A COMPREHENSIVE REVIEW ON GRID CONNECTED PV SYSTEM

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***Abstract*: The installation of photovoltaic (PV) system for electrical power generation has gained a substantial interest in the power system for clean and green energy. However, having the intermittent characteristics of photovoltaic, its integration with the power system may cause certain uncertainties (voltage fluctuations, harmonics in output waveforms, etc.) leading towards reliability and stability issues. In PV systems, the power electronics play a significant role in energy harvesting and integration of grid-friendly power systems. Therefore, the reliability, efficiency, and cost-effectiveness of power converters are of main concern in the system design and are mainly dependent on the applied control strategy. This review article presents a comprehensive review on the grid-connected PV systems. A wide spectrum of different classifications and configurations of grid-connected inverters is presented. Different multi-level inverter topologies along with the modulation techniques are classified into many types and are elaborated in detail. Moreover, different control reference frames used in inverters are presented. In addition, different control strategies applied to inverters are discussed and a concise summary of the related literature review is presented in tabulated form. Finally, the scope of the research is briefly discussed.**

***Keywords*: grid-connected PV system; grid-connected PV inverters; multi-level inverters; modulation techniques; control strategies; current control**

I. INTRODUCTION

Renewable energy (RE) plays a pivotal role in supporting the power system to meet the ever-increasing load demand. Among the renewable energy resources (RES), photovoltaic (PV) power units are gaining more interest due to (a) clean and emission free energy, (b) simple access, and (c) high return on investment [1]. Up to the year 2009, the majority of PV installations were made at a small level and were only connected to the distribution level. However, when the USA installed the first transmission level (230 kV) PV system in Florida [2], it drew the world's attention. Therefore, the interest in large scale PV installation (transmission and sub-transmission levels) increased rapidly and as a result, globally the installed capacity of PV reached 505 GW by the end of 2018. The total installed capacity of PV from 2008–2018 is presented. The figure shows a dramatic increase in PV installation as in 2008 the installed capacity is 15 GW, and it increases to 505 GW at the end of 2018 [3].

Depending on the conversion system, two types of configuration systems are used for grid-connected PV power plants (GCPPPs), i.e., single and two stage conversion/configuration systems. A configuration is said to be a single stage, when there is a direct connection between the inverter input side and the PV array and is then connected to the grid through the transformer as depicted in Figure 2a [4]. On the contrary, if a DC–DC converter is utilized to integrate the PV array with the inverter's input side then the configuration is said to be a two stage as presented in Figure 2b [4].

It shows that in both configuration systems, inverter plays a significant role in integration and DC to AC inversion. Therefore, for this purpose different inverter topologies were designed by researchers. Among these topologies, a conventional 2-level inverter topology is very popular and widely used for small scale applications. However, this inverter is not appropriate for medium and large-scale applications as it suffers from high voltage stresses and high thermal losses that significantly decrease the efficiency of the system [5]. To overcome these problems, multilevel inverter (MLI) topologies were introduced for GCPPPs as they have the ability to provide good quality output waveforms with low harmonic distortion, lower stress on switches, a lesser requirement of passive filter, and require less maintenance [6–8]. The MLIs are classified into various types based on the power circuitry structure such as reduced switch [9,10], asymmetric [11], modular [12], and hybrid [13,14], etc. The quality of output waveforms of MLIs greatly depends on the modulation technique (MT) applied to the switches (metal oxide silicon field effect transistor, insulated gate bipolar transistor, etc.). The main tasks of MTs are to control and enhance the output waveforms and to minimize the total harmonic distortion (THD) as well as switching losses. Based on switching frequency the MTs are classified into high switching frequency (HSF) [15,16] and fundamental switching frequency (FSF) [17]. Both types of modulation techniques are further classified into various types that will be discussed later in this article in detail.

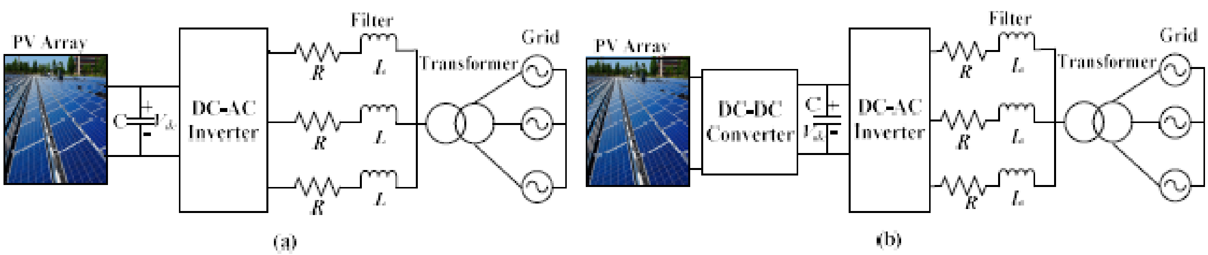

Fig 1 PV configuration systems: (a) single stage and (b) two stage

Grid (system) side controller: the system side controller must have the ability to perform many functions such as (a) grid synchronization, (b) control of reactive (Q) and active power (P), (c) control of DC-link voltage, and (d) injection of high-quality power [20,21]. In addition to these services, the grid operator may also demand intelligent services such as voltage regulation and harmonic compensation etc. [22].

In this article, the authors aim is to provide a comprehensive review on PV systems. Different classifications of GCIs are discussed, and the comparative study of current and voltage source inverters are presented in a table form. Moreover, the features, advantages, and disadvantages of four different PV inverter configurations are discussed and presented. A basic circuitry and a detailed analysis of the most commonly used grid-connected multi-level inverter (GCMLI) topologies and their MTs are elaborated. Furthermore, different characteristics such as MT, switching frequency, and capacity, etc., of numerous related scientific articles on MLI topologies are presented in the table. A detailed analysis of two main types of modulation techniques and their subtypes is elaborated in detail. Later, different control structures and controller types that are applied to grid-connected inverters are thoroughly demonstrated. The important characteristics (reference frame, modulation technique, controller type, etc.) of different scientific articles are presented in table. The scope and trends of this research are broadly discussed later. The main contributions of the proposed review article are summarized and critically compared and associated with the other review papers already published in literature.

II. Classification of Inverters

An inverter plays a very prominent role in grid-synchronization and is responsible for DC–AC inversion [35]. Inverters are generally categorized into line commutation inverters (LCI) and self commutation inverters (SCI) based on the commutation process (turned ON and turned OFF behavior). behavior). A detailed taxonomy tree of the inverter classification is presented in Figure 3. A figure shows that SCIs are further divided into current source (CSI) and voltage source inverter (VSI).

Moreover, VSIs are further divided on the bases for their conduction mode (CM) into current CM (CCM) and voltage CM (VCM). The different classification of inverters is explained through a taxonomy tree

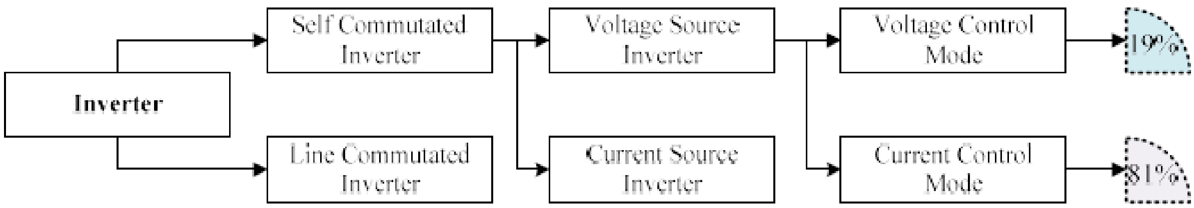

Figure 3. Classification of inverters [36].

2.1. Line Commutated Inverter

Generally, in LCIs semi-controlled semiconductor devices such as thyristors are used as switches.

In semi-controlled switches, the turn ON operation is controlled through the gate terminal whereas the turn OFF characteristics of the switches depends on the circuit parameters i.e., direction of current or voltage polarity. Therefore, in LCI a forced commutation is required to turn OFF the switches. For this purpose, different approaches are presented such as in case of half-bridge LCI an antiparallel diode is attached to enable the force commutation process (to turn OFF the switch) [37].

2.2. Self Commutated Inverter

A MOSFET or IGBT devices are usually used in SCI. MOSFETs are used for high frequency (20–800 kHz) applications having power ratings less than 20 kW. On the contrary, IGBTs are used for low frequency (20 kHz) applications having power ratings greater than 100 kW. The commutation operations of these switches are fully controlled through the gate terminal [38]. Therefore, it controls both the current and voltage output waveforms. High switching frequency devices are preferably used in grid-connected applications to reduce the inverter weight, filter size, and output waveform harmonics [39]. Moreover, SCI improves the grid power factor, suppresses the current harmonics, and shows high robustness to the grid disturbances. Due to the development of sophisticated switching devices and improvement in the control strategies, SCIs are preferably used as compared to LCI. The SCIs are further classified into current source inverter (CSI) and voltage source inverter (VSI).

2.2.1. Current Source Inverter

In CSI, a DC current source is connected as an input to the inverter; hence, the input current polarity remains the same. Therefore, the power flow direction is determined by the input DC voltage polarity. The current waveforms obtained at the output side of CSI are constant in amplitude but variable in width. The main disadvantage of using CSI is the utilization of a large inductor that is connected in series with the input side to handle the current stability issue [40]. The usage of an inductor makes the circuitry less efficient, bulky, and expensive [20].

2.2.2. Voltage Source Inverter

A DC voltage source is connected as an input to the VSI, hence the input voltage polarity remains the same. Therefore, the direction of input current determines the direction of power flow. The waveforms of an output AC voltage are constant in amplitude but variable in width. Moreover, a major drawback associated with VSI is the usage of a large capacitor that is connected in parallel with the input source [40]. The VSIs are preferably used in grid-tied PV applications as compared to CSIs due to low power losses, high efficiency, low cost, and lightweight. Furthermore, based on their control mode VSIs are operated either in VCM or in CCM. In VCM, an AC voltage is controlled and maintained at the point of common coupling (PCC). Whereas, in CCM a core control parameter of the controller is the line current and is regulated at PCC. The fault short circuit current in VCM is high as compared to CCM. Moreover, VCM is commonly used in those applications where maintaining the phase, frequency, and voltage at PCC are of major concerns such as off grid or standalone PV systems. However, both CCM and VCM can be applied to the grid-tied PV VSIs, but the most preferable and commonly used method is CCM [36]. For grid-tied applications, about 81% of VSIs are operated in CCM while only 19% of VSIs are operated in VCM. The reason behind is that the VCM has no control over current while in CCM the current is the main control parameter. Therefore, in case of any grid disturbance, CCM can easily mitigate the current transients and harmonic distortion, and due to its current control structure, it can achieve a high power factor easily [41].

3. Configuration of PV Inverters

There are many types of PV array configuration in literature such as series, honeycomb, parallel, bridge linked, etc. [42]. Among them, the most commonly used configurations are the series or parallel and series connections. If the PV panels are attached in series with each other, it is called a string, and if these are then connected parallel it forms an array. Basically, the PV modules are arranged in four types of configurations based on inverter type [43]. The design characteristics and main characteristics of these inverters are explained below.

3.1. Central Inverter

In this configuration system, to avoid the voltage amplification numerous panels are attached in series to make a string [44]. However, to increase the power level these strings are then attached in parallel to make an array. A complete diagram of the integration of series/parallel PV array with the grid through the central inverter is depicted in Figure 4a [45]. During shading (cloud cover) the PV output voltage are step-up by using a DC–DC boost converter and will be then fed to GCI.

The most important drawback of this technology is the usage of a single MPPT for the whole system that causes panels mismatching; thus, the e_ciency of the PV system decreases [43]. The other main drawback in this topology is that if the central inverter fails to operate, then the whole PV system will not be able to operate [46]. The central inverters have the lowest overall cost as compared to other configuration systems and are generally used for power ratings between 1–50 MW. Moreover, it shows and have low AC power losses [2,20].

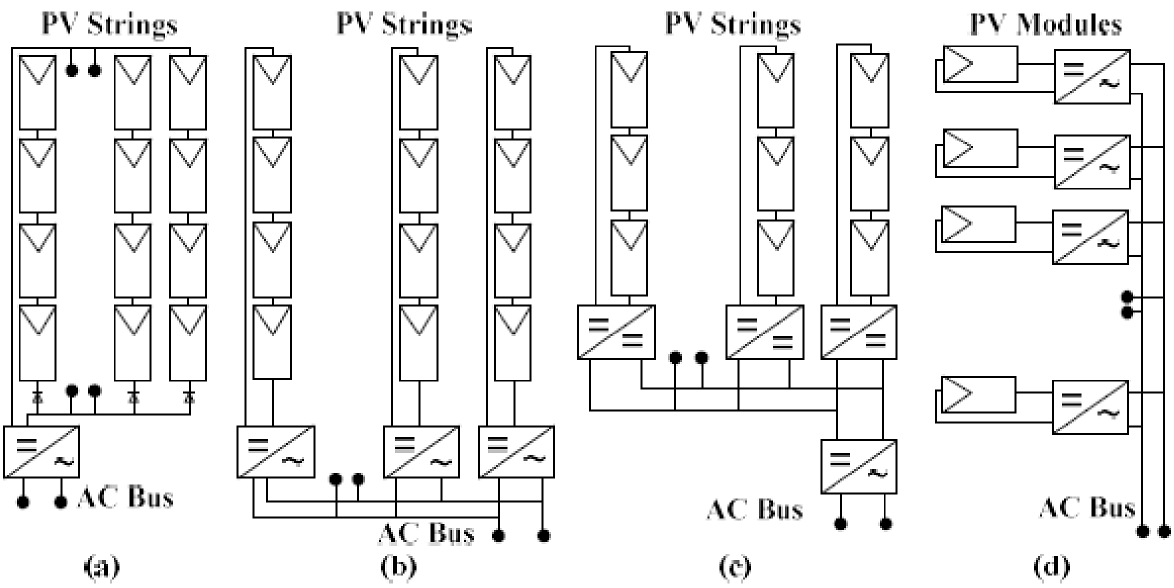

Figure 4. Configuration of grid-connected PV inverters: (a) central; (b) string; (c) multi-string; and (d) AC modules [45].

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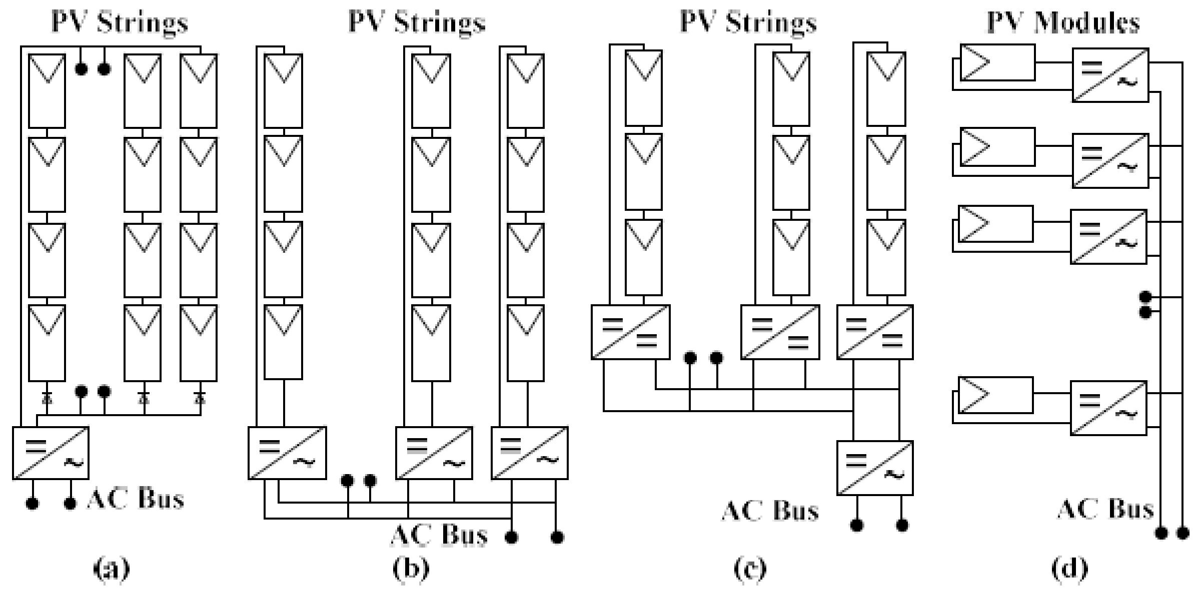

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3.2. String Inverter

Currently, string inverter is the most frequently and commonly used technology and considered as a standard in GCPPPs [24]. In this configuration each string is connected independently to the inverter, thus it eliminates the usage of a string diode as presented in Figure 4b [45]. An individual MPPT is applied to every string therefore, partial shading and panels mismatching problems are greatly reduced in this configuration. Consequently, the overall system efficiency increases and is 1–3% higher as compared to the central inverter [47]. The application range of string configuration is up to 5 kW per string. Due to its modular structure, it can be expended to high ratings easily. In this topology, if the string inverter fails to operate it will only affect the operation of its related string rather than the whole PV system like in central configuration. String inverters have high flexibility, high reliability, low DC power and switching losses, and low cable cost. However, the overall cost of this configuration as high as compared to the central configuration due to high installation cost [2,20].

3.3. Multi-String Inverter

It is a hybrid configuration, as it combines the beneficial and advantageous features of both string and central inverter configurations. Several strings are individually connected to the converter for voltage amplification (have a separate MPPT system) and are then connected to a centralized or single inverter as shown in Figure 4c [45]. This topology can integrate the PV strings of different orientation and different technologies to a grid. It has high structure modularity; therefore, it can be extended easily to high power ratings by connecting a new PV string to an already existing system [48].

The multi-string topologies are expensive as compared to central inverters but are cheap as compared to module integrated inverters. Multi-string configuration system covers a wide range of PV applications up to 50 kW [49]. However, due to its capability of integrating deferent ratings of PV strings causes a problem of high voltage variation at the inverter input side [2,20].

3.4. Module Integrated or AC Module

An AC module presented in Figure 4d [45] has a low power rating, small in size, and is also known as micro-inverter [2]. AC modules are more suitable and preferably used in low power applications.
In AC module, all the functions such as MPPT, voltage amplification, and inversion of DC–AC are performed in a single device called a module. These modules are separately connected at the back of every PV module through MPPT controller to eliminate the mismatch losses [50]. As modules have low power rating therefore high amplified voltage is required which causes a reduction in system's efficiency. However, this shortcoming can be fully filled by using a highly efficient MPPT technique that makes it the most efficient topology as compared to other three topologies [51]. Due to its modular structure the enlargement can be made easily. As all the functions are carried out in a single module that makes this circuitry complex and requires high initial cost and maintenance.

IV. Multi-Level Inverter Topologies

Due to rapid improvement and advancement in grid-connected inverter (GCI) topologies the overall cost of GCPPPs has decreased significantly. The MLI shows very efficient performance and offers many advantageous features for high and medium level grid-tied PV applications in comparison with 02 level inverter such as (a) as levels increase, the staircase in output waveforms also increase and a pure sinusoidal output is obtained; (b) generates low distorted input current; (c) has superior harmonic spectrum; (d) smaller common-mode voltage; (e) voltage change (dv/dt) is smaller in MLIs; f) low switching losses; (g) has low filter requirement; and (h) can operate at low switching frequency [52].
A lot of research has been conducted on grid-connected MLI (GCMLI) and many topologies were introduced by researchers in the past. Therefore, based on power circuitry the GCMLIs are classified into VSI and CSI, these are then further classified into many subtypes as depicted in Figure 5.
The VSIs are further classified into multilevel and 02-level inverter. The multilevel inverters are further divided into a single DC source (uses single DC source as input) and multiple DC sources GCMLIs (uses multiple identical or non-identical DC input sources). A single DC GCMLIs include flying capacitor (FC), neutral point clamped (NPC), active NPC, hybrid NPC, magnetic coupled, diode clamped with second capacitive divider, and full-bridge configuration with an ancillary circuit MLIs. While the multiple DC source MLIs include modular (M), assisted modular, dual voltage source, hybrid full-bridge, and cascaded H-Bridge (CHB) MLIs. Similarly, CSMLIs are divided into single DC source MLIs and multiple DC source MLIs. Among these MLIs the most commonly used topologies are NPC-GCMLI, FC-GCMLI, CHB-GCMLI, and M-GCMLI [29].

4.1. Neutral Point Clamped GCMLI (NPC-GCMLI)

A three-level NPC for the first time was introduced by researchers in [43]. For generalized n-level, NPC topology uses $2(n-2)$, $2(n-1)$, and $(n-1)$ number of clamping diodes, switches, and DC-link capacitors respectively as per phase [21]. In this topology, two conventional VSIs (2-level inverters) are stacked over one another. The positive point of lower inverter and negative point of upper inverter are accumulated mutually to make a new phase for the output. In this topology, every switch opposes the half of inverter's voltage [34].
A basic circuit configuration of 03 level NPC is presented in Figure 6a, comprises of 02 clamping diodes (D1 and D2), 04 switches (S1, S2, S3, and S4), and 02 capacitors (C1 and C2). This inverter can attain 03 voltage level (0, $+V_{dc}/2$, and $-V_{dc}/2$) at the output. A 0 level is attained by turning ON S2 and S3, a value of $+V_{dc}/2$ is accomplished in a case when S2 and S1 are in ON state, and a voltage level of $-V_{dc}/2$ is attained by turning ON S3 and S4 [53]. Moreover, due to its modular structure, it can be expended easily for high power ratings. A detailed analysis of a 5-level NPC presented in [55] utilizes eight switches, 04 DC-link capacitors, and 06 free-wheeling diodes to achieve five voltage levels at the output. The capacitance requirement in this topology is low as it shares a common DC bus, makes it lightweight. However, the main disadvantage in NPC topology is that the complexity to balance the DC-link capacitor increases with the increment in the number of levels. Therefore, a proper DC-link voltage regulation is required to balance the DC-link. NPC is widely used in grid-connected applications due to fast dynamic response, small leakage current, simple structure, and high efficiency .

4.2. Flying Capacitor GCMLI (FC-GCMLI)

The FC-MLIs were first introduced by Foch and Maynerd in 1992 and are also known as clamping capacitor MLIs . As compared to NPCMLI, the diodes are replaced with flying capacitors in FCMLI [25]. For a generalized n-levels, FC-MLI uses number of flying capacitors, switches, and DC-link capacitors respectively as per phase. A schematic circuitry of 3-level FC-GCMLI is presented in Figure 6b; 02 DC-link capacitors (C1 and C2), utilizes 04 switches (S1, S2, S3, and S4), and 01 auxiliary capacitor (C0) and can achieve 03 levels (0, $+V_{dc}/2$, and $-V_{dc}/2$) at the output.
A voltage level of $+V_{dc}/2$ is attained when S1 and S2 are turned ON, and a $-V_{dc}/2$ is accomplished by turned ON S3 and S4. While a 0 voltage level can be achieved when either S2 and S4 or S1 and S3 are turned ON [54]. As the researchers in [58], utilize 08 switches, 04 DC-link, and 06 auxiliary capacitors to attain the 05 voltage levels at output. However, this topology has high installation cost and has low efficiency due to high switching losses. Just like NPC-GCMLI, this topology also has a high modularity in structure and can be expended easily.

4.3. Cascaded H-Bridge GCMLI (CHB-GCMLI)

A CHB-GCMLI is formed by connecting 2 or more 1-F H-bridge inverters having separate DC sources are connected in series to increase the voltage levels. For generalized n-levels, this topology utilizes switches and DC sources respectively as per phase [59]. The output voltage for n-level is $n = 2s + 1$, where s presents the input DC voltage sources count [60]. Each 1- F H-bridge can generate 03 levels (0, $+V_{dc}/2$, and $-V_{dc}/2$). $+V_{dc}$ and $-V_{dc}$ voltage levels are accomplished by turning ON S1 and S4, and S2 and S3, respectively. However, the voltage at the output port of the inverter is achieved by turning

ON either S3 and S4 or S1 and S2 respectively. Furthermore, a 05 level CHB-GCMLI is formed by connecting two 1-F H-bridge modules in a series manner as presented in Figure 6c. As 05 level CHB topology is the combination of series connected 02 H-bridges; therefore, the inverter output will be the summation of individual H-bridge output i.e., Vout = Va1+Va2. Due to its scalable feature and high structure modularity, it can easily be expended to accomplish high voltage levels just by connecting a 1-F H-bridge module in series. Moreover, CHB topology is compact as compared to NPC and FC due to the absence of clamping diodes and capacitors [29]. However, due to usage of an individual DC source for every 1-F H-bridge this inverter faces the problem of voltage misbalancing among different phases.

Based on the nature of input sources, the CHB-GCMLIs are further categorized into symmetric and asymmetric topologies [31]. The topology is said to be symmetrical if the input voltage sources have the same magnitude. If the input DC voltage sources have different magnitudes, then it is said to be an asymmetrical topology. The asymmetrical topologies are further classified into binary and trinary (voltage in a ratio of 2 and 3, respectively). The binary asymmetric CHB-GCMLIs are selected in the ratio of 20Vdc, 21Vdc : : : 2n□1Vdc [32], whereas the trinary asymmetric topologies are selected in the ratio of 30Vdc, 31Vdc : : : 3n□1Vdc [33]. The number of 1-F modules required for the generalized m-level binary CHB-GCMLI are (m+8)/9, while trinary CHB-GCMLI required (m/9+3)/2. The input sources are arranged in a trinary manner to achieve 09 level voltages in a topology proposed in [11]. It uses 02 H-bridges, and among them, one of the bridges is being fed into the FC inverter.

4.4. Modular GCMLI (M-GCMLI)

M-GCMLI is a scalable technology, where the number of sub-modules (SM) used in a topology is determined by the acquired output voltage level. It is formed by connecting several SMs (with a separate control system for every SM) in a cascaded manner. Due to the usage of a separate controller for every SM, very small harmonic contents are generated [24]. The features such as high quality output waveforms with low THD, high structure modularity, low component count, and compact size make this topology very feasible for high voltage applications. Moreover, with the increment in the levels the switches count does not increase. A circuit configuration of a 3-F M-GCMLI, have upper and lower arms connected in a series among the 2 DC terminals. Each arm contains many series connected SMs, and every individual SM is composed of 02 switches (S1 and S2), 01 DC capacitor (C), and 02 reverse diodes. Both the switches of SM cannot be operated at the same time i.e., when S1 is turned ON S2 must be turned OFF and vice versa. Hence, the operation of the SM can be defined for two operation modes. The first operating mode also known as the interleaved state is achieved by turning ON S1 and turning OFF S2. In the second operating mode, when S1 is turned OFF and S2 is turned ON, the SM is said to be in a bypassed state. Under usual operating situations, the voltage at the terminal of SM can either be 0 or equal to capacitor voltage [25]. Moreover, the fluctuation in the capacitor voltage and inter-phase current circulation will occur in SM if the DC voltage is unstable. Therefore, to make sure the DC voltage stability the arm of the lower bridge is required to be disconnect every time when SM gives an input at the upper arm and vice versa [26].

V. Conclusions

This review article presents a comprehensive review on grid GCIs, their modulation techniques, and control strategies. In this paper, initially the global status of PV along with the configuration systems used for the integration of PV with the grid is discussed. Then the inverters are classified
into various types, and finally the VSIs and CSIs are compared with each other based on load dependency, power losses, etc. Based on the control modes VSIs are further classified into VCM and CCM, and it is concluded that about 81% of VSIs are operated in CCM while only 19% of VSIs are operated in VCM. In addition, four different configurations of GCPVIs are discussed and numerous features of these configurations are compared and presented in a tabular form. It is accomplished that the least expensive and the highest power rated technology is the central inverter and is most suitable for grid-tied applications. On the other hand, the most expensive, highly efficient, and low power rated technology is the module-integrated inverter and is very suitable for small residential applications. Moreover, string inverter configuration is the most commonly used technology for the grid-tied applications.

Furthermore, the circuit configuration, advantages, and disadvantages of the most commonly used GCMLIs are discussed and presented in a schematic manner. From the literature review, it is accomplished that the MLIs are most suitable for the grid-tied PV applications. As compared to 2 level conventional inverters, MLIs reduce the stress on switches, decrease the switching losses, and produce good quality output waveforms with low harmonic contents and high efficiency. Moreover, modulation techniques are divided into two main types based on their switching frequency. A detailed analysis of these two types of MTs and their sub-types are elaborated in detail and it is concluded that the most popular and commonly used MT is PWM.

References

1. O'Shaughnessy, E.; Cutler, D.; Ardani, K.; Margolis, R. Solar plus: A review of the end-user economics of solar PV integration with storage and load control in residential buildings. Appl. Energy **2018**, 228, 2165–2175.
2. Shah, R.; Mithulananthan, N.; Bansal, R.C.; Ramachandaramurthy, V.K. A review of key power system stability challenges for large-scale PV integration. Renew. Sustain. Energy Rev. **2015**, 41, 1423–1436.
3. Renewables 2018 Global Status Report. Available online: https://www.ren21.net/wp-content/uploads/2019/08/Full-Report-2018.pdf (accessed on 15 March 2020).
4. Zhu, Y.; Yao, J.; Wu, D. Comparative study of two stages and single stage topologies for grid-tie photovoltaic generation by PSCAD/EMTDC. In Proceedings of the 2011 International Conference on Advanced Power System Automation and Protection, Beijing, China, 16–20 October 2011; pp. 1304–1309.
5. Daher, S.; Schmid, J.; Antunes, F.L.M. Multilevel Inverter Topologies for Stand-Alone PV Systems. IEEE Trans. Ind. Electron. **2008**, 55, 2703–2712.

6. Villanueva, E.; Correa, P.; Rodriguez, J.; Pacas, M. Control of a Single-Phase Cascaded H-Bridge Multilevel Inverter for Grid-Connected Photovoltaic Systems. IEEE Trans. Ind. Electron. **2009**, 56, 4399–4406.
7. Abu-Rub, H.; Holtz, J.; Rodriguez, J.; Ge, B. Medium-Voltage Multilevel Converters—State of the Art, Challenges, and Requirements in Industrial Applications. IEEE Trans. Ind. Electron. **2010**, 57, 2581–2596.
8. Mehta, P.; Kunapara, A.; Karelia, N. Improvement in Switching Strategy Used for Even Loss Distribution in ANPC Multilevel Inverter. Procedia Technol. **2015**, 21, 386–392.
9. Metri, J.I.; Vahedi, H.; Kanaan, H.Y.; Al-Haddad, K. Real-Time Implementation of Model-Predictive Control on Seven-Level Packed U-Cell Inverter. IEEE Trans. Ind. Electron. **2016**, 63, 4180–4186.
10. Wu, H.; Zhu, L.; Yang, F.; Mu, T.; Ge, H. Dual-DC-Port Asymmetrical Multilevel Inverters With Reduced Conversion Stages and Enhanced Conversion E_ciency. IEEE Trans. Ind. Electron. **2017**, 64, 2081–2091.
11. Chattopadhyay, S.K.; Chakraborty, C. A New Asymmetric Multilevel Inverter Topology Suitable for Solar PV Applications With Varying Irradiance. IEEE Trans. Sustain. Energy **2017**, 8, 1496–1506.
12. Khodaparast, A.; Azimi, E.; Azimi, A.; Adabi, M.E.; Adabi, J.; Pouresmaeil, E. A New Modular Multilevel Inverter Based on Step-Up Switched-Capacitor Modules. Energies **2019**, 12, 524.
13. Sandeep, N.; Yaragatti, U.R. Operation and Control of a Nine-Level Modified ANPC Inverter Topology with Reduced Part Count for Grid-Connected Applications. IEEE Trans. Ind. Electron. **2018**, 65, 4810–4818.
14. Bassi, H.M.; Salam, Z. A new hybrid multilevel inverter topology with reduced switch count and dc voltage sources. Energies **2019**, 12, 977.
15. Alexander, S.A. Development of solar photovoltaic inverter with reduced harmonic distortions suitable for Indian sub-continent. Renew. Sustain. Energy Rev. **2016**, 56, 694–704.
16. Abdel-Rahim, O.; Alamir, N.; Abdelrahem, M.; Orabi, M.; Kennel, R.; Ismeil, M.A. A Phase-Shift-Modulated LLC-Resonant Micro-Inverter Based on Fixed Frequency Predictive-MPPT. Energies **2020**, 13, 1460.
17. Steczek, M.; Chudzik, P.; Szelag, A. Combination of SHE- and SHM-PWM Techniques for VSI DC-Link Current Harmonics Control in Railway Applications. IEEE Trans. Ind. Electron. **2017**, 64, 7666–7678.
18. Hernández-Callejo, L.; Gallardo-Saavedra, S.; Alonso-Gómez, V. A review of photovoltaic systems: Design, operation and maintenance. Sol. Energy **2019**, 188, 426–440.
19. Athari, H.; Niroomand, M.; Ataei, M. Review and Classification of Control Systems in Grid-tied Inverters. Renew. Sustain. Energy Rev. **2017**, 72, 1167–1176.
20. Zeb, K.; Uddin,W.; Khan, M.A.; Ali, Z.; Ali, M.U.; Christofides, N.; Kim, H.J. A comprehensive review on inverter topologies and control strategies for grid-connected photovoltaic system. Renew. Sustain. Energy Rev. **2018**, 94, 1120–1141.
21. Sinha, A.; Chandra Jana, K.; Kumar Das, M. An inclusive review on di_erent multi-level inverter topologies, their modulation and control strategies for a grid-connected photo-voltaic system. Sol. Energy **2018**, 170, 633–657.
22. Blaabjerg, F.; Teodorescu, R.; Liserre, M.; Timbus, A.V. Overview of Control and Grid Synchronization for Distributed Power Generation Systems. IEEE Trans. Ind. Electron. **2006**, 53, 1398–1409.
23. Zeb, K.; Khan, I.; Uddin,W.; Khan, M.A.; Sathishkumar, P.; Busarello, T.D.C.; Ahmad, I.; Kim, H. A review on recent advances and future trends of transformerless inverter structures for single-phase grid-connected photovoltaic systems. Energies **2018**, 11, 1968.
24. Hassaine, L.; Olias, E.; Quintero, J.; Salas, V. Overview of power inverter topologies and control structures for grid-connected photovoltaic systems. Renew. Sustain. Energy Rev. **2014**, 30, 796–807.
25. Barghi Latran, M.; Teke, A. Investigation of multilevel multifunctional grid-connected inverter topologies and control strategies used in photovoltaic systems. Renew. Sustain. Energy Rev. **2015**, 42, 361–376.
26. Islam, M.; Mekhilef, S.; Hasan, M. Single phase transformerless inverter topologies for grid-tied photovoltaic system: A review. Renew. Sustain. Energy Rev. **2015**, 45, 69–86.
27. Obi, M.; Bass, R. Trends and challenges of grid-connected photovoltaic systems—A review. Renew. Sustain. Energy Rev. **2016**, 58, 1082–1094.
28. Mahela, O.P.; Shaik, A.G. Comprehensive overview of grid interfaced solar photovoltaic systems. Renew. Sustain. Energy Rev. **2017**, 68, 316–332.
29. Hasan, N.S.; Rosmin, N.; Osman, D.A.A.; Musta'amal, A.H. Reviews on multilevel converter and modulation techniques. Renew. Sustain. Energy Rev. **2017**, 80, 163–174.
30. Mahlooji, M.H.; Mohammadi, H.R.; Rahimi, M. A review on modeling and control of grid-connected photovoltaic inverters with LCL filter. Renew Sustain. Energy Rev. **2018**, 81, 563–578.
31. Kavya Santhoshi, B.; Mohana Sundaram, K.; Padmanaban, S.; Holm-Nielsen, J.B.; Prabhakaran, K.K. Critical Review of PV Grid-Tied Inverters. Energies **2019**, 12, 1921.
32. Dogga, R.; Pathak, M.K. Recent trends in solar PV inverter topologies. Sol. Energy **2019**, 183, 57–73.
33. Ebrahimi, S.; Moghassemi, A.; Olamaei, J. PV Inverters and Modulation Strategies: A Review and A Proposed Control Strategy for Frequency and Voltage Regulation. Signal Proc. Renew. Energy **2020**, 4, 1–21.
34. Parvez, M.; Elias, M.F.M.; Rahim, N.A.; Osman, N. Current control techniques for three-phase grid interconnection of renewable power generation systems: A review. Sol. Energy **2016**, 135, 29–42.
35. Liu, H.; Zhou, B.; Li, Y.; Chen, J.; Loh, P.C. High-E_ciency T-Source InverterWith Low Voltage Spikes Across the Switch Bridge. IEEE Trans. Power Electron. **2020**, 35, 10554–10566.
36. Al-Shetwi, A.Q.; Sujod, M.Z.; Blaabjerg, F.; Yang, Y. Fault ride-through control of grid-connected photovoltaic power plants: A review. Sol. Energy **2019**, 180, 340–350.