power generation system will not transfer the power to public grid, so that the system can operate stably and reliably. Grid-connected solar power generation is the development direction of solar photovoltaic power generation system and is the energy utilization technology with the most potentiality in the 21st century.
Grid-connected photovoltaic system structure is as shown in figure 2. Typical grid-connected photovoltaic system includes photovoltaic array, DC/DC converter, inverter and integrated replay protection device. DC loop can be set up between converter and inverter through DC/DC boost chopper converter. Boost chopper increases voltage of photovoltaic array to a suitable level based on grid voltage; at the same time, DC/DC converter increases the economic performance of photovoltaic grid-connected system as the maximum power point tracker. The inverter is used to provide power to AC power system; replay protection system can guarantee the safety of photovoltaic grid-connected system and power network.

2.3. Conversion efficiency of solar cell and cost of solar power generation

Photovoltaic power generation is with inexhaustible, convenient to get electricity, clean and environmental-friendly characteristics, which display great development potentiality. The laboratory efficiency of monocrystalline silicon battery has been increased from 6% in 1950s to current 24.7%. The laboratory efficiency of polycrystalline silicon battery has reached 20.3%. The research work of thin film battery has attained great success. The experimental stability efficiency of amorphous silicon thin film battery has reached 16.6%, the laboratory stability efficiency of cadmium telluride (Cd Te) has reached 16.4% and the laboratory efficiency of copper indium gallium selenium (CIGS) has reached 19.5%.

In the aspect of commercial battery, the conversion efficiencies of various batteries are increasing gradually. In view of the investigation data of EPIA (Northeast Securities Research Institute) in 2016, GaAs thin film cell is with the highest commercial photoelectric conversion efficiency at 22%, but the manufacturing cost is high, the resource is poor and manufacturing pollution degree is high, all these shortages make it unable to be used universally; amorphous silicon thin film battery is with low manufacturing cost, rich resources and low manufacturing pollution degree, but its conversion rate is less than 10%, which restricts its development; for crystalline silicon, especially for polycrystalline silicon, the conversion rate reaches more than ten percent, the manufacturing cost is low and the manufacturing pollution degree is low, so that it can be popularized among numerous battery materials. At the moment, crystalline silicon is with the highest market share at 90% among various batteries.

The cost of solar power generation is decreasing continuously with the progress of technology and the popularization of commercialization. The cost of photovoltaic module has decreased from USD70/Wp in 1970s to USD3/Wp in 2008. The progress of technology and commercialization are key factors of cost decrease. Table 1 lists the costs of photovoltaic power generation system of install equipments in different regions in 2007 estimated based on EPIA and the costs are ranging from Euro 0.22-0.44 per kWh and the average is about Euro0.32 per kWh. If calculate based on the exchange rate between Euro and RMB at about 9.5 in the end of 2008, the price is about RMB3/kWh. However, under the attack of global economic crisis, the overcapacity of photovoltaic module exceeds 1GW. The prices for the raw materials of photovoltaic decrease greatly. The price of terminal PV module also experiences great decrease. It is believed that this will greatly decrease the installation cost of photovoltaic system.

<table>
<thead>
<tr>
<th>Cities</th>
<th>Sunshine hours</th>
<th>Cost (Euro)</th>
<th>Cost (RMB)</th>
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<tr>
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<td>900</td>
<td>0.44</td>
<td>4.18</td>
</tr>
<tr>
<td>Paris</td>
<td>1000</td>
<td>0.39</td>
<td>3.705</td>
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<tr>
<td>Washington</td>
<td>1200</td>
<td>0.33</td>
<td>3.135</td>
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<tr>
<td>Hong Kong</td>
<td>1300</td>
<td>0.30</td>
<td>2.85</td>
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<tr>
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<td>1400</td>
<td>0.28</td>
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<tr>
<td>Bangkok</td>
<td>1600</td>
<td>0.25</td>
<td>2.375</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>1800</td>
<td>0.22</td>
<td>2.09</td>
</tr>
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</table>

3. Maximum power point tracking technology for solar cell

The output power of solar cell array is in close relationship with the changes of sunshine intensity, temperature and load; its output characteristics are non-linear. Under certain temperature and sunshine intensity, solar cell is with the only maximum power point. The solar cell can output the maximum power under current temperature and sunshine only when it works at this point. Therefore, in solar power generation system, an important way of improving the overall system efficiency is to adjust the working point of solar cell in real time and make it near the maximum power point all the time, which process has been called as maximum power point tracking.

3.1. Working principle and output characteristics of solar cell

Solar cell is a device which converts the light of solar radiation into electricity through semiconductor...
material with adoption of photoelectric conversion principle. This photoelectric conversion process is usually called as “photovoltaic effect”, which refers to that the sunlight makes inhomogeneous semiconductor or semiconductor and different parts of metal combination produce potential difference. At present, the production cost of solar cell is high and the efficiency is low, which become bottlenecks that restrict its development. Therefore, it becomes a big research subject of developing solar industry to master the working principle and characteristics of solar cell and then attain the maximum power generation amount within unit area.

3.1.1. Working principle of solar cell

It is generally hoped that there are more minority carriers in optically excited carriers move to P-N node area. Drift to the other side through the traction function of P-N node for minority carrier and form photo generated electric field with opposite direction to P-N junction barrier electric field. There will be electricity once it connects the external circuit. When combine numerous of such small solar photovoltaic cell units together in series and parallel mode to form photovoltaic cell module, it will output enough electricity under the role of solar energy.

The numbers of electron hole pairs produced by semiconductor materials under different temperatures and light radiations are different. Photovoltaic cell is produced with adoption of photovoltaic effect principle. P-N node is the core of its working principle. Photovoltaic cell can be made into P+/N structure or N+/P structure, in where the first symbol of P+ and N+ represents the conductive type of semiconductor material of front illumination layer of photovoltaic cell; the second symbol of N and P represent the conductive type of substrate semiconductor material of photovoltaic cell. The electrical property of photovoltaic cell is related to the characteristics of semiconductor material used by cell manufacturing. Under light radiation, the polar of output voltage of photovoltaic cell takes P type lateral electrode as positive and N type lateral electrode as negative.

3.1.2. Equivalent circuit and output characteristics of solar cell

The ideal form and actual form of equivalent circuit of photovoltaic cell are as shown in figure 3 (a) and (b), in which Iph is photocurrent. Iph value is proportional to the area of photovoltaic cell and irradiance of incident light. With the rising of ambient temperature, Iph value will increase a little bit. ID is dark current, which refers to the single phase current run through P-N node under external voltage function when there is no sunshine for photovoltaic cell. Its side reflects the changing situation of the total diffusion current produced by P-N node under current ambient temperature. IL is load current of photovoltaic cell output. Uoc is the open circuit voltage of cell. RL is external load resistance of cell. Rs is series resistance, which is usually smaller than 1Ω and is mainly composed of volume resistance of cell, surface resistance, electrode conductor resistance, contacting resistance between electrode and silicon surface as well as metal conductor resistance etc. Rsh is bypass resistance, which is generally thousands of ohms. Both Rs and Rsh are inherent resistances of silicon type photovoltaic cell, which are equal to the internal resistance of photovoltaic cell. For an ideal photovoltaic cell, because the Rs in series is small and Rsh in parallel is big, when make ideal circuit calculation, they can be neglected, which makes that the ideal equivalent circuit only equals to the parallel connection between constant current source and one diode, as shown in figure 3 (a).

![Figure 3. Equivalent circuit diagram of photovoltaic cell](image)

3.1.3. Temperature characteristics and illumination characteristics of solar cell

The temperature characteristics of photovoltaic cell refers to the influence of working environment temperature increasing of photovoltaic cell and temperature increasing after cell absorbing photon on the performance of cell; as most of parameters within photovoltaic cell materials are the functions of temperature and light intensity, such as intrinsic carrier concentration, carrier diffusion length and photon absorption coefficient etc, so the reflected illumination characteristics refer to the relationship between electrical performance of silicon type photovoltaic cell and light intensity.
Figure 4 is the temperature characteristics of solar cell. It can be seen that the open circuit voltage of solar cell decreases with the increasing of temperature, the short circuit current increases with the increasing of temperature, the output power of cell decreases with the increasing of time in general. The illumination characteristics of solar cell are as shown in figure 5. The open circuit voltage of solar cell increases logarithmically with the increasing of light intensity and it increases fast with weak light and it tends to be saturated with strong light. It can also be seen from figure 2.4 that the short circuit current and output power of solar cell is in proportion to light intensity.

3.2. Design of maximum power point tracking system

Maximum power point tracking technology is mainly realized through three parts of signal detection and conditioning circuit, MPPT control system and output conditioning circuit.

(1) Signal detection and conditioning circuit: the detection of output voltage and output current of solar array is very important for realizing maximum power tracking function. Accurate voltage and current measured values are good for improving the accuracy of the maximum power point tracking. When the amplitude of converted analog quantity is too big, too small or has strict requirements for conversion accuracy, it usually needs to adjust the signal output by sensor.

(2) MPPT control system: MPPT control system mainly accomplishes the computational function in maximum power point tracking algorithm and it adopts multi-channel A/D within DSP chip to make digital to analog conversion for output voltage and output current of solar array; interrupt mode has been adopted to handle affairs; computational results have been output by PMW pulse train; distribute certain amount of I/O in DSP chip for status display and fault signal input interface; store historical data into EEPROM.

(3) Output conditioning circuit: results after DSP chip operation will be taken as current specified values of grid-connected converter. To attain high-accurate output, it needs to design output conditioning circuit to make filtering and other conditions for output PWM signal. The software program module of maximum power tracking is composed of program module, system initialization module, PWM output program module, A/D conversion module of current and voltage, disturbance observation algorithm program module and fault handling module etc.

4. Conclusions
With the continuous increasing of people’s understanding of energy and environmental problems, developing and utilizing clean and renewable energy has drawn more and more attentions from governments in all countries. As a clean and safe renewable energy, solar energy is becoming one of the main alternative energies of fossil energy with high pollution. In recent decades, solar photovoltaic power generation technology has gained unprecedented development, in which photovoltaic grid-connected power generation technology has become one of the main ways of utilizing solar energy. Due to the limitations of level of knowledge and practical experience, this paper makes the most preliminary exploration of photovoltaic grid-connected inverter system. It is hoped that his paper will plays a trigger role to arouse more readers’ reflections on solar power generation system.

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