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A Review of Single Phase Inverter Topologies for Grid-tied Photovoltaic System and Control Strategy Methods

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ABSTRACT

Grid-tied inverters are crucial in distributed generation systems, serving as an interface between renewable energy sources and utility. Transformer-less inverters are increasingly popular due to their higher efficiency, lower cost, and smaller size. The inverter's current control quality impacts the power quality and converter system performance. Inverter connections must meet the following requirements: maximum power point, high efficiency, control power fed into the grid, and low overall harmonic distortion of the grid currents. As a result, the performance of grid-connected inverters is heavily influenced by the control method described in the first section. In distributed power generation (DG) systems, inverters serve several important purposes. These include converting direct current (dc) to alternating current (ac), ensuring the quality of the output power, implementing different protective measures, and controlling the system. The classification of different types of inverters and their topologies is thoroughly studied, defined, and shown in a graphical fashion. A succinct overview of the control techniques for single-phase inverters has also been provided. Furthermore, a range of controllers are utilized for grid-tied inverters.

1. Introduction

Renewable energy sources (RESs) are increasingly used in electricity generation due to their variety and utility grid support. However, planning, operation, maintenance, and management challenges remain. Government regulations for distributed generation and demand side management (DSM) regulations utilize interoperability plans for generation facilities like PVs, wind turbines, fuel cells, and micro sources. Grid-connected inverters and DC-DC converters are crucial for resource management [1]**.** A single-phase grid-connected transformer-less inverter is an essential part of solar photovoltaic systems because of it is smaller and more efficient than a standard inverter with a transformer [2]. Transformers are not necessary with these inverters, which might reduce leakage current problems brought on by common mode voltage fluctuations [3].Transformer-less grid-connected PV systems have various topologies to eliminate leakage current, including full-bridge inverters with bipolar SPWM, three-level neutral point clamped inverters, and special topologies with unipolar SPWM. Bipolar SPWM generates a constant common mode voltage, but requires a large output filter. NPC inverters improve efficiency but require high DC bus voltage, limiting PV panel operating voltage range. Heric, H5, and H6 inverters operate with unipolar SPWM strategy [4]. Grid-connected inverter control has attracted a lot of attention, and researchers are investigating various control strategies to satisfy the intricate demands of grid connection [5]. However, the grid is AC. Therefore, grid-connected inverters (GCIs) are the significant interface between renewable energy resources and the grid Compared with the isolated single-phase GCIs, transformer-less single-phase GCIs are becoming more and more popular in the home market because of their increased power density, higher efficiency, and lower cost [6].

The main functions of PV power converters, such as PV power maximization, DC to AC power conversion and transfer, synchronization, grid code compliance, reactive power control, islanding detection and protection, etc., are the same even though their configurations vary [7]. In order to meet tailored requests and operate various PV features, intelligent controls are also needed. This is where communication, forecasting, and monitoring technologies help improve PV integration [7], [8]. Solar energy systems are used in various applications, including solar photovoltaic (SPV) power plants, residential PV, and building integrated PV. Residential PV systems can be operated as stand-alone systems or grid connected systems. Stand-alone systems are used in remote areas, while grid connected systems inject power output into the grid. Single phase distribution systems are used in residential areas, with a voltage source inverter facilitating power exchange[9].Grid synchronization is a significant challenge for distributed generating systems that are

linked to the utility grid via Power Electronics systems. During grid disturbances, disconnecting large-scale grid-connected single-phase DG systems can have a negative impact on the reliability, stability, and availability of the distributed grid. In this situation, a well-designed synchronization strategy is crucial for effectively managing single-phase grid linked equipment. An intermittent grid fault often occurs for a brief duration, so a precise and rapid synchronization technique is crucial for maintaining optimal performance of all grid-connected equipment during grid failure operation [10].

Transformer-less inverters have several economic advantages over traditional inverters, including reduced operation, modularity, transformer voltage and current scalability, high redundancy, and fault tolerance in the switching states. However, these advantages come at the expense of a wide range of passive and active components, including DC sources, flying condensers, inductors, diodes, and switches, which increase the inverter's size, cost, and complexity.2 As a result, one of the most significant research advances in this sector is the present suggestion for unique mixes that increase the level number while employing a minimal number of components.3 The usage of transformer-less inverters can minimize the total cost of the system when compared to standard transformer-based inverters. [11].

In this paper a transformer-less PV inverter topologies are reviewed, analyzed and compared, the goal is to design efficient transformer-less inverters for grid-connected photovoltaic systems, ensuring lower losses and improved power density. The review also proposed control techniques of single phase inverter, to achieve low Total Harmonic Distortion (THD) and enable the integration of more renewable energy into the grid system.

2.Classification of grid-tied PV inverter

The inverter in a grid-connected photovoltaic system translates DC electricity from the PV module into AC and interacts with the utility grid. It guarantees adherence to IEEE 1547.1-2005, EN 50106, IEC61727, and VDE0126-1-1, thereby tackling problems including total harmonic distortion (THD), leakage current, injected DC current level, frequency and voltage ranges, power factor (PF), and automated system reconnection[12]. Grid-connected PV inverters are classified as isolated or non-isolated based on galvanic isolation between power grid and PV module, monitored by high-frequency or line frequency transformers that adjusts the DC voltage of the converter[13,14],.Typically, a transformer is used to identify galvanic isolation, which has a significant impact on grid-connected PV systems' DC-to-AC efficiency [15]. In countries such as Italy and the UK, mandatory galvanic isolation is carried out either on the DC side with a high-frequency transformer or on the grid side with a low-frequency step-up transformer, as shown in Figs. 1 (a) , (b) , (c). Line frequency transformers are often excluded in new converter designs due to weight, size, and cost considerations. However, high-frequency transformers require multiple power stages, making it difficult to enhance efficiency and reduce costs [16]. Conversely, in nations like Germany and Spain where various technical solutions are employed to split the PV array from the electrical grid, galvanic isolation is not necessary.

In single-phase grid-connected solar inverters, filters are employed to lower the harmonic orders. For this, the LCL filter which consists of a grid-side inductor L2, a capacitor C1, and an inverter-side inductor L1 is frequently utilized. To save total costs and provide efficient harmonic reduction, the filter parameters must be properly selected. Active dampening controllers are required to counteract resonant currents that may arise from the LCL filter's inherent resonance frequency. To successfully dampen the resonance and enhance the single-phase inverter's overall performance, better active damping controllers have been created. The entire cost and efficiency of the solar inverter system can be greatly impacted by the filter architecture and its design parameters. Harmonic mitigation, system efficiency, and cost concerns must all be carefully balanced during optimization [1].

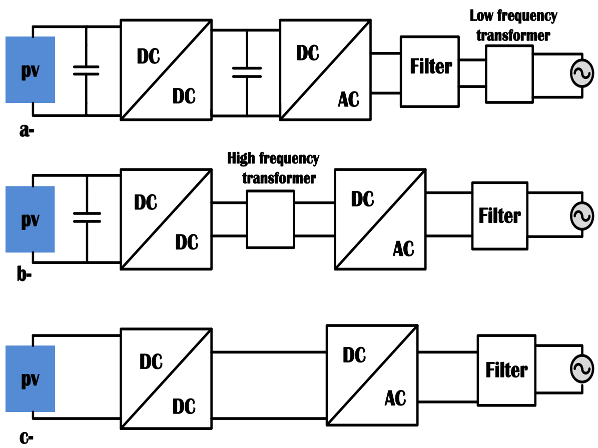

Figure 1: Grid- connected PV systems with (a) a low-frequency transformer, (b) a high-frequency transformer, and (c) a transformer-less inverter [12].

A different types of grid-tied PV inverter. Central inverters, string inverters, multistring inverters, and Ac modules inverters**.** The multi-string and central converters are intensively used for solar PV power plants/farms as three-phase systems [17]. On the other hand, single-phase systems using module and string converters are commonly used in residential settings [18,19]. The most commonly used inverter topology is the single-phase Full Bridge (FB) string inverter due to its simplicity in terms of less power switching devices.

2.1 Central inverter

Those inverters were large, heavy, hard to install, and unstable, and their efficiency was in the 85–90% range[20], as shown in Fig.2(a). Nowadays, thyristors have been replaced by advanced switching devices like Power BJTs, Power MOSFETs, and IGBTs. Most modern inverters are self-commutated and typically connected to three-phase applications, eliminating the need for decoupling. The series-connected module voltage usually meets the inverter's input voltage requirement [21]. The central inverter topology has several drawbacks, though. These include: (a) string diode losses, voltage mismatch losses, PV module losses, and central MPPT power losses. (b) connecting the PV modules and inverter requires high voltage DC cables. (c) line-commutated thyristors, which are commonly used in this topology, produce poor power quality and current harmonics. (d) the design isn't modular or flexible. (e) the central inverter can cause the PV plant to fail in specific cases[22,23].

2.2 String inverter

The string inverter system is coupled to a string formed by number of panels connected in series that feeds AC power to the grid. The power rating of an inverter is low up to 5Kw as the single string is attached to it [24]. String topology consists of the string inverter module. The string topology is an advanced method of centralized inverter. This topology's input voltage might be high enough to prevent voltage amplification [25]. The basic structure of the string inverter topology is represented in Fig. 2(b). The main characteristics of the string topology are its lack of losses and the ability to apply separate MPPT to each string, which raises system efficiency overall and lowers price rating because string diodes are not needed. String inverters of today provide the main benefits of central inverters, including a wide range of DC system voltages and three-phase output while maintaining the high efficiencies. As a result, there will be losses in AC and DC cabling, increasing yield. To ensure that more power is used from the panels, many maximum power point trackers are used. Additionally, simple cabling is also achievable because string combiners and external string monitoring are not needed.

2.3 Multi-string inverter

The multi-string inverter is an assessment of the string inverter shown in Fig. 2(d), where each string made of several solar panels is coupled to its own DC-to-DC converter with individual MPPT and feed energy to a common DC to AC inverter. Consequently, each PV power plant with a few modules can be functioned separately. The advantages of string and module integrated inverter is combined here. Since each PV string is controlled individually, the overall efficiency is higher. There are several advantages of multi-string inverters such as cost reduction, more flexible, small DC-link capacitor, and high energy reveal due to local MPP tracking and optimum monitoring of the PV system[26], [27].

2.4 AC module

In this system, inverter and PV module integration is accomplished in one electrical device. This is a "plug and play" gadget; installation calls for no knowledge whatsoever. This architecture eliminates the mismatched losses of the PV modules [28]. Its modular architecture makes it easy to add on. This design allows for the inverter and PV module to be adjusted optimally. These days, DC-AC inverters are AC modules that use the self-commutated converter architecture [29]. As mentioned, the single module performs all the operations including DC to AC conversion, MPPT, and voltage amplification; so, the circuit becomes more complicated and the price per wattage, as seen in Fig.2(c).

3. DC – DC Converter topologies used in solar inverters

This part will examine in great depth the often used converter candidates for the DC-DC stage of a multi-stage PV MI. The power capacity of the DC-DC converter will directly contribute to the capacity of MI [32]. In order to attain a high power conversion rate, it is crucial to have power converters that possess Maximum Power Point Tracking (MPPT) capacity as integral components of photovoltaic (PV) systems. Furthermore, a significant issue with MIs is the use of electrolytic capacitors, which greatly impacts the longevity of inverters. A DC-DC converter with a high step-up capacity is necessary in order to remove the electrolytic capacitors. When selecting a suitable converter architecture, several criteria need to be considered, including galvanic isolation, the number of power components, power rating, and voltage conversion capabilities [33,34,35,36]. Wide operating voltage, changing irradiance and temperature impacts, growing power density resulting from PV module power rise, and high efficiency need constitute technical problems in DC-DC converter stages. Flyback and interleaved are recent converters; enhanced circuit construction and control techniques are generating new topologies in interleaved flyback systems.

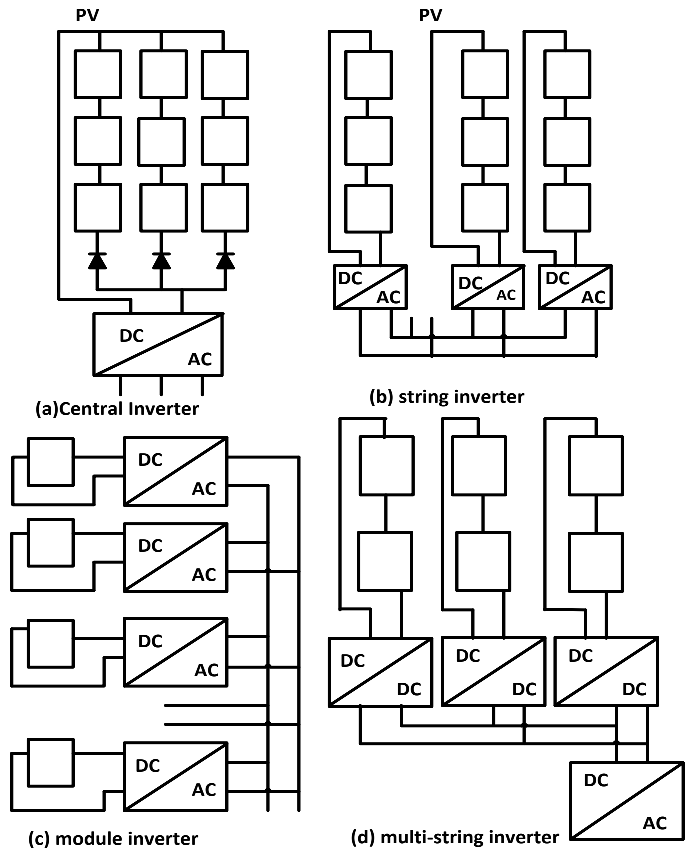

Figure 2: Different types of grid-tied PV inverter: (a) central inverter; (b) string inverter; (c) Module inverter; (d) multi-string inverter [30].

Table 1 presents a comparative analysis of several system architectures, outlining their advantages and disadvantages as well.

Table1. Comparison between different inverter topologies [31]

Topology	Advantages	Disadvantages	Costing
Central	Central inverters offer high efficiency, optimal power conversion, and long operational lifetimes for PV modules, enabling parallel connection, sustained performance, and extra ride-through capability during power outages.	Centralized inverters with line-commutated technology may face issues like poor power quality, integrated MPPT system losses, module mismatches, and string diode losses, necessitating multiple DC bus capacitors for design complexities.	Lower cost
String	String inverters enhance efficiency, control, and scalability of PV module strings by eliminating losses, requiring fewer components, simplifying maintenance, and making them cost-effective for mass production.	String inverters, despite their efficiency and control, may face power losses due to PV module mismatch and require separate DC sources for real power conversion.	Higher cost

AC module	**AC module technology integrates inverter and PV module, improving system efficiency, allowing easy system expansion, and requiring less manufacturing cost compared to traditional setups.**	**AC module technology offers efficiency, modularity, and cost-effectiveness, but requires separate DC sources for real power conversion, adding complexity and reducing mismatch losses, posing challenges in system design and operation.**	**Lower Cost**
Multi-string	**Multi-string inverters, advanced technology connecting multiple strings to DC and AC inverters, optimize power production, enhance efficiency, improve system performance, and enable precise monitoring of PV output.**	**Multi-string inverters offer advantages but may introduce complexities in system design, increase maintenance costs, and require higher initial investment compared to traditional string inverters, impacting the overall cost-effectiveness of the system.**	**Higher cost**

3.1 Flyback DC converter

One kind of switched-mode power supply that is frequently used in applications that call for voltage step-up or step-down with electrical isolation between the input and the output is the flyback DC-DC converter.

3.1.1 With Center-Tapped Secondary Winding

Fig.3 shows the main circuit configuration of a proto-typed PV power conditioner the flyback converter is a buck-boost converter with a transformer, consisting of three IGBTs, two diodes, and a secondary winding. It generates AC power and isolates between the PV array and the AC utility grid line to prevent electric accidents. Two sets of AC semiconductor switches, IGBT2 and IGBT3, are connected to the secondary winding, which can switch reciprocally and synchronously with the AC utility grid line's polarity of the ac utility grid line. Mode I and II are defined by IGBT1 and IGBT2, respectively, where IGBT1 is on-state and all others are off, and stored energy is discharged to the AC utility grid line, with mode I and II alternately switched during the positive half cycle. The peak current through the flyback transformer's primary winding is modulated by IGBT1's pulse width modulated gate pulse, forming a sinusoidal envelope in phase with AC utility grid line voltage, with mode III controlling current in both positive and negative half cycles [37].

3.1.2 The improved Flyback-inverter Topology

The paper proposes an improved flyback-inverter topology that employs three MOSFETs, two diodes, and a flyback transformer with center-tapped secondary winding. The topology consists of an interleaved-flyback converter and a line-frequency GT inverter, similar to the fundamental flyback-inverter. It analyzes and provides a mathematical model to describe the relationship between the output current (iout) and the reference current (iref) in BCM (Boundary Conduction Mode) operation. The paper also proposes a control strategy for the reference current (iref) and switching frequency (fs) to achieve MPPT (Maximum Power Point Tracking) in the improved flyback-inverter operating in BCM. and improves power rating by having two flybacks, phase-shifting 180° in each switching cycle, reducing secondary current ripple, and eliminating the need for a transformer with center-tapped secondary winding. This reduces transformer design difficulties and voltage stress[38]. Fig.4 shows the topology of the improved flyback-inverter.

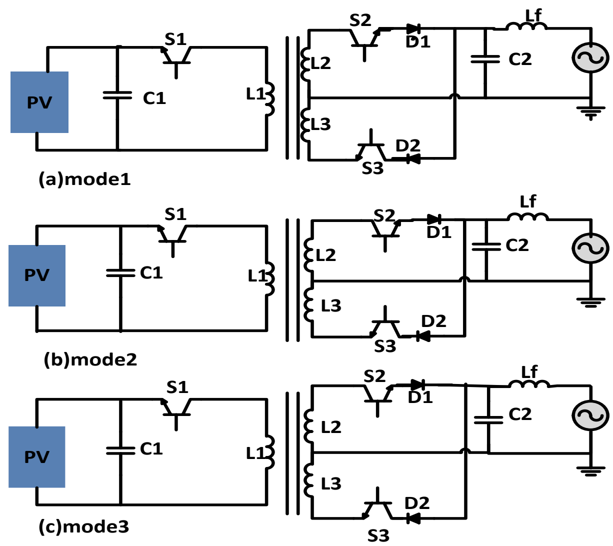

Figure 3: Circuit configuration and operation modes of flyback inverter with center-tapped secondary winding.

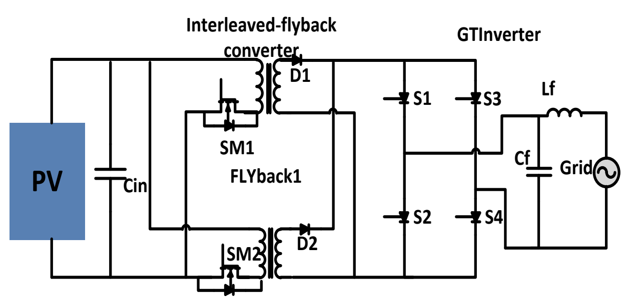

Figure 4: Improved flyback-inverter topology.

3.1.3 Three-port Flyback

Fig.5, shows the circuit configuration of three-port flyback micro inverter. The topology is a modified version of a conventional flyback, by adding an additional switch S2 and another transformer winding at the primary side to implement the power decoupling function. The power decoupling capacitor CD functions as both an energy storage element and a snubber capacitor to recycle the transformer's leakage energy. The diode D2 prevents reverse current from the power decoupling capacitor CD to the PV source, and the diode D3 offers a leakage energy discharge path. Two secondary windings are designed to pump an AC current into the grid, and the D4/S3 and D5/S4 series connections block the power output of either secondary winding. The paper presents simulation and experimental results for a 100-W micro inverter prototype, demonstrating its power decoupling topology, peak efficiency of 90.6%, and well-regulated voltage ripple. The three-port flyback topology offers low component count, compact power stage, low cost, and decent efficiency [39].

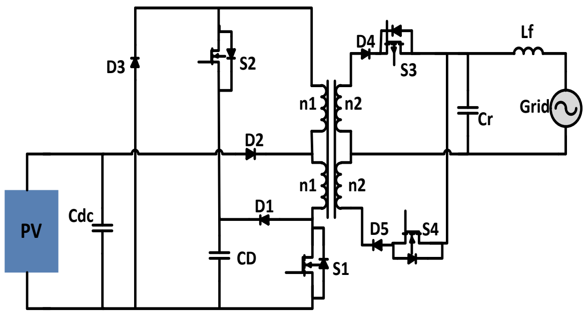

Figure 5: Circuit configuration of three-port flyback micro inverter topology.

3.2 Interleaved Flyback

The proposed converter's circuit configuration as shown in Fig.6, uses a photovoltaic array as the input source, feeding current into a three-stage interleaved flyback converter via a decoupling capacitor(C), which eliminates harmonics and maintains balance. A MOSFET switch operates as a flyback switch, allowing current to flow through the magnetizing inductance (Lm) and the primary winding during the switch's on phase, storing magnetic field energy. When the switches turn off, this energy is released as current to the grid. Operating in Discontinuous Conduction Mode (DCM), the converter acts as a voltage-controlled current source, generating stable AC current at the grid interface[40] .

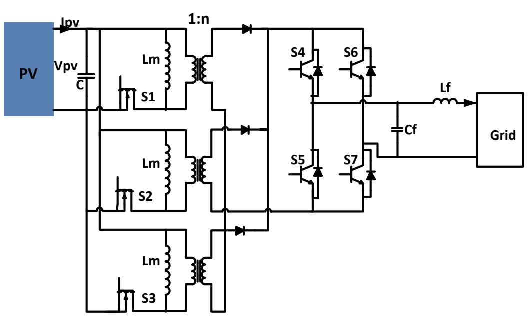

Figure 6: Circuit configuration of interleaved flyback inverter.

Fig.7, shows the main circuit of two-phase interleaved flyback micro inverter topology. The inverter consists of two-phase-interleaved flyback converters and a CSI (Current Source Inverter). S1 and S2 serve as the primary power switches, while D1 and D2 function as the rectifier diodes. NP 1 and NP 2 represent the primary windings, and NS1 and NS2 denote the secondary windings. Sections 3 to 6 comprise the Current Source Inverter (CSI) responsible for decomposing the rectified sinusoidal waveform into the grid. S3 and S6 are activated during the positive half of the grid cycle, whereas S4 and S5 are activated during the negative half of the grid cycle [41].

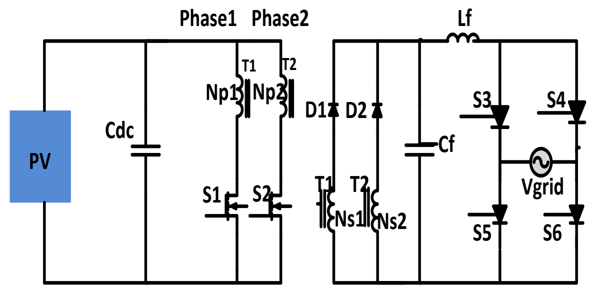

Figure 7: Two-phase interleaved flyback micro inverter topology.

4. Transformer-less Inverters Topology

Transformer-less inverters are most preferred for grid connected photovoltaic (PV) generation system due to higher efficiency and lower cost, smaller size, and weight [42].The various transformer-less inverter topologies documented in the literature encompass H5, HERIC, H6, and the Flying capacitor. The majority of these configurations belong to the category of Voltage Source Inverters (VSI), requiring an input voltage level surpassing the peak value of the grid voltage. In VSI setups, a significant capacitance must be linked across PV terminals to diminish input voltage fluctuations. Conversely, the utilization of a current source inverter, incorporating an inductor in series, can elevate the input voltage and diminish the required input capacitance. This enhancement enhances system reliability and simplifies the task of extracting maximum power from the PV array [43].However, in case of transformer-less inverter, a galvanic connection between the PV module and the grid exists that can create a common-mode resonant circuit.

The use of innovative HERIC-based topologies to solve the patent problem of the HERIC inverter, though the generation methodology and topology derivation law for these types of transformer-less inverters remain unclear. The development of topologies with reduced number of switching devices and simpler modulation strategies, as the main disadvantages of current multilevel topologies include excessive switching devices, rise of the highest voltage H-bridge form, and complex modulation strategy and control system. Balancing the loss distribution for the high-frequency switches through the use of unipolar SPWM and double-frequency unipolar SPWM to decrease filter inductor size and enhance the quality of the grid current. Improving the performance of transformer-less inverters by adding extra capacitors across certain switches to eliminate leakage current [12].

4.1 Inverters based on Full H-bridge Topology

4.1.1 H4 (full bridge) Topology

The complete H-bridge (H4) architecture, which is a single step dc-ac conversion topology, is the most popular choice for grid-connected solar inverters. The four transistors that make it up are linked in the way seen in Fig.8. Built with four active switches (S1-S4) and four anti-parallel body diodes (D1-D4) to complete the current route while the device is free running. The efficiency, leakage current, and current maximum voltage (CMV) of H4 transformer-less PV inverters may be altered by employing one of three alternative modulation techniques: bipolar, hybrid, or unipolar. Though it eliminates leakage current, bipolar SPWM is less efficient than unipolar SPWM because of its larger core and switching losses. A PV terminal connected to the freewheeling circuit during zero voltage states causes high-frequency CMV fluctuation in unipolar SPWM; galvanic isolation can reduce this effect. A number of inverter topologies combine bipolar and unipolar approaches to produce low leakage current and good efficiency [44].

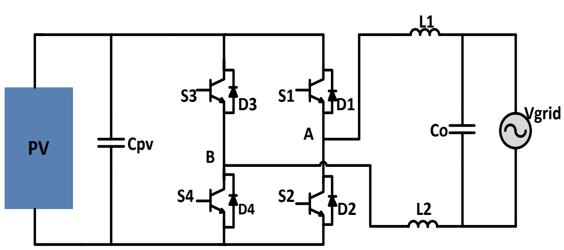

Figure 8: H4 Topology.

4.1.2 H5 Topology

The paper introduces a two-stage H5 transformer-less inverter for photovoltaic systems, as seen in Fig.9. It designed to address leakage current issues including an MPPT controller for power extraction and an H5 inverter for grid integration. Simulation results show that this system effectively reduces leakage current, maintains low RMS values, and lowers total harmonic distortion (THD) in grid current compared to conventional transformer-based inverters. However, it has slightly lower efficiency due to additional losses in the boost converter. The simpler MPPT algorithm used demonstrates performance comparable to the conventional Incremental Conductance technique, highlighting a trade-off between system efficiency and complexity, with the simpler MPPT algorithm offering a more practical solution [45].

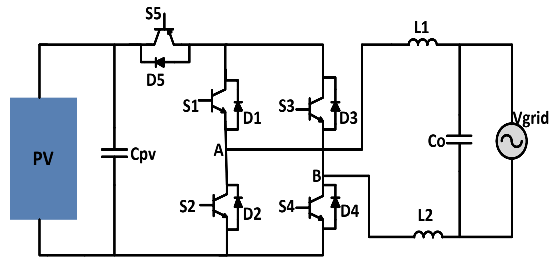

Figure 9: H5 Topology.

4.1.3 H6 Topology

A Novel H6 Transformer-less Inverter for Grid Connected Photovoltaic System to Reduce the Conduction Loss and Enhance Efficiency was proposed as shown in Fig.10. In this inverter circuit, two additional switches S5 and S6 are added symmetrically to the H-bridge inverter. The switches S1 and S4 in one leg of the H-bridge operate at the grid frequency while the switches S3 and S2 commutate at switching frequency. The two additional switches S5 and S6 alternately commutate at grid frequency and switching frequency to act as a DC decouple. Accordingly, there are four modes of operation. Switches S5, S1, S2 and S6 conduct during the positive half cycle of grid voltage. During the freewheeling period, S2 and S6 are turned off and the current freewheels through the antiparallel diode of S3 and switch S1 [46].

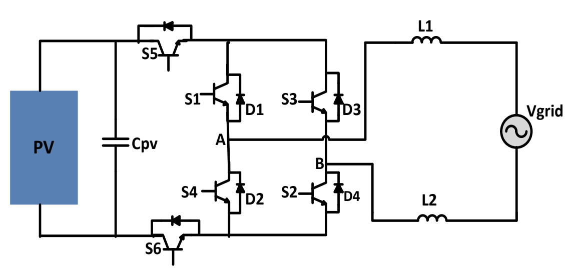

Figure 10: H6 Topology.

4.1.4 HERIC Topology

The researchers proposed an enhanced HERIC (Highly Efficient and Reliable Inverter Concept) transformer-less inverter with a hybrid clamping cell to eliminate common-mode leakage current as plotted in Fig.11. The new topology maintains a constant common-mode voltage, reducing leakage current and achieving high efficiency with low grid current total harmonic distortion (THD). They identify high-frequency leakage current issues in conventional

HERIC inverters due to resonance between output inductors and power switch parasitic capacitors. To solve this, the hybrid clamping cell, including an active switch (S5) and a three-phase diode rectifier (D1-D6), clamps the common-mode voltage during switching. The paper details the modulation strategy and operating principles of the proposed inverter. The proposed enhanced HERIC-based inverter with the hybrid clamping cell successfully addresses the common-mode leakage current issue by ensuring a constant common-mode voltage throughout the switching period. This is achieved through the clamping ability of the hybrid clamping cell, which provides a decoupled freewheeling path for the inductor current. The experimental results validate the effectiveness of the proposed topology in terms of leakage current elimination and achieving excellent differential-mode characteristics [47].

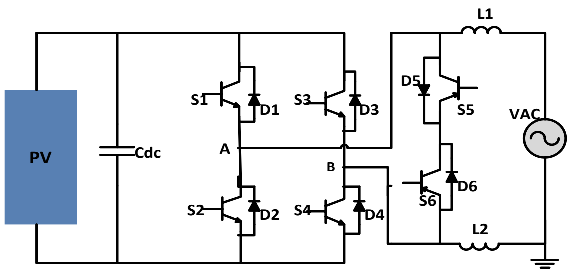

Figure 11: HERIC Topology.

4.2 Inverters based on multilevel topology

The multilevel topologies are based on a particular configuration of the inverter's semiconductors and passive components, resulting in three or more distinct DC voltage levels at the power converter output. Although these topologies have been widely utilized in high power applications, they have not yet been considered as an alternative to the traditional topologies used in small-power transformer-less inverters, owing to the additional expense of the requisite power diodes and transistors. However, because to the cost reduction of semiconductors, multilevel topologies are now being used to the construction of small-power transformer-less inverters [48].

4.2.1 NPC Topology

This kind of inverter has the benefit of lowering the entire system size and cost as well as the filter used size. Fig. 12 shows three voltage levels on the NPC inverter. Four switches on one leg separate the NPC inverter into upper stage and lower stage from the middle of the leg. Every diode is linked to the middle of the dc-link; the opposite side of each diode is connected between the higher and lower stage switches accordingly. The single-phase adaptation of the multilevel topology is the NPC Half-bridge [49].

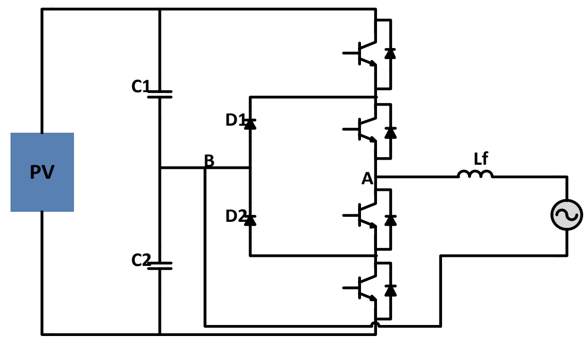

Figure 12: NPC Inverter.

4.2.2 Active NPC

The Active NPC in Fig.13 is a modified version of the NPC inverter topologies. In this variation, the diodes $D1$ and $D2$ that are typically found in the NPC are substituted by switches $Q5$ and $Q6$. The higher clamping is activated when switches $Q2$ and $Q5$ are in the ON position, while the lower clamping is activated when switches $Q3$ and $Q6$ are in the ON position. By substituting the diodes of the NPC inverter with switches in the Active NPC inverter, it becomes possible to regulate the losses of the inverter [50].

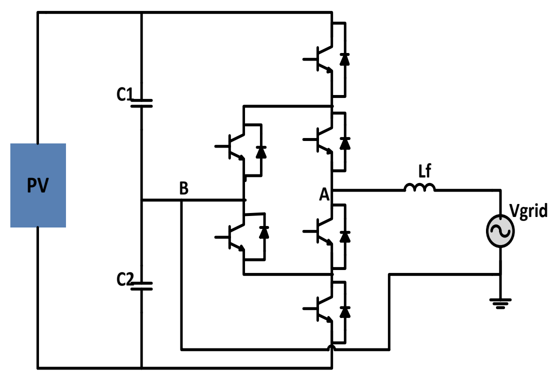

Figure 13: Active NPC inverter.

4.2.3 Flying capacitor (FC)

One viable workaround for some of the issues of the NPC topology is the three-level flying capacitor architecture, as illustrated in Fig.14. With this topology, capacitors that "float" in relation to the dc source reference are used to provide additional levels and voltage clamping. It removes the need for additional clamping diodes and presents redundant switch states that may be used to manage the capacitor charge even under loads of dc level. However, more capacitors are needed for bigger structures, and extra circuits are needed to start the charge of the capacitors [51]. Use of a flying capacitor in a transformer-less inverter for grid-connected photovoltaic systems. The capacitor generates a negative supply voltage during negative cycles, using four switches and a diode. The inverter's operation reduces losses, EMI, and filter requirements, enhancing the efficiency and effectiveness of the transformer-less inverter design [52].

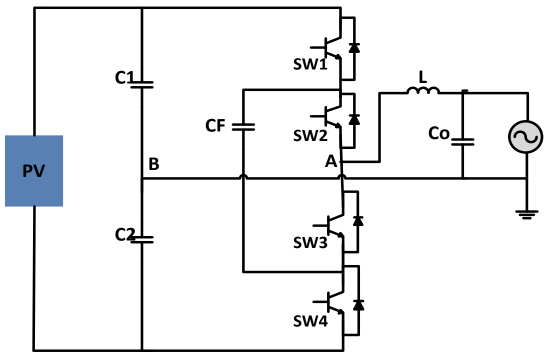

Figure 14: Flying capacitor.

4.2.4 Cascaded H-bridge

The simplest multilevel arrangement consists of linking H-bridge cells in series on the AC side, with each DC-link powered by a different solar panel. This design, illustrated in Fig. 9 with a two-stage CHB multilevel inverter and a second-order output filter, necessitates as many isolated power sources as there are H-bridge stages. While this can be troublesome in typical power applications, photovoltaic modules satisfy this requirement, making the CHB design an intriguing option for photovoltaic inverters. One major feature is its capacity to increase output voltage levels by stacking modules in series, allowing it to inject current into the grid without the use of a transformer or boost converter. This modular construction allows for maximum power point tracking, autonomous control of each module group, and may even work with broken cells, increasing dependability. However, the number of semiconductors required influences cost and reliability, and the leakage current may be large depending on the number of series-connected cells [53].

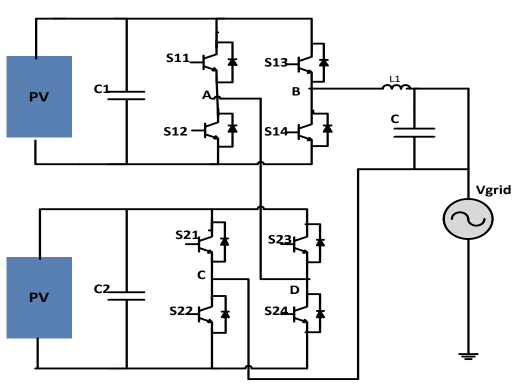

Fig. 9. The cascaded multilevel inverter.

5. Control method of single phase inverter

Two distinct control infrastructures are needed, one at the PV side and the other at the inverter's output to integrate the whole device with the utility grid. This is because the solar inverters are the ones that connect the power generated at the PV side to the grid. The converter side control mechanism, which is primarily MPPT, is represented by the PV side control. On the other hand, grid side control is required to raise the inverter's efficiency and power quality in order to guarantee dependable operation. For controlling a single-phase grid-connected inverter, the fast and accurate detection of utility voltage and current information is important since it is used in generating the reference signals [54]. The grid side control performs several operations including the regulation of frequency and voltage, the synchronization of the grid, the control of the DC link, the control of the reactive (Q) and active power transmitted to the grid, and the high quality of the injected power[55]. As a result, the grid side controller of a solar inverter needs to have capabilities for power decoupling, secure grounding, and grid connections. Improved inverters designed for single-phase grid operation should adhere to the grid specifications outlined in several international and regional standards. Various types of inverter controllers were introduced.

Mohammad-Hassan and Behzad [56] A novel deadbeat current controller for single-phase PV grid-connected inverters was presented, using a predictive control approach to calculate necessary inverter voltage for current reference tracking. Simulations showed it accurately tracked current references under various conditions, maintained low total harmonic distortion (THD), and demonstrated improved performance and simplicity over previous methods, making it a valuable contribution to grid-connected PV inverter control.

Meriem Merai , Mohamed Wissem Naouar, Introduced An Adaptive PI Controller Design for DC link Voltage Control of Single-Phase Grid Connected Convert [57] Proposed an adaptive PI controller for DC-link voltage control of single-phase GcCs, aiming to reduce DC-link voltage fluctuations and grid current harmonics. The controller adjusts gains based on operating conditions, achieving a better compromise between the two objectives. The controller dynamically adjusts the natural frequency (ωn) of the DC-link voltage control loop, increasing it during transients to reduce voltage fluctuations and reducing it during steady-state operation to limit grid current harmonics. Simulation and experimental results show the controller effectively balances the trade-off between these two objectives.

Phong Tra [58] The paper proposed a computed current control method (PI controller) for grid-connected PV systems, which stabilizes the system but has steady-state error. It introduces a new MPPT topology to handle PV array nonlinearity, MPP oscillations, and inverter filter design. A control algorithm computes current reference from PV voltage and current, ensuring stability. The 3C-MPPT controller, compared to the conventional RCC method, shows better tracking speed and stability under irradiation changes, with the PI controller eliminating steady-state error and the 3C-MPPT controller enhancing dynamic performance with a derivative term.

Ahmad Ali Nazeri and Federico Martin Ibanez [59] The paper presents a design methodology for a Proportional Resonant (PR) controller in a single-phase grid-connected VSI with an LCL filter, comparing its performance to a traditional PI controller. It highlights the PR controller's improved tracking of sinusoidal waveforms, better disturbance rejection, and zero steady-state error. The methodology includes selecting proportional and resonant integral gains using the extended Symmetrical Optimum method and implementing a practical PR controller with a harmonic compensator. Simulations and real-time experiments validate the PR controller's superior performance.

Enaga D. ∗, V. Sankaranarayanan [60] Presents a nonlinear sliding mode controller (SMC) for a single-stage grid-connected photovoltaic (PV) system. The controller aims to ensure maximum power extraction from the PV system while maintaining a unity power factor at the grid interface. The controller is designed to be robust against parameter variations and external disturbances, such as changes in solar irradiation. The authors developed a nonlinear mathematical model of the system, designing sliding surfaces and controller inputs. The results show the controller can achieve maximum power extraction while maintaining a unity power factor at the grid interface, is more robust to parameter variations, and closely matches numerical simulation findings. The controller's advantages over existing sliding mode controllers include improved performance of maximum power point tracking objectives.

Zulkhairi1,*,Mochammad Facta2* , Trias Andromeda [61] Presents the design and implementation of a single-phase AC current controller using the hysteresis method. The research aims to provide a constant voltage with variable current in electrical applications where traditional voltage-based power supplies are insufficient. The system includes a full-wave bridge rectifier, MOSFET driver, current sensor, and digital-to-analog converter. The hysteresis control algorithm compares actual current with reference current, adjusting inverter switching to maintain current within specified limits. Simulation and experimental results show the inverter output current can follow the reference current, with a small current error.

Ilham Nassar-Eddine, Abdellatif Obbadi and Youssef Errami [62] explores control strategies for a single-stage grid-connected photovoltaic (PV) system, focusing on improving power quality and grid interconnection. The fuzzy logic approach is used to extract maximum power from the PV generator, regulate DC-link voltage, and control inverter output currents. The strategy outperforms classical proportional-integral (PI) controllers in terms of accuracy, stability, and response time. The fuzzy logic MPPT algorithm extracts maximum power from the PV generator quickly and accurately, even under changing solar irradiance conditions. The fuzzy logic approach is robust, simple, and capable of handling imprecise inputs, making it a significant contribution to PV system control and optimization.

Xingang Fu and Shuhui Li [63] Explores a novel recurrent neural network (RNN)-based vector control method for single-phase grid-connected inverters with LCL filters. The authors propose a nested-loop structure, with the inner current loop controlled by the RNN and the outer loops using traditional PI controllers. The RNN-based control method outperforms conventional PI-based and PR control methods, achieving better current tracking performance, lower sampling and switching frequencies, and improved robustness to system parameter changes. This work contributes to the development of efficient and robust control strategies for single-phase renewable energy integration.

Suzan Eren, Majid Pahlevani, and Alireza Bakhshai [64] Proposes a fast DC-bus voltage controller for a single-phase grid-connected Voltage Source Inverter (VSI) with an LCL output filter for renewable energy applications. The controller addresses the second harmonic ripple in the DC-bus voltage control loop and improves the converter's transient response and steady-state performance by varying the DC-bus voltage to minimize losses for the output filter. The control scheme also eliminates the third harmonic distortion caused by the second harmonic ripple. The droop control concept is applied to the DC-bus voltage regulation, achieving stable equilibrium points. The proposed droop controller has a fast and stable transient response, addressing issues with conventional PI controllers. The adaptive droop control technique optimizes the operating point to minimize power losses in the output filter.

Table 2 represents a list of single phase inverter designs and proposed controllers for grid interconnection.

Table2. Single- phase inverter controllers and characteristics

Ref.	Controller Type	Advantage	Disadvantage
Jahanbakhsh (2015)	Deadbeat	Deadbeat controllers simplify voltage equation models and cancel current reference errors, but they have variable harmonics limitations compared to current controllers using fixed PWM.	Sensitivity to model and parameter inaccuracies, which can impact the accuracy and effectiveness of current control in single-phase PV grid-connected inverters.
Merai (2019)	PI Adaptive	The system self-tunes gains based on its operating state, ensuring optimal performance in reducing DC-link voltage fluctuations and grid current Total Harmonic Distortion compared to standard PI controllers.	Cannot simultaneously reduce DC-link voltage fluctuations and grid current Total Harmonic Distortion, resulting in a trade-off between control objectives.
Phong (2015)	PI Current controller	The P-type controller's steady-state error is eliminated by replacing the control variable u with a linearized expression, ensuring the desired value is maintained.	Face a trade-off between reducing DC-link voltage fluctuations and minimizing grid current harmonics.
Nazeri (2019)	PR Controller	The PR controller improves power factor and system stability by offering zero steady state superiority, disturbance rejection, sinusoidal waveform tracking, and better harmonic attenuation.	The system's complexity increases due to its neglect of the filter capacitor, inability to extract active and reactive powers in the Synchronous Reference Frame.
Menaga D. (2020)	Sliding mode control	The controller enhances maximum power point tracking performance by tracking DC-link voltage, achieving unity power factor, unlike existing controllers that track desired currents.	
Zulkhairi1 (2019)	Hysteresis	Hysteresis control is a simple, stable, and reliable technique that provides a desirable current loop control response without the need for a carrier. It is widely used due to its insensitivity to parameter changes.	Hysteresis controllers can cause higher THD in output waveforms, increase switching losses in power electronic devices, and be challenging to set, making them unsuitable for high-power applications requiring efficiency and precise control.
Eddine (2019)	Fuzzy	Fuzzy logic is a simple, intelligent control method that reduces harmonic pollution, improves performance, and enhances efficiency in PV system control strategies by reducing current harmonics and improving response time.	Fuzzy logic controllers, while reducing harmonic pollution in semiconductor switching, may introduce complexity in control system design and implementation, potentially causing system integration and maintenance challenges.
Xingang Fu (2015)	RNN	The RNN controller, a super PI controller, efficiently approximates optimal control for a single-phase grid-connected converter using an LCL filter, minimizing dynamic programming cost function, and improving voltage control loop performance by eliminating double frequency ripple.	(RNN) controller, a 'super-PI' controller without feedback connection, which may limit adaptability and responsiveness. Its recurrent nature may introduce complexities in the control system, making it more challenging to analyze and tune compared to traditional controllers.
Suzan Eren (2014)	DC-Bus Voltage Controller	The system improves voltage control loop performance by eliminating double frequency ripple on DC-bus voltage, utilizing a droop control approach for optimal voltage and fast transient response.	Double frequency ripple can cause sluggish transient performance and load changes, requiring overrating DC-bus capacitor and VSI switches to improve system costs and transient performance.

6. Conclusions

Grid-connected inverters play a crucial role in facilitating the efficient integration of renewable energy resources (RER) with the utility grid in a distributed generation system. The Single-Phase transformer-less PV inverter has garnered extensive interest owing to its low cost, light weight, small volume and high efficiency compared to single-phase inverters with galvanic isolation. In this paper, various single-phase transformer-less inverter topologies are reviewed. Current inverters use power MOSFETs or IGBTs for low-power and high-frequency switching, but IGBTs struggle with high-frequency switching. Grid-connected inverters are recommended for photovoltaic systems due to their high power factor and efficiency. Transformer-less inverters are popular due to affordability and compactness. The various controllers and their capacity to offset low-order harmonics in the grid were covered. The deadbeat controller improves power quality in single-phase PV grid-connected inverters using current control strategies, a discrete-time model, resistance incorporation, and predictive control principles. A DC-bus voltage controller removes double frequency ripple and low frequency AC components. Fuzzy logic controllers reduce harmonic pollution from semiconductor switching. PR controller enhances transient response and minimizes steady-state errors. Nonlinear sliding mode controller maximizes power extraction and robustness against uncertainties. PI controller minimizes steady-state errors and ensures system stability. Hysteresis control ensures accurate current control. Neural network controller outperforms conventional methods. The grid-connected solar PV system is anticipated to have reduced costs and increased overall performance in the near future.

This review study will aid engineers in choosing the most appropriate control method and inverter topology based on the particular power requirements, location, and capacity for grid connection.

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