Leakage Current Analysis of Non-Isolated Photovoltaic Grid-Connected System

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Abstract. Amidst mounting concerns over energy scarcity and the environmental repercussions of fossil fuels, renewable sources, spearheaded by solar energy, have garnered substantial societal attention, thereby propelling advancements in photovoltaics (PVs). In the realm of grid-connected (GC) PV systems, a pressing issue is the leakage current suppression in non-isolated GC PV inverters. As a ubiquitous architecture in PV systems, the non-isolated GC configuration is of paramount importance in practical applications. Yet, intrinsic attributes of PV systems have amplified the leakage current challenge within this setup. This paper endeavors to dissect the leakage currents in non-isolated PV GC systems, delving into the salient factors influencing them. It embarks on an exploration of the origins of leakage currents, subsequently analyzing the repercussions of LC filter parameters—spanning filter capacitance, Y capacitance, and common-mode inductance—on these currents. Drawing insights from extant scholarly discourse on leakage current mitigation, this study offers a synthesized perspective accentuated with augmented strategies, elucidating a comprehensive path forward for leakage current suppression.

Keywords: Leakage current; photovoltaic inverter; grid-connected system; common mode voltage.

1. Introduction

With the global energy crisis and the deteriorating climate, the electricity demand continues to grow, thus reducing greenhouse gas emissions and alleviating the adverse impact of non-renewable energy on the natural environment. Climate change has become the top priority. In recent years, using renewable energy such as solar, wind, nuclear, and tidal energy to generate electricity has been vigorously promoted and widely used. Among them, solar photovoltaic power generation (PVPG) has attracted worldwide attention because of its many advantages, such as renewability, large reserves, pollution-free and wide distribution, and has gradually become an important strategic leading industry to promote economic development. Since the 1970s, the world has highly valued PVPG system research and has made substantial progress. It significantly impacts environmental pollution, reducing the global greenhouse effect and alleviating the energy crisis. At the same time, with the rapid growth of PVPG, its huge market space is key to achieving carbon neutrality and carbon peak.

According to the statistics of Prospective Industry Research Institute, a think tank service organization, the proportion of PVPG in the total electricity consumption of the whole society increased year by year from 2014 to 2022. Fig. 1 provides the proportion of various energy sources in the total PG installation of the power grid in China in 2022. In 2022, China's PVPG accounted for 5.1% of the total electricity consumption of the whole society. In the future, PVs will be one of the important engines to promote China's energy transformation. Sunshine Power also predicted the future development prospects of PVs by citing industry data in the White Paper on 5A Convergence-Ground Power Station Solutions. In 2023, the newly installed PV capacity will exceed 350 gigawatts; by 2030, the newly installed capacity will be close to 700 gigawatts [1].

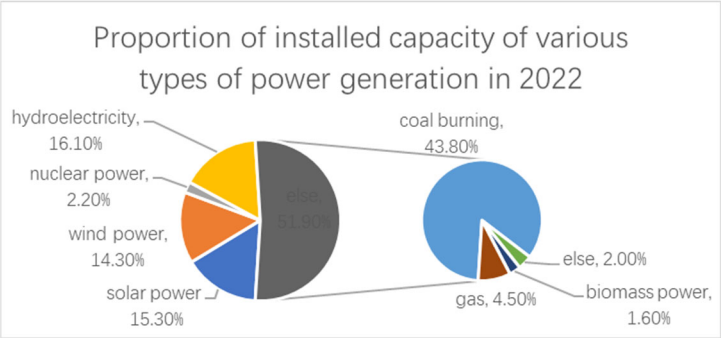


Fig. 1 Proportion of installed capacity of various types of PG (Photo/Picture credit: Original)

2. PVPG System

2.1. Off-Grid PVPG System

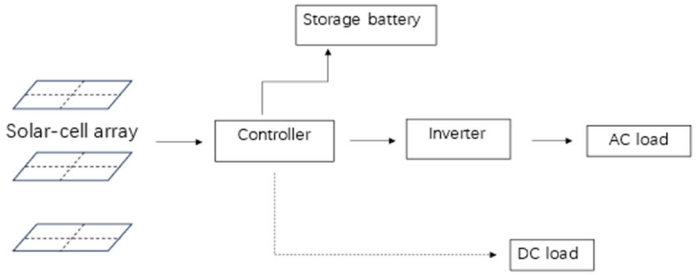


Fig. 2 Off-grid PVPG system (Photo/Picture credit: Original)

Fig. 2 is an overview diagram of an independent PVPG system. Working principle: The solar cell semiconductor device first effectively absorbs the solar radiation energy, translates light energy into electric energy, and then uses a DC/DC converter to charge a storage battery. However, the voltage of the storage battery is low. Increasing the voltage through the DC/DC converter is necessary to convert it into the required voltage and realize stabilization. The off-grid PVPG system is mainly used in areas not covered by electric power, such as islands or remote mountainous areas, and the off-grid PVPG system is provided with an energy storage battery so that when the power consumption of the equipment is greater than the PG of the solar PV cell panel, the storage battery can be discharged and supplied to a user; the energy storage battery is charged. Therefore, the energy storage battery plays an important role in the independent system, but the high cost and limited capacity of the energy storage battery cause the loss of excess power after full charge, which greatly reduces the efficiency of the PG system.

2.2. GC PVPG System

The GC PV pow generation system is divided into a dispatchable PV pow generation system and a non-dispatchable PVPG system, wherein that dispatchable type PVPG system is suitable for small-scale PG, and the non-dispatchable-type PV pow generating system is suitable for large-scale PG. The design of a standalone PV power-producing system is seen in Fig. 3. Three components typically make up a GC PV power-producing system: solar panel, GC solar inverter, and public grid. Solar modules make up the solar array, while single PV modules and series-parallel connections of modules can be used in real scenarios.

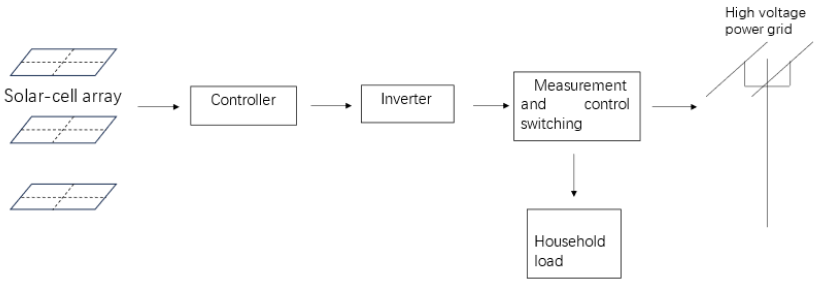


Fig. 3 GC PVPG system (Photo/Picture credit: Original)

3. PV GC Inverter

A PVPG is a form of renewable energy that converts solar energy into electricity. The PV GC inverter plays an important role in producing alternating current by converting the direct current produced by solar PV cells. The performance of the inverter directly affects the overall efficiency and stability of the PVPG system. Therefore, it is of great significance to study and analyze the classification and detailed introduction of PV GC inverters. According to the structure and topology of the inverter, the PV GC inverter can be divided into the following categories:

i) Single-phase inverter: Single-phase inverter is suitable for single-phase PVPG systems, and its working principle is to convert DC into single-phase AC. Single-phase inverter has a simple structure and low cost, but its output power is low. ii) Three-phase inverter: The three-phase inverter applies to the three-phase PVPG system, and its working principle is to convert direct current into three-phase alternating current. The three-phase inverter has high output power and good performance stability, suitable for large-scale PVPG systems. iii) Intermediate frequency inverter: The intermediate frequency inverter converts the direct current into high-frequency alternating current by increasing the frequency of the direct current and using the intermediate frequency transformer for voltage conversion, and then converts it into alternating current by reducing the frequency of the high-frequency transformer. Medium-frequency inverter is suitable for distributed PVPG systems because of their high efficiency and small size. iv) Multilevel inverter: Multilevel inverter adopts multiple cascaded inverters, and each inverter level is responsible for converting a part of DC into AC and finally outputting AC. The multilevel inverter has high output quality and low harmonic distortion.

4. Analysis of Leakage Current in GC PV System

4.1. Causes and Hazards of Leakage Current

To improve the efficiency of PV systems, reduce the volume and weight of the topology, and consider the cost, most of the PV GC inverters are non-isolated without transformers. Generally speaking, the solar panel has a large area, and the aluminum alloy frame and the internal circuit of the panel form a planar structure, which makes the PV cell produce parasitic capacitance to the ground. Furthermore, the lack of a transformer for electrical isolation in a non-isolated GC PVPG system results in direct electrical connections between the AC power grid and the solar panels. When the power switch is in the high-frequency on-off period, high-frequency common-mode voltage will be generated on parasitic capacitance, resulting in a common-mode current, that is, leakage current. The international standard IEEE 929-2000 stipulates that the THD value of GC current should not exceed 5%. The high-frequency common-mode leakage current will reduce the system efficiency and increase its loss, and the current harmonics injected into the public grid aggravate the PID effect, threaten personal safety, and cause EMI problems.

4.2. Treatment of Leakage Current in the Inverter

In PVPG systems, leakage current can be classified into two types. One is due to dielectric coupling effects such as capacitance and mutual inductance in the PV panel circuit or indirect leakage current caused by common mode interference of the power supply. This leakage current can cause interference with the control system and detection measurement and also affect the normal operation of the equipment. Another type is caused by grounding faults or impedance insulation issues in equipment lines, usually caused by the power supply flowing to other components or the ground. This leakage current is a potential threat and may cause electric shock accidents. In the common-mode resonant circuit, the influence of the leakage current caused by the impedance is slightly small, and the existing literature mainly focuses on improving topology, proposing new modulation strategies, and common mode filtering in studying common mode problems.

4.3. Existing Methods and Problems

The problem associated with reducing the Y capacitance: Reduce the value of the Y capacitance. Reducing the value of the Y capacitor can increase the leakage current impedance outside the PVPG system, but reducing the value of the Y capacitor will reduce the electromagnetic interference performance index of the PVPG system. Increasing the common mode inductance value can effectively reduce the leakage current if the common mode voltage is constant. However, as the common mode inductance value increases, the price of solar PG systems and the size of inductors will also correspondingly increase.

The parasitic capacitance between the PV panel and the ground can cause a voltage difference between the inverter output and the ground, directly affecting the public power grid by current harmonics, and there may be EMI problems. The literature provided a harmonic compensation strategy for 3-ϕ GC solar energy conversion systems and added a new algorithm. The conversion system has leakage current attenuation characteristics, and the harmonic controller is used to suppress harmonics and leakage current within a limited range, aiming to suppress harmonics, correct power factor, and reduce leakage current [2]. Increase the filter capacitance of the LC filter: The oscillation circuit formed by the LC filter capacitor and the bus capacitor provides a low impedance channel inside the inverter for leakage current, which can serve as a shunt. The larger the capacitance value of the LC filter capacitor, the greater the leakage current in this path, which can effectively reduce the leakage current of the external system of the inverter [3]. Suppression of leakage current by zero common-mode voltage: Connecting PV panels to an inverter and interconnecting them to the grid through coupled inductors reduces leakage current by achieving zero common-mode (CM) voltage for transformerless PV GC systems [4].

This work introduces a unique three-phase transformerless inverter design and suggests a modulation method based on sinusoidal-triangular pulse width modulation to lower the leakage current of the inverter while it is operating [5]. A CMV-clamp topology may reduce the leakage current, which injects reactive power into the grid. During inverter operation, the suggested topology's CMV remains constant. Hence, no extra CMF is required [6]. Other studies propose a new method to suppress the leakage current of a single-phase five-level converter using an SVPWM algorithm [7]. The Asghar inverter with voltage-boosting capability is another new type of inverter whose topology consists of four active switches and two diodes [8].

5. Bipolar Sine Pulse Width Modulation (SPWM) Technique

5.1. Bipolar SPWM Technique Existing Defects

There are three kinds of modulation technologies: unipolar, bipolar and hybrid modulation. Single-phase bridge inverter with bipolar PWM modulation has good leakage current characteristics, and it produces a constant CMV, so the leakage current is relatively lower. In addition, although the leakage current problem could be resolved via bipolar SPWM techniques, the lower efficiency of bipolar

SPWM inverters compared to unipolar SPMW inverters is attributable to the higher core losses and switching losses of the filter inductors.

Through circuit analysis, the common-mode voltage value of the single-phase bridge inverter with bipolar PWM is constant at $U_{dc/2}$. Although the leakage current can be effectively suppressed, the system's efficiency is greatly reduced. The switching loss of bipolar PWM is nearly twice as much as that of unipolar PWM when working at power frequency, while unipolar PWM is mostly used in practical applications. In addition, previous studies have compared the performance differences between induction motors, and the results showed that the total harmonic distortion of unipolar PWM is lower than that of bipolar PWM, requiring a filtering circuit [9].

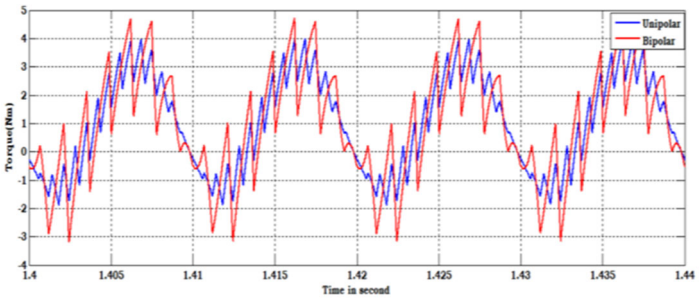


Fig. 4 Torque of the induction motor [9]

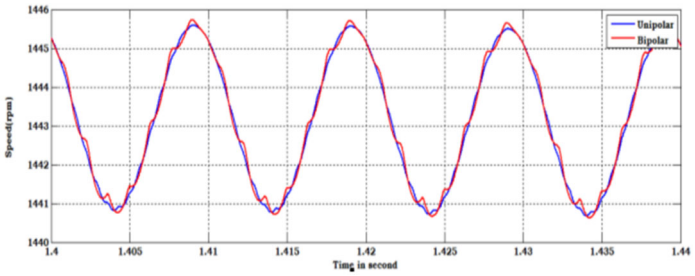


Fig. 5 Speed of the induction motor [9]

However, by comparing Figs. 4 and 5, the speed and torque of unipolar PWM are smaller, which means that the utilization rate of bipolar PWM switches is higher [9]. The literature proposed a scheme that can improve the system's overall efficiency but still meet THD requirements. Considering the characteristics of losses and current ripple relative to instantaneous switching frequency during the optimization process, the switching losses of SPWM bipolar inverters were effectively reduced. The 1 kW full bridge inverter was constructed using SiC MOSFET and ferrite cores [10].

5.2. HERIC, H5 and H6 Series Defects

Bipolar SPWM can address leakage current. However, compared with the unipolar SPMW inverter, the efficiency of the bipolar SPWM inverter is lower because the filter inductor's core loss and switching loss are higher. Moreover, according to international regulations and standards, the inverter should input a certain amount of reactive power into the grid. According to the IEEE-1547 standard, Topologies like H6, H5, and HERIC series do not meet their standards if the CMV clamping structure is not applied. In addition, in the freewheeling stage or power transmission, the current only flows through two switch tubes in the H5 topology, while Heric uses one more switch tube compared with the H5 topology and is additionally equipped with a CMF (common mode filter) in the topology structure, so the structure is complicated, and the system hardware cost is increased.

6. Conclusions

This paper takes the non-isolated PV GC inverter as the research object, and the causes of the leakage current of the traditional non-isolated GC inverter system are analyzed. In addition to isolating the AC side and DC side to block the common mode loop, it is a common strategy to

disconnect the AC side and PV within the freewheeling time of the inductor in the current source inverter. In practice, due to the high-frequency common-mode loop formed at the on-off time of the switch, the suppression method of leakage current needs to be improved. On this basis, the leakage current suppression measures based on the improved topology, common-mode filtering and modulation mode are supplemented. Some problems in the topology are pointed out, and the feasible scheme is supplemented. Finally, it should be pointed out that the key factor in reducing the leakage current is the modulation strategy. Bipolar sinusoidal pulse width modulation technology can reduce this current to the greatest extent in PV applications, but it is difficult to apply because of its complexity and switching loss problems, so most of the existing applications are unipolar modulation.

This paper offers a broad overview of the most recent developments in GC inverters with low leakage current. The primary categories of solar systems and inverters are also introduced. The transformerless GC inverter examines the theory and effects of leakage current. Additionally, a comparison of the most popular topologies is provided. The topic's primary issues and emerging research directions are then outlined. Hopefully, this review will further the study and exploration of transformerless inverter leakage current reduction.

References

[1] Dong Zitong. PV Inverter development faces three challenges. China Energy News, 2023.

[2] Shah Priyank, Bhim Singh. Power quality improvement using three-phase transformerless grid interfaced SECS enabling leakage current suppression. IET Power Electronics, 2021, 14(12): 2067-2083.

[3] Wang Kaixin, Fang Gang, Cheng Yao, et al. Analysis and protection of leakage current in non-isolated GC photovoltaic power generation system. Solar Energy, 2021.

[4] Mlay Joshua John, Xie Yuanhao, Jiang Dong. Photovoltaic power system leakage current reduction by paralleled inverters. In 2021 IEEE 4th International Electrical and Energy Conference, 2021, 1-7.

[5] Chamarthi Phani Kumar, Al-Durra Ahmed, EL-Fouly Tarek HM, et al. A novel three-phase transformerless cascaded multilevel inverter topology for GC solar PV applications. IEEE Transactions on Industry Applications, 2021, 57(3): 2285-2297.

[6] Ahmad Zameer, Singh S.N. Single phase transformerless inverter topology with reduced leakage current for GC photovoltaic system. Electric Power Systems Research, 2018, 154:193-203.

[7] Grishanov Evgeny V., Brovanov Sergey V. Aspects of common-mode leakage current suppression in single-phase PV-generation systems. In 2017 18th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices, 2017, 541-546.

[8] Jahan Hossein Khoun. A new transformerless inverter with leakage current limiting and voltage boosting capabilities for GC PV applications. IEEE Transactions on Industrial Electronics, 2019, 67(12): 10542-10551.

[9] Krishna T. Murali, KrishnaVeni K., Babu G. Suresh, et al. Performance evaluation of induction motor for unipolar and bipolar pulse width modulation techniques. International Journal of Innovative Technology and Exploring Engineering, 2019, 8(10): 3626-3629.

[10] Xia Yinglai, Roy Jinia, Ayyanar Raja. Optimal variable switching frequency scheme for GC full bridge inverters with bipolar modulation scheme. In 2017 IEEE Energy Conversion Congress and Exposition, 2017, 4260-4266