Research Review of Photovoltaic Power Generation System

Jiabei Jiang *
Shenzhen College of International Education, China.

*Corresponding author e-mail: sjdjfjrb0703@gmail.com

Abstract. The non-renewable energy resources are being consumed at an increasing rate as the society develops. At the same time, the general public’s environmental awareness is improving in response to the deteriorating environment. All countries around the world are actively exploring an energy source that is suitable for sustainable utilization and causes no pollution. Solar power is a new form of energy that is efficient, pollution-free, and can be utilized globally in the future, therefore, the leaders of many countries are paying high attention to relating researches. As photovoltaic power generation is clean and having a high flexibility and broad utilization, it has advantages over other forms of energy. At the moment, grid-connected photovoltaic technology has a significant and enormous potential. As a result, it is necessary to study the PV generation technology, which is this article’s main research object. This is done by first reading related articles to learn the latest developments and current difficulties in this area, then focusing on articles that target these problems in order to find solutions theoretically, understanding the structure of the control system, and finally creating a digital simulation in MATLAB to enhance understanding.

Key words: Photovoltaic power generation; grid-connected inverters; control strategies; maximum powerpoint tracking.

1. Introduction

1.1. Background and Significance
The mankind has been using fossil energy resources from thousands of years ago, the three most extensively used of which, coal, oil and natural gas, have played an important part in the social development of human beings. When animals and plants dead they are buried by sediment, while fossil fuels are formed from these remains of organisms underground which are impacted by high temperature and pressure for a very long period of time, therefore, they are not renewable. By now the proven and predicted reserves of fossil fuels can not keep abreast with human beings’ escalating demand for energy. Therefore, people must realize a energy transition from fossil fuels to a cleaner and renewable form, as a countermeasure against the impending energy crisis. In addition, the usage of fossil fuels have caused adverse effects on the environment, and some of the damages are irreversible. For example, every year 5,000,000 tons of sulfur dioxide is released during the combustion process of coal in the worldwide coal plants, giving rise to acid rain and other phenomena that harm the environment and people’s health. The extraction and combustion of all kinds of fossil fuels release green house gases including carbon dioxide.
and methane, which leads to global warming. The serious consequences including but not limiting to the melting of polar glaciers, increased probability of extreme weather, rise in sea level and destruction of ecological balance. However there is no such drawbacks and limitations when it comes to the usage of renewable resources. They are renewable, inexhaustible and pollution free, therefore, have a greater potential than non-renewable resources and contribute to a sustainable development. Recent years the demand for renewable resources increases fast: the International Energy Agency (IEA) estimates that there will be a 50% increase in the global renewable capacity from 2019 to 2014. Globally influenced by COVID-19, the demand for fossil fuels decreases in 2020, oppositely, the demand for renewable energy resources increases compared to the year before. Many countries are decreasing the usage of fossil fuels on purpose, for example the UN Secretary General proposes to stop building new coal plants [1]; the dutch government has prohibited houses that use natural gas from being built from 2018 and will provide subsidies with an aim of reaching zero-natural-gas-using residences by the year of 5050.

This article focus on photovoltaic power generation system that makes use of sunlight. Solar energy falls in to the category of renewable energy, can be considered endless in supply and does not pollute the environment. At the same time, Solar power has much less geographical restrictions than wind power, hydraulic power and other renewable energy resources: solar panels can be built at mountainous terrains and regions that are windless and waterless, they can even be built at the top of buildings, which is very space-saving. Solar power accounts for 60% growth of renewable energy mentioned above, and photovoltaic power capacity is predicted to reach 250% of 2019’s, which is 530GW [2], by the year of 2024. Since the first modern solar battery is invented in 1954, PV technology has developed rapidly. The following contents are about the development process and current status of solar energy in different countries.

1.2. The Solar Energy Industry at Home and Abroad
China has a vast territory and hence abundant solar energy. Most of the areas possess a light irradiance more than 4kWh/m², for Xizang tibet and other remote areas the light irradiance can reach to 7kWh/ m². According to the IEA’s estimation for 2019-2024, China will account for 50% of the gross solar power growth. China developed their first monocrystalline silicon in the year of 1958, after that in 1986 the State Development Planning Commission (SDPC) put forward the proposal in the seventh five-year plan, requiring six universities and six research institutions to research with a topic related to crystalline silicon solar cells. At the late 1980s, several production lines for photovoltaic cells were introduced, boosting the capacity from a few hundred kilowatts to 4.5GW. The Chinese government officially started to attach attention to solar power in 1988 and the growth became the most rapid during 2005-2016, with an annual growth around 40% and more than 5000 related manufacturing enterprises have been set up. For the thirteenth five-year plan from 2016-2020, the China National Energy Administration set the target in regard to industrial upgrading, lowering cost and expanding the application of solar power: It was planned to increase the PV power generation capacity up to 105GW and the area of heat utilization up to 800M m². The plan contributes to the long-term target that the usage of non-fossil fuels occupying 20% of the total primary energy consumption by 2030, and lowering human impact on the environment. According to calculations, it is equivalent to decreasing the emission of carbon dioxide by 370Mt, sulfur dioxide by 1.2Mt, nitrogen oxides by 0.9Mt and smoke by 1.1Mt.

America, Germany, Italy, Spain and other European countries are the leading countries in the solar power industry and played a major role in developing photovoltaic cells. In the early stage photovoltaic power generation was mostly used in outer space, as early as the year of 1966 NASA launched the first Orbiting Astronomical Observatory powered by a 1kW PV array, and the first solar building was built by the University of Delaware not until 1973, soon after that Solar Energy Research Institute (SERI) was set up in 1974. By now, the American government provides solar power related projects capital around 2.6G dollars per year. Germany was the first country to reach a capacity over 1GW together with Japan in 2004. Germany’s feed-in tariff accelerated the development of solar power industry that generating capacity increased 250-350MW per year, however, in 2012 the government announced a less
generous subsidy which slows down the development. Germany’s long term goal is to let solar energy occupying 40-45% of the total renewable energy used by 2020, and 55-60% by 2030.

2. Photovoltaic Generation System

2.1. The Structure of Photovoltaic Power Generation System
Photovoltaic power generation system transforms solar radiation energy into electrical energy, which can be classified into grid and off-grid systems according to their way of connection with the public power grid. The system is composed of photovoltaic array, storage battery, DC-DC boost circuit, MPPT controller, DC-AC inverter circuit and the load.

(1) Photovoltaic cells are usually made from semiconductors including monocrystalline silicon, polycrystalline silicon, amorphous silicon and others. On the account of the very small operating voltage and current of photovoltaic battery monomers, separate monomers cannot be used as a power source directly, but packaged Photovoltaic modules which is made by certain amount of series-parallel connected monomers are being used. The PV modules together constitute the solar panel array, which provides a DC output. (2) Storage battery is a DC power supply, which function is to store the electrical energy from the photovoltaic array as well as to provide electrical energy to the load under the circumstance of generation deficiency. Storage batteries with the characteristics of low self-discharge rate, long service life, wide operating temperature and low price should be chosen. It is a compulsory component for off-grid solar systems, and lead-acid storage battery and cadmium-nickel storage battery are the most widely used. (3) The operating voltage of solar panels is 5V-48V, in order to reach a higher output voltage, a boost circuit is needed to boost the voltage to what is required. (4) The output of photovoltaic array has a strong non-linear characteristic, which is easily influenced by the ambient environment including light irradiance, cell temperature and loading condition. The controller is used to measure input current and voltage, output current and voltage, temperature and other variables, then a feedback is made to increase the efficiency of energy transforming. The controller is responsible for maximum power point tracking (MPPT) and the regulation of the charging and discharging of the storage battery. (5) An inverter is a device that converts direct current into alternating current. In the photovoltaic power generation system, the inverter converts the direct current from the solar panels to an alternating current, so that it can be used by electric appliances and equipments.

In short, the solar panels transform solar energy into electrical energy on the principle of photovoltaic effect, the output from which is direct current. The boost circuit boost up the voltage to the desired value, the inverter circuit converts direct current into alternating current, and after that it can be connected with the public power grid [3]. The structure of the system is shown in figure 1.

![Figure 1. The main structure of the PV generation system](image)

2.2. The Operating Principle of Photovoltaic Cells
Photovoltaic cell, the foundation of PV power generation system, is the device that transforms solar radiation energy into electrical energy. The principle of photovoltaic cell is the photovoltaic effect, which means when sunlight falls on a semiconductor a difference in potential is produced. When phosphorus impurities are added to silicon crystals, N-type semiconductors with extra electrons are formed; when boron impurities are added to silicon crystals, P-type semiconductors with extra holes are formed. When the two types are placed together, the interface is called a PN junction, and a single photovoltaic cell can be considered to be a PN junction with a non-linear output. When light is shone on PV cell, electrons move to the N-type side and holes move to the P-type side, as a result there is a potential difference across the cell, and when connected to a load a current will pass through.
Figure 2 shows the equivalent circuit for a photovoltaic cell. Because of the resistance of the material used and leakage of electricity from the cell’s surface and edge, a corresponding series resistor is added.

![Equivalent circuit for a photovoltaic cell](image)

**Figure 2. The equivalent circuit for a photovoltaic cell**

### 2.3. The Control Strategy of Photovoltaic Power Generation System

The output of photovoltaic arrays has a strong non-linear characteristic, which is largely influenced by external factors. Light irradiance, operating cell temperature, and loading conditions all affect the output power to a great extent. The V-P curve of which changes as to follow the changes in light irradiance and cell temperature. Its maximum point indicates the output power reaching its maximum, therefore it is called the maximum power point (MPP), at this point the utilization rate of solar energy is the highest. Photovoltaic cells can work under different potential differences, however, under fixed light irradiance and cell temperature there is only one MPP with a certain output voltage.

There are significant changes in environment throughout the day, especially for those areas with large temperature difference between day and night. Whenever the light irradiance or cell temperature changes, the current operating voltage is no longer the MPP, which causes wastage of energy. Maximum power point tracking (MPPT) is a process of optimization, it ensures the PV cell is working near the MPP and enables the system to reach a maximum output power under different conditions. MPPT has greatly improved the efficiency of the system, the manufacturing cost of solar panel is very high, so MPPT helps lower the total cost of the system as well. Therefore, developing a favorable means of MPPT is of great importance [4]. This article will introduce two methods of MPPT, which are perturbation and observation method and incremental conductance method [5].

Perturbation and observation method is to perturb the output voltage at a set intervals by increasing or decreasing the out put voltage with a certain step size. The output power before and after the perturbation is calculated by the formula $P=IV$, and the following control strategy is determined by the change in output power in order to realize maximum power point tracking. If $\Delta P>0$, the direction of perturbation is correct and the next perturbation should be in the same direction; if $\Delta P<0$, the direction of perturbation is incorrect and the next perturbation should be in the opposite direction. Setting a suitable step size is important, if too big, the tracking error and the oscillation around the MPP will be too large; if too small, the time required to reach MPP is too long. In both conditions there is a wastage in energy. Therefore, a big step size can be set at first, when the perturbations from both side cause a decrease in output power, it means that the solar panel is working near the MPP, in this case the step size should be decreased in order to achieve a more precise tracking, however the oscillation can not be eliminated, which is a limitation of this MPPT method. The other limitation is that misjudgments will occurs when the environment is changing rapidly, because the controller will mistake perturbation for the change in power that is actually due to a change in light irradiance or cell temperature, hence the working point deviates from the MPP [6].

Incremental conductance method make use of the continuous and differentiable characteristics of the V-P function. The gradient of the maximum power point equals to zero when taking the derivative of the function. The computer measures output current and voltage and controls the operating voltage of the solar panel according to the result of function fitting. When $dP/dV>0$, the operating voltage is lower than the MPP voltage; when $dP/dV<0$, the operating voltage is higher than the MPP voltage; when
dP/dV=0, the operating voltage equals to the MPP voltage. This method is more precise than perturbation and observation method above, because there will be no oscillations and errors around the MPP, and it is able to carry out MPPT successfully even when the environment changes rapidly. However, there are more calculations of data involved when using the incremental conductance method, in addition the two parameter, voltage and current, change in a very slight extent, therefore, the computer used must have a high computational speed, and sensors with high precision must be used to measure the minimal changes. As a result, the high requirement of devices increases the cost of PV power generation system.

2.4. Photovoltaic Power Generation Circuit Topologies

The circuit structure of photovoltaic power generation system can be classified into current source inverter and voltage source inverter by properties of DC power input. The most common current mode and voltage mode photovoltaic generation circuit topologies are shown in figure 3 and figure 4 separately. In the circuit of the current mode, an inductor is connected in series to the direct current side for DC energy storage, as a result the direct current side shows the characteristic of high resistance. In the circuit of the voltage mode, a capacitor is connected in parallel to the direct current side for DC energy storage, as a result the direct current side shows the characteristics of low resistance. However, as the inductor in the current mode gives rise to a poor dynamic response performance, most of the photovoltaic power generation systems around the world adopt the voltage mode, therefore this article mainly focus on the voltage mode topology [8].

![Figure 3. Structure of current source inverter](image)

![Figure 4. Structure of voltage source inverter](image)

According to different ways of insulation of the system output, the circuit structures of photovoltaic power generation system can be split into three types which makes use of industrial frequency transformer, high-frequency transformer and no transformer.

Industrial frequency transformer has a relatively simple circuit, only one transformation, and its ability of eliminating sharp waves is of a high level. In addition, because of a relatively small number of electronic components used, this type of transformer can work in hostile environments better.
frequency transformer has a smaller volume and mass than industrial frequency transformer, therefore a lower costs. However, the circuit is complex as there are more than one transformations, and high frequency electro-magnetic interference is severe that suppression measures must be adopted. The cost is lowered even more if no transformer is used. A boost circuit is already contained the PV generation system, which can be matched with PV arrays that output different voltages, and ensures the stability of input voltage to the inverter circuit, lowering the current and cutting the wastage. Therefore, the topology with no transformer used is chosen in this article, which is shown in figure 5.

![Figure 5. Topology with no transformer used](image)

There are DC-DC converters with and without output isolation transformers. The main types of DC-DC converters with output isolation transformers include forward converter, flyback converter, and full-bridge-isolated converter. Circuits with output isolation transformers are big in size and weight, hence they are mostly used in switching converters with demand for DC isolation between input and output. The DC-DC converters without output isolation transformers consist of boost converter, buck converter, buck-boost converter, cuk converter, SEPIC converter and ZETA converter. SEPIC converter and ZETA converter are relatively complicate and difficult to control, therefore, boost converter, buck converter, buck-boost converter and cuk converter are the mostly used converters in photovoltaic power generation systems. As typical grid-connected PV power generation systems do not contain storage battery and input voltage is low, boost converter is chosen as the from-end DC-DC converter. Boost converter has a simple circuit structure and is easy to control, which can boost the voltage output under different light irradiance and cell temperature conditions to a suitable level according to the voltage used in the grid. This enables a wide range of voltage input and realizes the maximum power point tracking of the system, hence lowers the cost of the system.

DC-AC inverters include push-pull inverters, half-bridge inverter and full-bridge inverter. For push-pull inverter, the two power tubes can be driven at the same time, but the switching voltage is twice the DC bus voltage, therefore, more suitable for circumstances with low DC bus voltage. For half-bridge inverters, the utilization rate of DC side voltage is low, and there will be large harmonics in current compared to other converters at the same switching frequency. For full-bridge inverters, the circuit structure is simple, but a high DC side voltage is required. By comparing the advantages and limitations of the three types of inverter above, the full-bridge type is chosen to be used in the inverter circuit, this realizes the hierarchical control with MPPT and lowers the complexity of system control. Putting the demand of high quality electrical energy from the power grid into consideration, a passive filter is added in order to filter the output voltage.

In conclusion, on the basis of the discussion about DC-DC converter circuit and DC-AC inverter circuit above, the circuit of the system can be drawn as figure 6.
Figure 6. Main circuit of the system

The topology consists of a boost converter circuit and a full-bridge inverter circuit. The converter circuit ensures the fluctuation of DC voltage is within the range that the system allows and carries out the function of MPPT. The inverter circuit uses the PWM control to connect to the grid with the power factor is unity, and realizes island detection. These two circuits applied are classical and mature, therefore simple and reliable. In addition the front-end and rear-end are controlled separately, which simplifies the control algorithm. Therefore, this topology is easy to implement.

3. Simulation Analysis of Photovoltaic Power Generation System

3.1. Introduction of the Simulation Software MATLAB

This study chooses MATLAB as the software platform, which enables the stimulation of algorithm and the control system. Section 3.1 will introduce the basic functions of MATLAB and related tools that will be used when doing circuit design. MATLAB is a large-scale integrated software including the functions of numerical calculation, symbolic analysis, pictorial display and word pressing. It was first developed by Dr. Cleve Moler, with a purpose of offering a convenient approach for matrix operations from linear algebra and other courses. After years of market competition and improvements, MATLAB has become a mathematical software that is extensively used in all areas including automatic control, biomedical engineering, signal analysis and processing, language processing, image signal processing, statistic analysis, finance and mathematics.

To sum up, MATLAB is easily learned and have wide application, mighty function, and rich resources. The powerful function of which liberate users from tedious computational process and allow them to concentrate more on their research and design. Hence, MATLAB has become popular among the undergraduates, the graduates and the doctoral students. MATLAB provided the users with all kinds of modules for control system, therefore is suitable for general simulations. In addition, modules for engineering applications have been supplied, for example blocksets for motor system and communicational system. Simulink is one of the most important modules of MATLAB due to its ability to simulate very complicated system making use of itself and other blocksets. It brings forth an integrated environment including dynamic systems modeling, simulation and analysis, in which there is no need to write a large amount of code, but the simulation can be completed by an easy and intuitive operation.

3.2. System Modelling

3.2.1. Module Construction of Boost Circuit. The boost converter is selected for the DC-DC boost circuit. According to the principles of the circuit, input, constant, sum, gain, output and other components are pulled from the component library to build the output of the photovoltaic array. Then sigum, memory, zero-order, hold, constant, input, sum, gain, product, output and other components are pulled from the component library to build the MPPT module. Finally universal bridge, diode, RLC and other components are used to construct the boost circuit. After completing the construction of the module,
the parameters are set to L=1mH, C1=500μF, R=10Ω, IGBT switching frequency equals to 10KHZ, and C=100e-6.

3.2.2. Module Construction of DC-AC Inverter Circuit. The voltage source full-bridge inverter is chosen for the DC-AC inverter circuit. First pulling components including input, constant, sum, gain, and output from the component library to build the direct-current output. Then construct the circuit using universal bridge, diode, RLC and other components. The inverter circuit built is shown in figure 8.

3.2.3. Module Construction of Test Circuit. In order to measure the I-V and V-P graph of the photovoltaic cell, we can obtain that the range of current output is 0-8.3A, the range of voltage output is 0-27V. Therefore, a 10A ammeter and a 50V voltmeter can be used. There are two ways of measuring current and voltage, in which the ammeter is internally connected and externally separately.

When the ammeter is internally connected: The current measured is more precise than the voltage measured. Because the ammeter is in series with the resistor, the current measured is the current through the resistor, however, the voltage measured is the voltage across both the resistor and the ammeter, therefore there is an error in the measurement. The error will be small if the resistance of the resistor is very large or if the resistance of ammeter is very small, vice-versa. When the ammeter is externally
connected: The voltage measured is more precise than the current measured. Because the voltmeter is in parallel with the resistor, the voltage measured is the voltage across the resistor, however, the current measured is the current through both the resistor and the voltmeter, therefore there is an error in the measurement. The error will be small if the resistance of the resistor is very small or if the resistance of voltmeter is very large, vice-versa.

As the variable resistor used in this simulation has a relatively large resistance compared to the ammeter’s resistance, Ammeter is chosen to be internal connected for the means of measurement.

3.3. Analysis of Stimulation Result
I-V and V-P characteristics at different luminous intensities and different temperatures are drawn from the data of simulation. Under standard condition, where E=1000W/m² and T=298K, the simulated graph is shown in figure 9. The maximum output power is 180W, short-circuit current is 8.3A and open-circuit voltage is 29.5V.

![Figure 9. I-V and V-P characteristics when E=1000W/m² and T=298K](image)

When light irradiance (E) is set to be 1000W/m² and cell temperature (T) is changed to 320K and 360K, the simulated graphs are figure 10 and 11 separately.

![Figure 10. I-V and V-P characteristics when S=1000W/m² and T=320K](image)
Figure 11. I-U, I-V and V-P characteristics when S=1000W/m² and T= 360K

From the simulated graphs above we can see that when all other factors are kept the same, the increase in temperature will decrease the open-circuit voltage $V_{oc}$ and slightly increase the short-circuit current $I_{sc}$, which leads to a lower output power of the solar cell. The temperature characteristic of the solar cell is usually represented by a temperature coefficient, the smaller the coefficient, the smaller the change in output power when the temperature changes.

(3) When cell temperature (T) is set to be 298K and light irradiance (E) is changed to 750W/m² and 500W/m², the simulated graphs are figure 12 and 13 separately.

Figure 12. I-V and V-P characteristics when E=750W/m² and T= 298K

Figure 13. I-V and V-P characteristics when E=500W/m² T= 298K

From the simulated graphs above we can see that when all other factors are kept the same, the increase in light irradiance will increase the short-circuit current $I_{sc}$ and slightly increase the open-circuit voltage $V_{oc}$, which leads to a higher output power of the solar cell. The output power is fluctuating around 180W is shown in figure 14, as a result of the perturbation and observation method to realize maximum power point tacking.
Finally, the simulation effect of DC-AC inverter circuit is the production of PMW wave, impulses with 120° are used to control the conducting time of the four IGBT to realize the inversion. The DC-DC circuits’s stable output voltage of 69V is converted to the alternating form, which is represented by the AC sine-wave shown in 15.

By compare the simulation results with relative parameters, it can be concluded that the modeling and the results are correct.

4. Conclusion and Prospect
This research is a very special after-class investigation as I have never come across with detailed knowledge about solar cells or used MATLAB for construction for a mathematical model of the system. Through this study, I realized that building simulation model and setting the parameters are my weakness, as it is the first time I use this software and I received lots of help from the teachers. I will strengthen my ability by doing more study on basic subjects including mathematics and physics to learn more about the principle of knowledge. I also learned the method of searching related articles to find the piece of information that is needed.

During this study I have learned the principles of solar cells, formula derivations, a number of common methods for MPPT, the principles of DC-DC boost circuit and DC-AC inverter circuit, and the construction of a simulation model. Not only have I realized my shortcomings, but also made an self-progress by learning new knowledge related to engineering, the abilities of thinking independently and solving problems of mine are improved.

There are still many unanswered questions in the area of photovoltaic power generation system waiting people to explore and solve. In today’s society where the renewable energy resources are increasingly scarce, the applications of solar energy and other forms of renewable energy are more
valued by the human beings. Up to today, the PV generation technologies are becoming mature, but we still need to develop a better control method so that the system becomes more efficient and stable. In this way, we can make better use of solar energy through wider application. For example if the miniaturization of solar panels is realized, the panels can be installed at the housetop or the frame of windows, and supply sufficient energy at the same time, becoming energy source for millions of ordinary households. A new material with a black outer side suitable for absorbing solar radiance energy, but seems transparent from the inner side can be developed, which can be used for the glass part of tall buildings. People should also aim for a better storage ability and more stable and efficient circuit, and someday the mankind will realize the high utilization of clean energy in the real terms.

References
[1] Zhenya Liu. Global energy internet [M]. Beijing: China Electric Power Press, 2015.
[2] National Energy Administration. http://www.chinapower.com.cn/dwzcxs/20170210/809492.html, 2017.
[3] Wen Liu, Bin Zhu. [J]. Controll of electric system, 2012, (14) 152-155.
[4] Yu Zhou, Xianyun Li. Research about grid connected PV power generation system. [J]. Journal of Nanjing University of Engineering, 2015, (1): 42-48.
[5] Liqun Liu. Research on maximum power point tracking [D]. Shanghai: Shanghai Jiaotong University, 2011.
[6] Hao Jin. [D]. Beijing: North China Electric Power University, 2012.
[7] Stvens. J. Development of sorcees and a testbed for CERTS microgrid testing [J]. In: Proceedings of 2004 IEEE Power Engineering Society General Meeting. Denver, CO, USA, 2004, 2032-2033.
[8] A. Bertani, C. Bossi, F. Fornari, S, Massueco et al. A Mieroturbine Generation System for Grid Connected and Islanding Operation [J]. Power Systems Conference and Exposition, 2004, IEEE PES, 2004, 10(1):360-365.