Proceedings of Urban Intelligence: Machine Learning in Smart City Solutions - CONFSEML 2024
DOI: 10.54254/2755-2721/65/20240496

Comprehensive analysis on topologies for limiting leakage current in transformerless inverter

Hao Li

Faculty of Engineering and Information Technology, University of Melbourne, Melbourne 3010, Australia

1910841235@mail.sit.edu.cn

Abstract. With the evolution of science and technology, human beings' demand for electric energy has increased rapidly. Traditional power generation methods such as using fossil fuel will result in serious greenhouse gases emitting, which leads to an intensification of the global greenhouse effect. Using clean energy to replace traditional power generation methods becomes urgent. As a reliable energy source, sunlight could continuously provide energy for human beings and Solar energy has accounted for a large proportion of new energy. Solar energy is converted into Direct Current (DC) by solar panels and the power transmitted from the power grid to factories and houses requires Alternating Current (AC), in this condition, inverters that could convert DC to AC are important components in photovoltaic (PV) systems. As the development of inverter technology gradually matures, inverters begin to develop with the characteristics of small, low-cost, and transformerless. This article introduces a common technical problem encountered in developing transformerless inverters-the generation of leakage current. Several different transformerless inverter topologies are compared to find reliable methods to limit leakage current, and some suggestions are raised for the future development of transformerless inverters.

Keywords: Transformerless inverter, leakage current, common-mode voltage, solar system.

1. Introduction

In recent years, the use of green energy for power generation has become a key research topic in the field of new energy generation. The importance of finding renewable energy to replace existing fossil fuel power to generate electricity can be seen from the following set of data: since industrialization, the average temperature of global has increased by 1.1 degrees Celsius, and sea levels have risen 4 feet since January 1993. In 2022, carbon dioxide emissions caused by power generation in the United States were 1.65 billion tons. The use of renewable energy to replace traditional fossil energy power generation has become a major tendency. At present, the world's main renewable energy include wind energy, biomass, tidal energy, solar energy, etc. PV systems have the advantages of long life, low annual failure rate, and measurable solar radiation, which make photovoltaic power generation stand out from many renewable energy generations and become a key research field of clean energy power generation in today's society [1]. Figure 1 shows a traditional PV system from solar panel to users, the sunlight received by the solar panel can be converted into Direct Current (DC) then through the inverter to turn into Alternating Current (AC), filtered out harmonics by a filter, and finally transmitted to the user's home [2].

© 2024 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

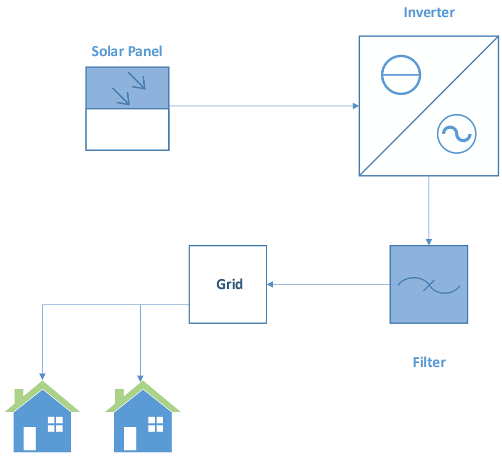

Figure 1. PV System [2]

In this condition, inverters that could convert DC to AC are important components in photovoltaic (PV) systems. Regular PV systems include three main parts: solar panels, transmission lines, and inverters. The current provided by solar energy is DC, and household appliances generally require AC, inverters that can convert DC into AC are extensively used in PV systems. To improve the efficiency of the inverter, reducing switching losses and leakage current have become two main aspects in the present inverter research field. Based on the nature of the power source, inverters in PV systems are mainly divided into three categories: Voltage Source Inverter, Current Source Inverter, and Reactance Inverter. According to whether there is a transformer, inverters are mainly divided into two categories: transformer inverter and transformerless inverter [3].

Transformers are widely used in traditional inverters which consists of an inverter circuit and a transformer. The function of the transformer is to synchronize the voltage levels of the grid with household appliances. Although the inverter is small, the existence of the transformer greatly increases the size of the transformer inverter. Moreover, the transformer will cause a large waste of energy, which will seriously reduce the efficiency of the system, so transformer inverters are unsuitable for future use in the PV systems.

The process of voltage level synchronization is necessary, transformerless inverters use electronic components to substitute transformers to achieve the same function. The transformerless inverter has the following advantages: without the transformer, the weight of the transformerless inverter becomes lighter and the size becomes smaller; the energy loss of the transformer part is reduced; using electronic switches reduces the generation of heat and the operating temperature compared to the transformer inverter. Also, the transformer will increase the cost of the inverter and reduce the efficiency of the PV system, transformerless inverters are widely used in many fields. There are researches has shown that the efficiency of the PV system can rise by 1-2% after removing the transformer [4]. The use of transformerless inverters is becoming the development trend of future PV systems.

Transformerless inverters can be divided into three categories: Zero-state Decoupling Topology, Zero-state Mid-point Clamp Topology, and Fixed Clamp Topology. Several typical topologies of transformerless inverters are shown in Figure 2. As the development of inverter technology gradually matures, inverters begin to develop with the characteristics of small, low-cost, and transformerless.

This article introduces a common technical problem encountered in developing transformerless inverters-the generation of leakage current. Several different transformerless inverter topologies are compared to find reliable methods to limit leakage current, and some suggestions are raised for the future development of transformerless inverters.

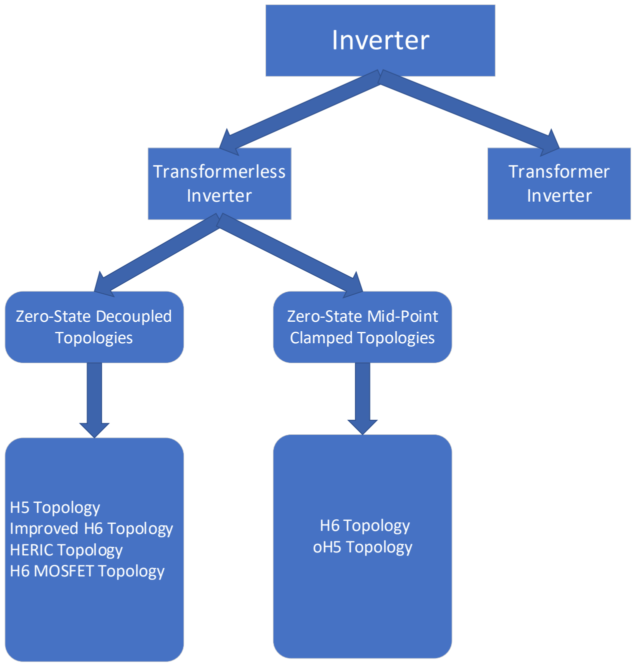

Figure 2. Classification of inverters [4]

2. Leakage Current

2.1. Generation of Leakage Current

Inverters that are without transformers could be affected by surges and shocks due to simplified structure. In addition to synchronizing voltage levels, the transformer also has the characteristics of galvanic isolation. The leakage current will inevitably be generated without the galvanic isolation of the transformer in transformerless inverter. Another reason for generating leakage current is there exists the Common-Mode Voltage (CMV) with high-frequency in the transformerless inverter. The CMV has the same frequency with switches will be generated during the running of the inverter. A Common-Mode Current (CMC) will be generated by the CMV, which is also called leakage current, with the same frequency.

Leakage current may cause many problems in PV systems. First of all, it will cause electronic devices to heat, leading to power losses and reducing the efficiency of the PV system. The existence of leakage current may also cause unexpected tripping of residual current protection and electromagnetic compatibility. Electromagnetic compatibility deterioration, shortened PV module life, current harmonic distortion, electric shock, and other problems will occur when staff touch PV modules [5].

2.2. Restriction of Leakage Current

The first part of this article mentioned that the use of transformerless inverters is the current tendency in PV systems. Lack of the galvanic isolation of the transformer is the reason why the leakage current in the transformerless inverter is large. To find an effective limiting solution for leakage current, it can start with the causes of leakage current. One main reason for leakage current is the existence of CMV, limiting the CMV could achieve the restriction of leakage current. Below are several methods of stabilizing the CMV:

1) Using common mode chokes (common mode inductor) [2]: The common mode choke has two coils with the same number of turns and opposite winding directions. When the leakage current flow through the coil of the common mode choke, induced magnetic fields in the same direction are generated in the two coils. A large induced magnetic field will generate a large induced current to balance the leakage current. Although the use of common-mode chokes can

DOI: 10.54254/2755-2721/65/20240496

effectively reduce leakage current, the disadvantages of this method are also obvious. For example, being equipped with the common mode chokes result in rising the manufacturing cost of the inverter, and the loss of the common mode chokes decreases the efficiency of the PV system.

2) Reducing the CMV variation: The change in the CMV is mainly caused by the unequal line impedance of the two terminals that change the DC direction in the inverter. Keeping the impedance of the two lines equal to each other could stabilize the CMV. The work in [5] proposed that two inductive filters with independent cores can be used in this condition though it will rise the cost and enlarge the volume of the inverter. In addition, using a full-bridge inverter with bipolar sinusoidal PWM, or adding switches in the inverter, using H5, Improved H6, and HERIC inverter topologies to isolate the connection between the PV system and the grid could achieve the galvanic isolation.
3) Connecting common-ground converter: By adding a common-ground converter to connect the negative terminal of the inverter and the neutral point of the grid, the leakage current can be eliminated. The inverter provides grounding for the PV system, so surges and shocks can be reduced at the same time. Before using a common-ground converter, a strict analysis of the characteristics of the PV system and calculation of parameters are needed to prevent the efficiency of the PV system from reducing [6].

3. Topologies of Transformerless Inverter

This part will discuss the inverter topology based on adding switches methods mentioned before, compare the advantages and disadvantages of various topologies of full-bridge inverters, and potential improvements to limit leakage current:The full-bridge inverter uses sinusoidal pulse width modulation (SPWM), the switching of the current phase is realized by the continuous opening and closing of the switches. The zero-state and the active state will continuous conversion in each cycle and common-mode voltage with high frequency will be generated. The PV module and the grid need to be disconnected when the capacitor releases freewheeling current for stabilizing the CMV. The following are several full-bridge inverter topologies based on this principle.

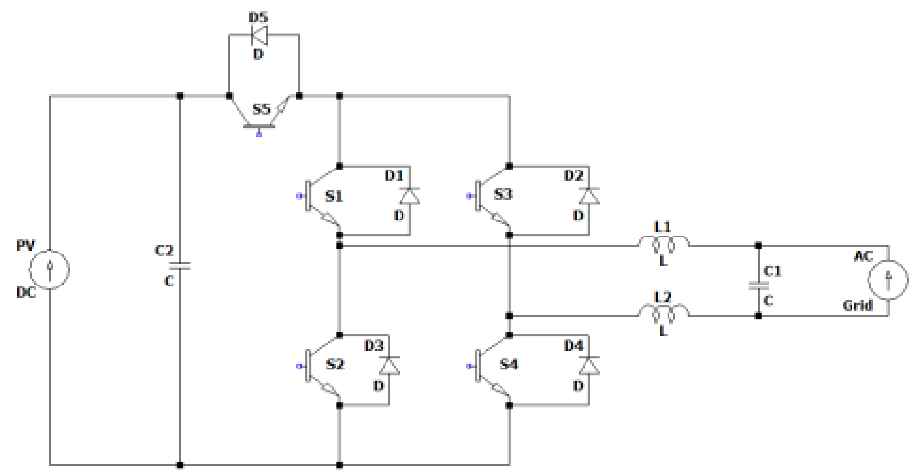

Figure 3. H5 Topology [6]

3.1. H5 Topology

The H5 topology, as shown in Figure 3, is based on the four switches of the positive and negative terminals of the full-bridge inverter. Adding a switch on the PV side that could disconnect the PV side and the grid side. There will be a zero state generated when the inverter switches from positive to negative in each half cycle. Turn off the additional switch S5 at the zero state, the freewheeling current flows through the switches S1 and S3. Similarly, when the current provided by the solar panel changes from negative to positive, the additional switch S5 is open and the freewheeling current of the capacitor flows through the switches S1 and S3. The CMV kept stable by keeping the freewheeling current flowing in the same path. The characteristic of H5 is that it uses fewer switches to limit the leakage current by isolating the PV side and the grid side which is also the basis for the following topology designs.

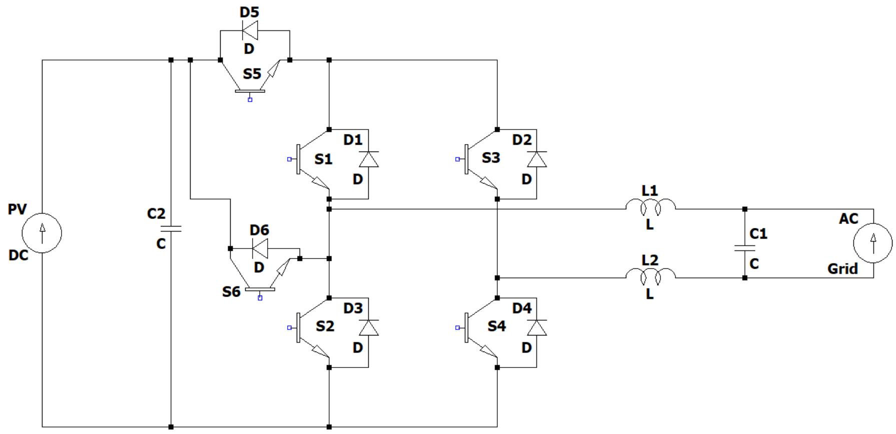

Figure 4. Modified H6 Topology [7]

3.2. Modified H6 Topology

The modified H6 topology, as shown in Figure 4, is designed based on the H5 topology. S6 is connected in parallel to the S5 and the four switches on the grid side work at the switching frequency. Added switches S5 and S6 on the PV side work at the line frequency. The principle of the modified the topology of H6 is identical as that of the H5, by limiting the direction of the freewheeling current to reduce the leakage current. Compared to the H5, this topology's leakage current is less in value [8]. The characteristic of modified H6 is the addition of switches, which enhances the leakage current limiting effect at the expense of part of the system efficiency.

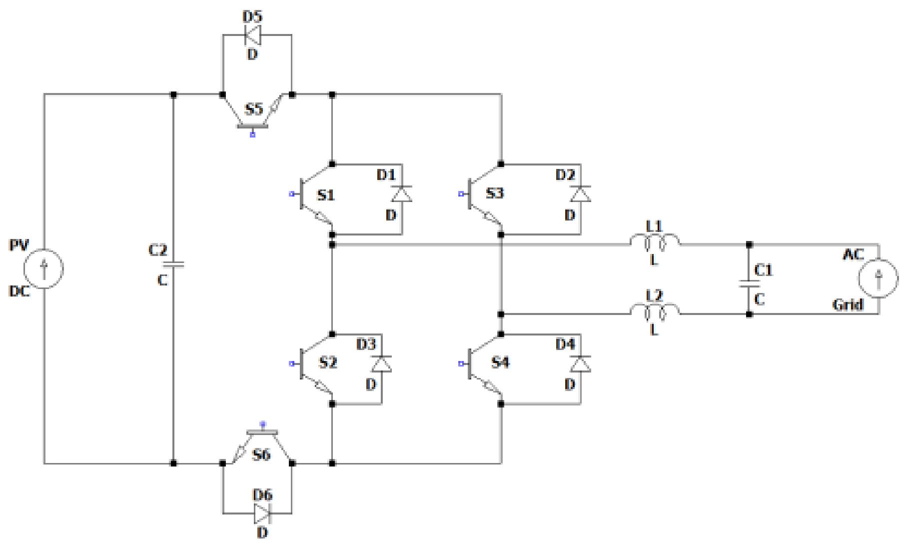

Figure 5. Improved H6 Topology [8]

3.3. Improved H6 Topology

The improved H6 topology, as shown in Figure 5, is based on the H5 topology and adds a switch between the PV negative terminal and the grid. Using the improved H6 topology can limit the leakage current by reducing the duty cycle of the maximum value of common-mode voltage in a single period. The

DOI: 10.54254/2755-2721/65/20240496

efficiency of this topology is lower compared to H5. The position of the switches added in the improved H6 is different from that of the modified H6, and the principles of limiting leakage current between the two topologies are also different. Although the efficiency of the two topologies is similar, the peak value of leakage current of the improved H6 is slightly larger than that of H6 [8].

3.4. MOSFET H6 Topology

The MOSFET H6 topology, as shown in Figure 6, uses six MOSFETs to replace the IGBTs in traditional full-bridge inverters. MOSFETs are more efficient than IGBTs, as a result, the overall efficiency of MOSFET H6 topology is higher. When the current passes through the zero-state from positive to negative, S1 and S4 are open, and the freewheeling current released by the capacitor passes through S5 and D1. When the current passes through the zero-state from negative to positive, S2 and S3 are turned off, and the freewheeling current released by the capacitor passes through S6 and D2. The CMV is also kept to be constant based on the principle of keeping the freewheeling current flowing through in the same path. Studies have pointed out that the H6 topology with MOSFET will reduce the inverter efficiency by 1.7%-1.9% [7]. However, the low reverse recovery problem caused by the parallel connection of MOSFET and diode will lead to a reduction in the system's reliability.

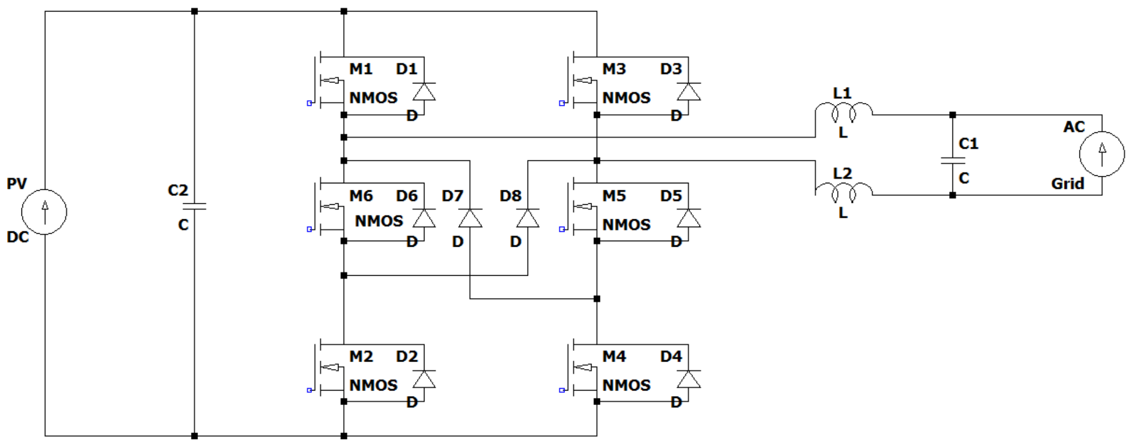

Figure 6. MOSFET H6 Topology [8]

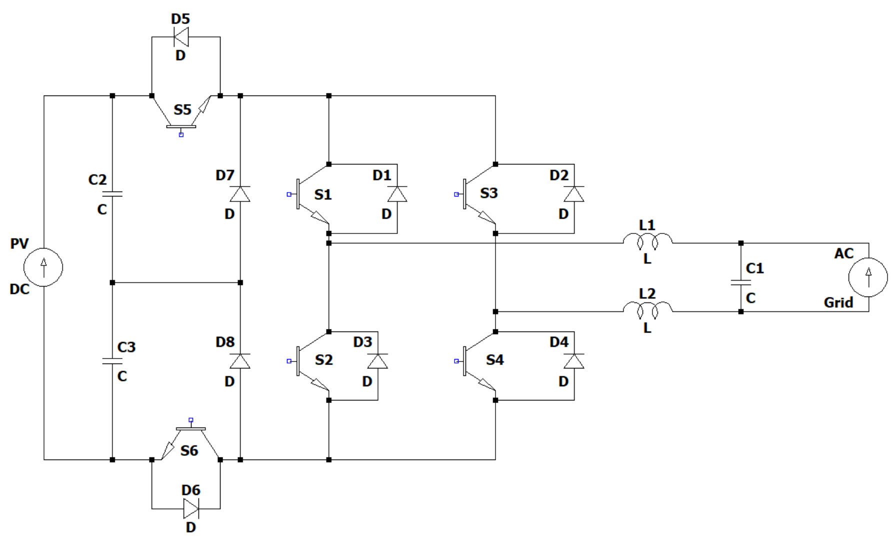

Figure 7. H6 Topology [8]

DOI: 10.54254/2755-2721/65/20240496

3.5. H6 Topology

The H6 topology, as shown in Figure 7, adds two switches and two diodes to the PV side of the full-bridge inverter circuit. In this topology, the short-circuit output voltage is clamped to the midpoint of the DC bus, and the CMV remains constant during the whole period. The clamp branch consists of one capacitive divider and two diodes, which reduces the CMV by half of the input voltage. The leakage current limiting effect depends on the switching speed of the clamp diode. However, the inductor current in this topology has a large loss in the switch. Research shows that using the H6 topology will reduce the efficiency of the system by about 2.6% [7].

3.6. HERIC Topology

The Highly Efficient and Reliable Inverter Concept (HERIC) topology, as shown in Figure 8, uses unipolar SPWM. Different from the H5, the HERIC topology adds switches on the AC side and turns on both in the positive and negative phases. Providing a channel for the freewheeling current of the capacitor on the AC side. Although there will be no freewheeling current through the DC side in theory, the voltage of the freewheeling path cannot keep in half of the input voltage, a varying common-mode voltage will still exist. Since the freewheeling current is limited to the AC side by the added switches S5 and S6, the efficiency of the HERIC is higher and the leakage current is smaller.

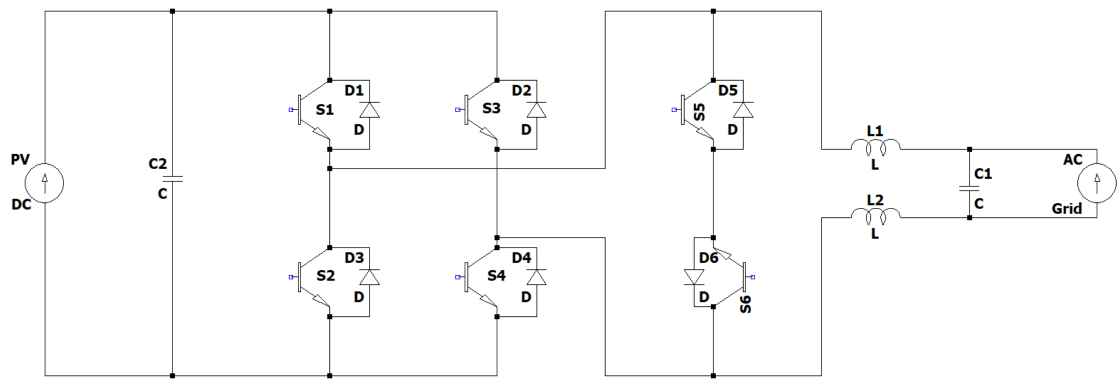

Figure 8. HERIC Topology [8]

4. Discussion

Using transformerless inverters has become the current mainstream choice. By comparing several different topologies, the conclusion is that the galvanic isolation and CMV influence the leakage current. Adding switching devices could stabilize the CMV, for example, the improved H6 has a leakage current which is lower by comparison with the H5. However, the increase in switches will reduce the efficiency of the PV system, as a result, compared with the improved H6 topology, the efficiency of an H5 topology will be greater. Using lower loss switching devices such as MOSFET to replace IGBT could solve this problem. Although this will increase the difficulty of design, as electronics technology matures, more and more switching devices with better performance will appear. To strengthen galvanic isolation, it is necessary to disconnect the PV side from the grid side when the current phase is in the zero state. For this reason, a higher-precision system could be used to control the switches. Balancing the value of leakage current and the efficiency of the PV system will be a key research field in future transformerless inverter design.

5. Conclusion

This paper explains the urgency of current society's demand for clean energy and compares the advantages and disadvantages of using transformer inverters and transformerless inverters in PV systems and explains the importance of using transformerless inverters. Compared with transformer inverters, transformerless inverters have small size and the cost is low, though the disadvantage is that the leakage current will appear because of the lack of galvanic isolation of the transformer. Based on the reasons for

DOI: 10.54254/2755-2721/65/20240496

leakage current, three main methods to limit leakage current are discussed: using common-mode chokes, keeping the CMV constant, and using common-ground converters. Several topologies of full-bridge inverters are analyzed in regard to the methods of keeping the common-mode voltage constant. Finally, the future development trends of transformerless inverters are discussed. Based on the developing tendency, some suggestions and ideas are raised.

References

[1] Y. Zhu et al., "Novel Fast-Speed Partial-Shading-Tolerant Flexible Power Point Tracking for Photovoltaic Systems With Explicit Key Points Estimation," in IEEE Transactions on Sustainable Energy, vol. 15, no. 1, pp. 466-485, Jan. 2024.

[2] Y. Zhu, H. Wen, Q. Bu, X. Wang, Y. Hu and G. Chen, "An Improved Photovoltaic Power Reserve Control With Rapid Real-Time Available Power Estimation and Drift Avoidance," in IEEE Transactions on Industrial Electronics, vol. 70, no. 11, pp. 11287-11298, Nov. 2023.

[3] Estévez-Bén, Adyr A, et al. “Leakage Current Reduction in Single-Phase Grid-Connected Inverters—a Review.” Applied Sciences, vol. 10, no. 7, 31 Mar. 2020, pp. 2384–2384.

[4] Li, Wuhua, et al. “Topology Review and Derivation Methodology of Single-Phase Transformerless Photovoltaic Inverters for Leakage Current Suppression.” IEEE Transactions on Industrial Electronics, vol. 62, no. 7, July 2015, pp. 4537–4551.

[5] Gaafar, Mahmoud A., et al. “Common-Ground Photovoltaic Inverters for Leakage Current Mitigation: Comparative Review.” Applied Sciences, vol. 11, no. 23, 1 Jan. 2021, p. 11266.

[6] Ponrekha A., Sahaya, et al. “A Topology Review and Comparative Analysis on Transformerless Grid - Connected Photovoltaic Inverters and Leakage Current Reduction Techniques.” IET Renewable Power Generation, 19 Dec. 2022,.

[7] Islam, Monirul, et al. “Single Phase Transformerless Inverter Topologies for Grid-Tied Photovoltaic System: A Review.” Renewable and Sustainable Energy Reviews, vol. 45, May 2015, pp. 69–86.

[8] Kibria, Md. Faruk, et al. “A Comparative Review on Single Phase Transformerless Inverter Topologies for Grid-Connected Photovoltaic Systems.” Energies, vol. 16, no. 3, 28 Jan. 2023, p. 1363.