Research on Grid-connected Voltage Improvement Technologies for High-penetration Photovoltaic Power Generation

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Abstract. The degradation in power quality due to the high penetration of grid-connected photovoltaic (PV) systems is a critical issue that urgently needs to be addressed in the field of renewable energy generation. Solar PV systems typically lack mechanical inertia, which means that they are unable to provide additional mechanical inertia to maintain voltage and frequency stability when the power system is subjected to external disturbances. Therefore, to ensure stable operation of the power system, alternative measures need to be relied on to maintain voltage stability. This article first analyzes the mechanism of voltage fluctuations when photovoltaic power generation is connected to the grid. It then delves into the challenges of power quality brought about by the grid integration of renewable distributed generation systems, as well as the current research status of mainstream voltage improvement technologies, customized power devices, and energy storage systems. Finally, the paper presents recommendations for improving grid voltage quality, enhancing the stability and reliability of the power system, and promoting the widespread application of renewable energy in power systems.

Keywords: High penetration rate; photovoltaic grid connection; voltage quality improvement.

1. Introduction

According to the IEA, renewable global renewable energy power generation will continue to grow in 2023 due to issues such as policy push, rising fossil fuel prices, and energy security. And photovoltaic power generation will contribute to two-thirds of the growth in renewable energy power generation capacity which will continue to increase in 2024. Currently, modern power systems are experiencing a dual high-penetration development trend, namely a high proportion of intermittent renewable energy generation equipment and a high proportion of power electronics, including inverters in PV systems, and distribution/utilization systems such as electric vehicles and microgrids. This trend has a strong influence on the stability of power systems which has new challenges for future power systems.

Voltage quality improvement technology (VQI) is a series of technologies and measures aimed at optimizing and stabilizing voltage quality in power systems, which can improve voltage fluctuations, improve voltage stability, and optimize grid performance. In the power system, especially when faced with intermittent and volatile renewable energy sources, VQI plays a key role in ensuring that the power grid can operate stably.

This article aims to deeply explore the principles and applications of voltage improvement technology. First, the customized power devices, energy storage technology, and energy conversion optimized voltage improvement technology are analyzed. Subsequently, an in-depth analysis is conducted on the application of voltage improvement technology in the direction of stability and optimization, and its future development trends are prospected.

2. Impact of Photovoltaic Grid Connection

A typical photovoltaic system includes an array of solar panels, a DC-AC converter, and related controllers. Fig 1 shows the general construction of a grid-connected photovoltaic power plant system.

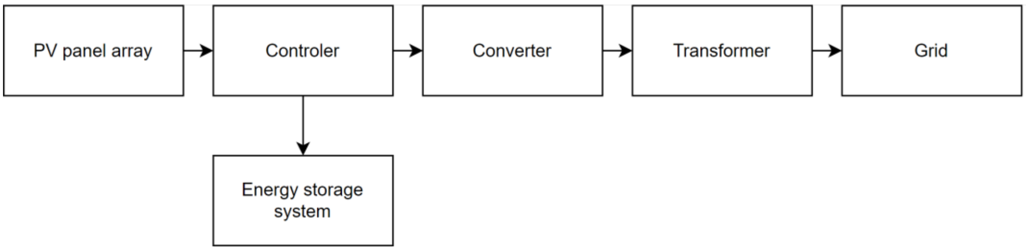

Fig 1. Typical solar photovoltaic system components.

Intermittency is an important characteristic of photovoltaic power generation, which depends on solar radiation and temperature. Therefore, most weather changes will cause fluctuations in photovoltaic power generation, especially when clouds shadow solar panels, which will significantly change the amount of solar radiation. As the penetration rate of photovoltaic grid connection increases, the intermittent components in the power grid will also increase, which will significantly affect the stability of the overall power grid. Literature [1] analyzes the impact of solar photovoltaic power grid connection on voltage stability, and its stability is highly dependent on the location of distributed energy resources.

In addition, these methods cope with grid unexpected events, reactive power, voltage fluctuations, and load demand fluctuations. As shown in fig 2 these technologies are developed to provide effective, economical solutions to ensure the reliability and efficiency of power systems.

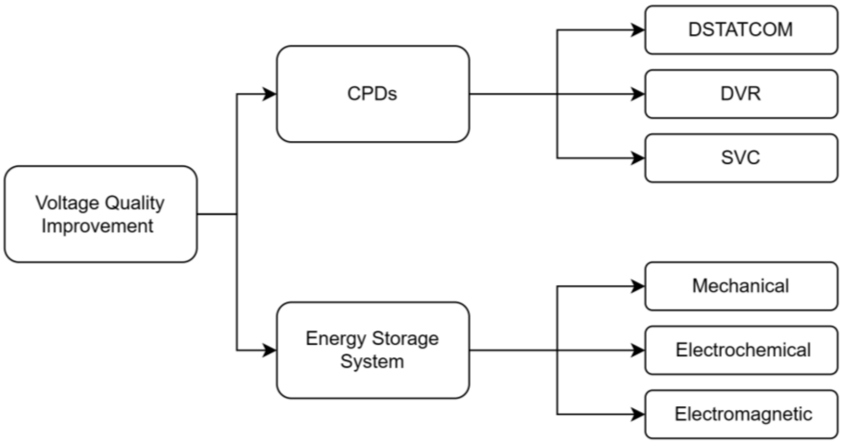

Fig 2. Voltage improvement technology.

3. Custom Power Devices

Custom Power Devices (CPD) play an important role in cost-effectively enhancing power quality in both traditional and modern distribution networks. With the development of power electronics technology, CPD technology is also constantly improving.

In the distribution network, due to the wide distribution of motors, the load generally presents an inductive state. The resulting lagging power factor may lead to increased network losses, unbalanced voltage distribution, and other problems. CPDs include distributed static compensator (DSTATCOM), dynamic voltage restorer (DVR), static var compensator (SVC), etc. These power devices are currently the main means of regulating reactive power and load imbalance in distribution networks, and their advantage is to provide effective solutions at lower costs.

3.1. Distribution Static Synchronous Compensator

DSTATCOM can improve the voltage stability of power systems by providing voltage support. When the grid voltage drops, DSTATCOM injects reactive power (inductive load) to boost the voltage; conversely, when the grid voltage is too high, it absorbs reactive power (capacitive load) to reduce the voltage to keep the voltage within an acceptable range.

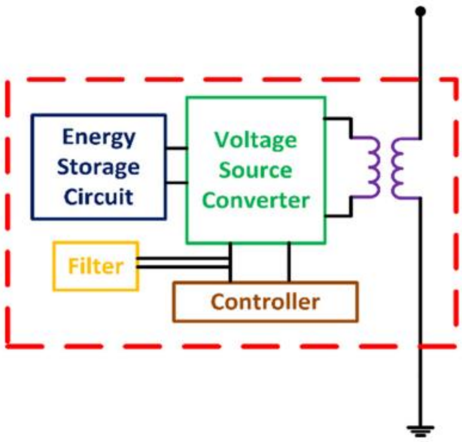

Fig 3. DSTACOM system block diagram [2].

The general working principle of DSTACOM is shown in fig 3, the energy storage device absorbs or releases real power to adjust the voltage. Literature [2] proposes a solution using the loss sensitivity factor (LSF) algorithm to optimize the location of distributed generation and DSTATCOM. When they are on the same bus, the loss and capacity requirements of DG and DSTATCOM are minimal and can effectively improve voltage distribution. This provides scope for the construction of new power grids in remote areas with limited power supply.

3.2. Dynamic Voltage Restorer

The DVR monitors the input voltage and when the detected signal deviates from a specified voltage level, the DVR system intervenes by providing a stable supply voltage to the connected load through its inverter system. This ensures that the output voltage remains stable and reliable despite fluctuations in the input power supply.

A three-phase dynamic voltage restorer system is introduced in [3], which adopts an efficient two-stage energy conversion topology. First, a DC-DC boost converter boosts the low voltage, and then a three-level voltage source inverter converts DC power to AC power, ensuring efficient energy transfer. The system adopts a control method based on fuzzy logic to effectively deal with grid disturbances such as voltage surges and dips and keep the grid voltage and frequency within the specified tolerance range. While simulation results are promising, actual implementation may face additional challenges, including varying environmental conditions and long-term maintenance requirements.

A DVR system integrates solar and wind energy in the DG system by adopting a wind-solar complementary strategy, significantly improving the overall efficiency of the system. This strategy not only reduces grid losses but also significantly reduces operating costs and system complexity compared to traditional DVR systems that rely on energy storage devices [4]. In addition, if a hybrid distributed generation system encounters energy support failure, the introduction of other renewable energy sources, such as specific types of fuel cells, will further improve the reliability of the system and reduce dependence on grid energy.

3.3. Static Var Compensator

SVC can dynamically adjust the reactive power balance of the power grid and is particularly effective in improving the dynamic response of the power grid. When the grid voltage is lower than the set value, SVC will provide reactive power support and increase the grid voltage; when the grid voltage is higher than the set value, SVC will absorb reactive power and reduce the grid voltage. SVC has the characteristics of fast response and can adjust reactive power output within milliseconds. In modern power grids containing large amounts of renewable energy generation, SVC helps to deal with the impact of the intermittency and instability of these power generation methods on the grid.

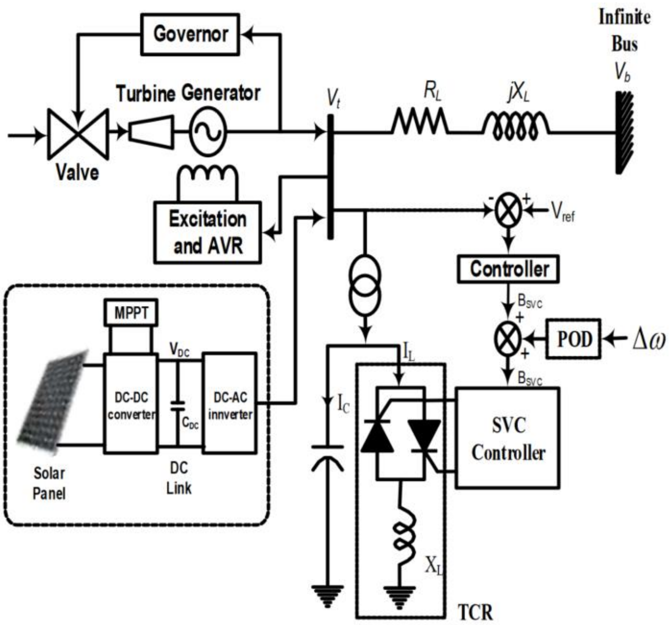

Fig 4. Stand machine infinite bus system with SVC [5].

Literature [5] aims at the dynamic stability problem of grid-connected power systems, using designed SVC and particle swarm optimization (PSO), differential search algorithm (DSA), and quasi-opposition differential search algorithm (QODSA) to optimize the gain of the PID controller and improve solar energy in various operating scenarios. The test system is shown in fig. 4, which simulates voltage and other disturbances on the Single Machine Infinite Bus (SMIB). Among them, PID-based QDSA technology can most effectively reduce oscillation.

4. Energy Storage System

Another solution to improve the quality of solar photovoltaic grid-connected voltage is the energy storage system (ESS), whose main function is to adjust peak power consumption and balance the demand of the solar photovoltaic power generation system. ESS can store energy when power demand is low and release it when demand is high, helping to reduce stress on the grid during periods of high demand. When solar output is insufficient to meet immediate demand, ESS can provide additional power to ensure continuity of supply. Helps smooth fluctuations in solar power generation and provides a more stable energy supply.

Currently, energy storage technology is broadly categorized into three main types: mechanical energy storage, electrochemical energy storage, and electromagnetic energy storage [6].

4.1. Mechanical Energy Storage

Mechanical energy storage systems can be classified into two main categories, taking into consideration their response time, power, and energy ratings. The first category is systems with slow response times and large capacities, such as pumped hydro storage (PHS) and compressed air energy storage (CAES). PHS generates electricity by pumping water into higher reservoirs during off-peak hours and then releasing the water flow when needed, accounting for the vast majority of global energy storage capacity [7]. The CAES system compresses the air stores it underground and releases the air to generate electricity when needed [7]. Both technologies are very mature and can provide stable power from several hours to hundreds of megawatts. The second category is a fast-response system, such as flywheel energy storage, which stores energy through a rotating mass, accelerates the rotating mass when charging, and transfers energy to a generator when discharging. Although the power rating of FES is low and the duration of switching power is short, the required power level can be achieved by connecting multiple units in parallel, resulting in a significant impact on the power output of the power system. Significant impact [8].

4.2. Electrochemical Energy Storage

A battery is a device that stores electrical energy in a chemical form and can convert that energy into electrical power when needed. Specifically, the electrical potential generated by the reaction causes ions to move through the electrolyte while driving electrons through an external circuit, creating an electric current. The main battery types on the market include lead-acid, alkaline, molten salt, and lithium-ion batteries, each with unique characteristics and applications [9]. For example, lead-acid batteries are low-cost; alkaline batteries are commonly used in small portable devices; molten salt batteries are known for their high-temperature stability; and lithium-ion batteries dominate mobile devices and electric vehicles due to their high energy density and long life.

4.3. Electromagnetic Energy Storage

Supercapacitors, also known as double-layer capacitors, are energy storage devices with practical commercial competitiveness in numerous technological fields. Unlike the electrochemical energy storage mechanism of batteries, the energy storage principle of supercapacitors is based on electrostatic fields rather than chemical reactions, and its voltage is generated by the internal electric field. The energy storage capacity of a supercapacitor is determined by the capacitance and the voltage.

Supercapacitors are considered a competitor to flywheel energy storage and are particularly suitable for applications requiring fast response and high-power output. Their advantage is that they can support millions of charge and discharge cycles and have an extremely long service life because their operation does not involve chemical reactions [10]. Supercapacitors are widely used in power systems for frequency control and providing uninterruptible power systems to protect critical loads from main grid faults.

5. Conclusion

Voltage quality improvement technology is crucial to improving the stability and power quality of the power grid, especially in the context of high penetration of photovoltaic grid connections. These technologies not only help improve the voltage stability of the grid but also provide voltage support, which is especially suitable for the growing proportion of renewable energy in the current power system. Customized power devices play an important role in enhancing power quality and optimizing grid performance by dynamically adjusting reactive power. Energy storage technology can effectively cope with the intermittency and volatility of solar photovoltaic power generation, helping to balance the grid load by storing energy when demand is low and releasing energy when demand is high. Faced with the growing proportion of renewable energy in the power system, voltage quality improvement technologies will need to meet more demands in the future, such as parallel connection of multiple machines, seamless switching between parallel and off-grid, low voltage ride through, etc. At the same time, as the scale of the power system expands, it will face the challenges of more parallel operating conditions of converters and different control strategy combinations. The effective combination of voltage quality improvement technology and other control technologies will be an important direction for future research.

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