The Study on System Stability and Power Compensation in the Distributed Grid-connected Photovoltaic System

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Abstract. New energy technologies are gradually matured and are being put into construction. The operation of conventional power grids is not able to meet the management of new energy generation and grid connection. When it comes to the distributed generation of electricity, the most representative is a photovoltaic system. It is essential to study the impact of the distributed grid-connected photovoltaic system on the stability, power, and voltage of the existing power grid. This paper mainly examines the effect of the distributed photovoltaic system on the balance of the power system and the optimization of reactive power compensation inspects the stability of the system through voltage fluctuations, and verifies the power compensation effect of the three-phase LCL photovoltaic grid-connected inverter combined with the photovoltaic system.

1. Introduction

The origin of photovoltaic (PV) technology was discovered by Becquerel in 1800 when semiconductor materials were irradiated with light, which would cause their volt-ampere characteristics to change. Therefore, flat silicon wafers made of silicon semiconductors became the earliest solar panels. Solar panels are the core of the entire PV system. However, the initial production of PV cells caused certain energy losses and emitted particular greenhouse and harmful gases. Life cycle assessment (LCA) studies have been conducted on the environmental impact of the energy payback time (TEPBT) and PV technology. The research results show that the energy recovery period of the grid-connected PV system is between 1.6 and 2.3 years. It is about 84% or more of the total energy consumption and total greenhouse gas emissions of the PV manufacturing process [1]. It is undoubtedly a considerable stumbling block for the development of large-scale PV systems and networks. In recent years, the development of PV technology has become more and more mature, the manufacturing process has been optimized, and large-scale production of solar panels has become a reality. The hardware is provided for future research and put into operation for the grid-connected PV system.

According to the current plan of the industry, there are two more feasible PV grid-connected projects: one is a large-scale PV array with the same output power as existing power plants in the power grid. The advantage is that the power generation equipment adjusts the energy in and out of power generation. The disadvantages are the high construction cost, large footprint, and limited locations for installation. Currently in operation is only in the western region of China. The other one, distributed grid-connected PV system, appears to be easier to install. It has a small footprint and can be erected on the top floors of various residential buildings. For the distributed PV system, its output power is low, the function of generation and consumption coexists, and grid-connected operation is periodical [2]. If it directly connects to the grid, the frequency, voltage, and reactive power of the network are affected frequently. If the problem for the voltage fluctuation and the self-optimization of the inverter's reactive power loss is not able to improve, the distributed PV system is not suitable for the application. After
comparing the working principle of solar panels with other power generation methods, the PV system and power generation using temperature differences under development are currently the only stationary power production. Therefore, the PV system does not consume part of the reactive power to compensate for the work done by mechanical friction like the generator rotor. On the contrary, the reactive power generated by the PV system is directly used as the output. The reactive power is used as the power supply for grid-connected inverters. By combining solar panels and inverters into a module, there is no reactive power consumption coming from the power grid. Also, the PV power station with intensive large power generation is performed a specific reactive power compensation on the power grid during the most active daylight (10 A.M.-2 P.M.). In this way, the distributed PV system becomes feasible, and for large-scale PV stations in western China or the world is being able to perform reactive power compensation for its connected grids. According to the above technical developments, this article has used the simulation to design the distributed grid-connected PV system, to verify that the operation is met the daily grid-connected standards, to minimize the impact on the power grid, and to maintain the system stability.

2. Simulation architecture and components of the pv system
After in-depth research and simulation on the feasibility of the grid-connected PV system scheme, it was initially determined that the following two points need to be resolved for the distributed grid-connected PV system. First, optimize the reactive power loss of the inverter connected between the PV system and the grid. With the development of power electronics technology, through the soft-switching techniques [3], the switching circuit in the inverter is redesigned to minimize its reactive power loss to the power grid. For the optimization of inverter’s reactive power loss, there are design solutions, such as three-phase LCL PV grid-connected inverters and independent dual-mode inverters [4]. Second, for the power loss problem caused by the switching action of the inverter, the PV system is used as the reactive power generated by itself to compensate for the inverter to maintain the stability and power consumption of the power grid. This article is tried to explore the impact of the PV system on the parameters of the network when it connects to the net during the period of its maximum output power and then analyzed whether the scheme to optimize the reactive power compensation of the PV system is feasible.

3. Grid-connected simulation of reactive power compensation for small PV system
The simulation is adopted the verified five-bus system for transformation, and the PV module is added to the system for further simulation experiments. The experimental result is to compare the two experimental data by the conventional generator and PV module under the same condition of power. The purpose is to explore whether the PV system can be maintained under the condition of reactive power consumption. Whether the output effect of power generation is the same as that of conventional generators, does it affect the original grid? The following is a simulation diagram and equivalent topology of the small grid-connected PV system:
Figure 1. Simulation diagram for the small grid-connected PV system.

Figure 2. The topology of the small grid-connected PV system.
Figure 1 is the simulation diagram of the small grid-connected PV system, which is the basic model for this project. The system is a 35kV power system, using two 10.5kV generators as the primary power source of the system. Three-phase motors with similar power as the system load constitute a typical five-bus model, and then the PV module is connected to the primary grid through the three-phase LCL PV grid-connected inverter to form the basic framework of this experiment in figure 2. First, the PV system is set to the maximum power output, and then the power flow analysis is performed to obtain three data, such as voltage, active power and reactive power. Second, the PV system is replaced with the conventional generator with the same power. Third, the power flow analysis is performed to collect another three data. Finally, the advantages and disadvantages of the PV system are determined through the comparison of two sets of data.

4. Optimization of reactive power compensation and LCL inverter

The architecture and idea of the grid-connected PV system are put forward. The next step is how to design the hardware circuit to realize the simulation. The problem of reactive power compensation is introduced first, which needs to clarify the impact of reactive power on the stability of the grid. The frequency is affected by the active power, as well as the voltage of the power grid is affected by the reactive power. The increase in power consumption is leading to a decrease in frequency, and some electrical appliances generate specific electromagnetic effects and mechanical losses during use. These losses are indirectly consumed the reactive power in the power system and caused voltage fluctuations. Therefore, to provide a certain amount of reactive power and maintain the stability of the voltage can make the entire power grid and electrical equipment operated normally. According to the reactive power balance of the network, it is expressed [5]:

\[ Q_{gc} - Q_{ld} - Q_l = Q_r \]  

, where \( Q_{gc} \) is the sum of reactive power from the power source, \( Q_r \) is the reactive power for backup that the system can provide, and \( Q_l \) and \( Q_{ld} \) are the reactive power loss between grid and users.

The reserve reactive power \( Q_r \) should be obtained after the reactive power generated by the power source minus the grid loss and the loss of the reactive load. When connecting the PV system to the grid, due to the power loss of the standard inverter, the \( Q_r \) must be increased to maintain the reactive power demand and stability of the system. The power output of the solar panel is also studied, and the reactive power generated by it is used to compensate for the PV grid-connected inverter so that the PV system does not consume the reactive power from the original system after it connects to the grid. The reactive power output of the PV system varies with the light intensity at different times of the day. According to the analysis of the reactive power output for the small-area solar panels at different times, the data collection is performed on a cloudless sunny day. The data is as follows:

![Fig. 3 Distribution of the reactive power output of the PV system](image)

**Figure 3.** Distribution of the reactive power output of the PV system.
In figure 3, the daily reactive power output of the PV system is directly proportional to the magnitude of its light intensity. At 10 A.M-2 P.M. of the day, the reactive power output is the largest. The reactive power output during this period can be used indirectly to compensate for the inductive reactive power consumed by the PV inverter. For distributed PV systems, it has a grid-connected solution. According to the daily weather conditions and the intensity of the light, one can choose to be at noon of the day (that is, 10 A.M-2 P.M.). At this time, the reactive power output by the solar module is the largest. The stability impact is minimal, and at the same time, in terms of energy utilization, the power factor of the grid can be as small as possible affected by the grid connection. It solves the grid-connected access time of the distributed PV system. It only facilitates our regulation of the entire power system. To truly eliminate the reactive power loss of the PV system, optimizing the design of its PV grid-connected inverter effort is essential. At present, the industry is optimizing the power loss during the switching of the inverter connected to the grid. For example, the ordinary three-phase inverter is replaced by the three-phase LCL PV grid-connected inverter [6]. The topology of the LCL PV grid-connected inverter is as follows:

![Figure 4. Three-phase LCL PV grid-connected inverter.](image)

The three-phase LCL PV grid-connected inverter in figure 4 is included a filter circuit and an inverter switch control unit in the ordinary inverter link. The LCL filter circuit has two functions. One is to eliminate the harmonics generated during the inversion process, ensure the quality of the output power, and fundamentally solve the impact of the harmonics on the voltage stability of the power grid. Another role is to act as an auxiliary compensation device for PV systems. The control unit added in the circuit samples the current and voltage from the inverter output and then converts it into corresponding pulse width modulation (PWM) signals to control the on and off time of the thyristor in the inverter so that it has the function of approximately soft switching and reduces system power loss. When the grid fault or abnormal situation causes the grid-connected voltage of the PV power station to be higher than 1.2p.u., the capacitive part of the reactive power compensation device should be immediately out of operation, and the inductive element should continue to operate for 5 minutes. It is because the inverter consumes inductive reactive power to generate a certain amount of capacitive reactive power during this fluctuation process, so it is necessary to promptly withdraw reactive power compensation such as shunt capacitors to prevent the power system from crashing. It is the design concept and principle of the three-phase LCL PV grid-connected inverter optimized by the typical inverter circuit. According to this design, the power loss problem of the inverter is eliminated, and the conversion efficiency is also improved.
5. System stability and voltage fluctuation
The reactive power optimization of the grid-connected PV system is to maintain the safe and stable operation of the entire system after grid connection. The supply of reactive power to the system directly affects the stability of the system voltage. The range of voltage fluctuation should not exceed 10% of the nominal voltage for the system. According to the voltage fluctuation rate of the PV system [7]:

\[
dP_v = \frac{0.8P_{COI}}{0.7 \times 3I_{COI} \times U_B}
\]  

(2)

The output power of the PV system has specific intermittent and fluctuating characteristics. Two characteristics cause a flicker and fluctuation of the grid voltage. According to the document, "Technical rule for distributed resources connected to the power grid," the voltage fluctuation rate \(dP_v\) for public connection points must be less than 5%. The power flow distribution during the access period is affected. The system is needed to monitor and manage in real-time for analyzing the power flow distribution. The current real-time tracking method for the distributed grid-connected PV system is maximum power point tracking (MPPT) [8] and Monte Carlo fuzzy analysis [9]. The daily reactive power curve of the system is obtained through the tracking analysis of the system voltage and load power to identify the adjustment of each reactive power compensation device of the system.

6. Simulation data analysis
According to the previous introduction of the simulation system architecture, the system used in this article is set to the small five-bus system as the fundamental backbone, and the system voltage is 1.0 p.u. The three-phase LCL PV grid-connected inverter is converted three-phase AC power through a step-up transformer (500V/121kV), and then connected in parallel to the first generator. The capacity of the solar panel is 98kV/A with the voltage of 500V, and the total short-circuit current in parallel is 200A. Since the system is only used to verify the impact of the PV system on the power grid, the production parameters, such as the number of integrated crystals of solar panels, are used the default factory settings. The Newton-Raphson method is applied to the power flow calculation. The two power flow results of the PV system and the generator are as follows:

**Table 1.** Data of grid-connected PV system.

| Bus | P(kW)   | Q(kVar) | V(kV)  |
|-----|---------|---------|--------|
| G1  | 198.17  | 77.1    | 11.5   |
| G2  | 192.3   | 62.38   | 11.187 |
| PV  | 93      | 24.21   | 0.498  |
| L1  | 32.7    | 12.73   | 21.09  |
| L2  | 34.1    | 20.6    | 31.37  |
| L3  | 16.3    | 11.4    | 19.76  |

**Table 2.** Power flow data of the ordinary generator.

| Bus | P(kW)   | Q(kVar) | V(kV)  |
|-----|---------|---------|--------|
| G1  | 198.17  | 77.1    | 11.5   |
| G2  | 192.3   | 62.38   | 11.18  |
| G3  | 96      | 24.15   | 0.51   |
| L1  | 32.7    | 12.73   | 21.09  |
| L2  | 34.1    | 20.6    | 31.37  |
| L3  | 16.3    | 11.4    | 19.76  |
From the comparison of the two power flow results, when the PV system is connected to the grid, it causes an inevitable voltage fluctuation, but it is stable after 1-3 seconds, and the voltage deviation does not exceed 5% for the system. After the PV system is connected to the power grid, it does not conflict with the system and cause a collapse of the network. In terms of power change, the main concern is the total reactive power of the system. Since the reactive power consumption of the load is unchanged, the reactive power reserved for the system is obtained based on the total reactive power provided by the power source minus the load loss. Since the inverter used in the PV system is an optimized LCL PV grid-connected inverter, so the reactive power reserved for the PV system is about 60Var more than the reactive power reserved for the conventional generators. The result shows that the idea of optimizing the PV grid-connected inverter is applicable, and the three-phase LCL PV grid-connected inverter has its power loss, so the system is not increased the burden of reactive power loss.

7. Discussion
After studying the grid connection of the PV system, the three-phase LCL PV grid-connected inverter is analyzed and designed. The relevant data is collected through the simulation. The PV system is connected to the optimized inverter to realize the grid-connected project as small as possible for the power grid. The PV system shows a better performance in terms of reactive power output, which also verifies the correctness and feasibility of the experimental grid-connected scheme.

8. Conclusion
After research on the grid connection of the PV system, the three-phase LCL PV grid-connected inverter was analyzed and designed. It can be obtained by embedding the relevant data analysis through the power system. After connecting the inverter with an optimized design, the PV system has achieved the smallest possible grid connection. Furthermore, the PV system showed relatively good performance in terms of reactive power output, which also verified the correctness and implementation ability of the experimental grid connection scheme. From an objective point of view, this experiment is to optimize the design of original equipment for PV power conversion to reduce the energy loss (reactive power loss of switching equipment) at the bus into the transmission and distribution network. Moreover, through the study and understanding of the nature of the PV system, it puts forward the idea of converting and using the excess capacitive reactive power generated at the end of power generation to provide a part of the reactive power loss for the operation of the power grid.

With the assistance of the simulation and reasonable deduction, the designed circuit was validated with individual results, and the actual effectiveness of the designed circuit was determined. The relevant reactive power data can also be seen from the two sets of comparative simulation experiments. After the optimized PV module is connected to the grid, it can achieve the effect of generators connected to the grid, and the total reactive power is slightly higher than the conventional rotor generator. It also corroborates the correctness of the experimental ideas. The experiment and design are only the results achieved through simulation. Some of the components in the simulation tool are working in an ideal condition, so the situation may fluctuate when the actual equipment is connected to the power grid. In different grades of the transmission line may also need to be adjusted according to the working conditions.

After the experimental simulation, it is possible to determine the possibility and directionality of the reactive power compensation for distributed PV systems. With the development of science and technology, there is an excellent solution to the power loss problem of power electronic switching circuits in the future. The distributed PV system can be implemented on a large scale, which is of considerable significance to the development of the energy reservation. China is currently building a power system at a very rapid rate, which was unprecedented in the past. According to the current development speed, in the next 10-20 years, distributed PV systems are installed in every household and truly realize the dream of universal electricity. The PV system is the method of generating electricity that is currently known to have the least damage to the natural environment.

With the rise of new energy technology, the original power flow method is no longer satisfy the analysis of multi-factor power systems. For example, wind energy follows the Weibull distribution, and some are the Gamma distribution [10]. Therefore, it is necessary to build an input random variable
probability distribution model that matches the actual system operating conditions based on a large amount of existing historical data of the real power grid. By obtaining as close as possible to the real value, the calculation efficiency and accuracy are realized.

9. References
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