Comparative Analysis of Different Converter Topologies Employed for Transformer-less Photovoltaic System - A Review

Sushama Meshram[1], Heena Sheikh[2]

[1]*PG Scholar, Dept. of Electrical Engineering, Ballarpur Institute of Technology, Balharshah, Maharashtra, India.*
[2]*Assistant Professor, Dept. of Electrical Engineering, Ballarpur Institute of Technology, Balharshah, Maharashtra, India.*

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Abstract – *In grid connected photovoltaic (PV) generation systems transformer-less inverters are widely used which induce leakage current due to the absence of galvanic isolation and unstable common mode voltage. However, transformer-less inverter topologies have a lot of advantages, such as low cost, light weight, small size and high efficiency, but their semiconductor devices are still on hard-switching state at present, which normally has low efficiency, since the power losses across the switching devices are high. In this paper different topologies of transformer-less inverters are compared to highlight their differences. The analysis considers the efficiency, the leakage current, and the quality of the output current when different modulation techniques are adopted.*

Key Words**: Photo-Voltaic (PV), Transformer-Less Inverters, Common Mode Voltage (CMV), Full Bridge Bipolar, H5, H6, HERIC.**

1. INTRODUCTION

The renewable sources are emerging as one of the most promising tools for this century, as conventional sources are limited and are causing fundamental problem of pollution. More and more countries are setting up high targets of renewable in their energy system production mix as they are free and readily available. Hence the guidelines for future energy production are being established according to Kyoto Protocol [1].

The options of alternative energy sources have attracted energy sectors to generate power on a large scale. The drawbacks common in renewable sources are their unpredictable nature and dependence on weather and climatic changes. It is well known that neither a standalone solar nor a wind energy system can provide a continuous supply of energy. Fortunately problems caused by these resources can be fully or partially overcome by integrating renewable resources in a proper combination using strength of one source to overcome weakness of other [2]. As India is endowed with high intensity solar radiations hence solar power generation systems are becoming prevalent options.
Large scale integration of single phase photovoltaic (PV) system impacts not only the grid planning but on the operation of distribution grid [3]. Due to booming installations of single phase PV systems, the grid demands pertaining to integration of PV systems with the grid are required to be modified [4]. The grid connected PV systems at low voltage residential level are designed such that they disconnect from the grid in the certain time period whenever the fault occurs at point of common coupling (PCC) [5]. As the penetration level of low voltage photovoltaic systems is increasing the disconnection may cause negative impact on the system stability and reliability [3,6-8]. The consequence of increased penetration is that the grid interconnection standards are becoming more restrictive [9-13].

The future generation PV systems would play important role like conventional power plants in grid regulation participation. Requirements like low voltage ride through (LVRT) related to reactive current injection and voltage control through reactive power support are already being thought of [14]. For generating appropriate reference signals so as to handle LVRT capability during grid faults, mostly the control methods for single phase PV systems are responsible. The single phase PQ theory [15-16] can be applied and active power can be controlled by properly regulating maximum power point tracking (MPPT) algorithm so as to avoid over current tripping during voltage sags in order to enhance LVRT capability. Droop control methods are also implemented to regulate active and reactive power [17-20] based on the assumption that the distribution line is mainly inductive.

2. GRID INTEGRATION REQUIREMENTS

A transition is witnessed by India in the solar market. Large scale grid connected projects were emphasized under Jawaharlal Nehru National Solar Mission and more are expected to come in future. The emphasis is on large scale grid connected projects the requirements for which are laid down by C.E.A [11, 41].

2.1 Technical specifications for inverter

The heart of a solar PV system is inverter hence it is also responsible for the quality of power that is generated. Therefore most regulatory standards have to be handled by the inverter [5, 9, 12-13, 21].

2.1.1 Voltage fluctuations

The voltage level is an important requirement for determining the penetration levels. According to IEEE 1547, distributed energy resources (DER) are not allowed to actively regulate the voltage at a point of common coupling (PCC) which permits the customer's voltage fluctuation of +_5%.

In India, the CEA mandates disconnection from the grid in 2 seconds if the voltage of the grid exceeds or falls below the operational range of 80-110% of the nominal voltage. Reconnection is allowed only after the voltage is in the prescribed limits and is stable for 60 seconds.

As the cumulative penetration of PV increases, the CEA could also consider mandating the Low/High Voltage ride through (L/HVRT) function. This function ensures that the inverter won't automatically disconnect for certain temporary faults on the grid side. This would benefit the grid in recovery after the occurrence of fault.

2.1.2 Frequency range

In India, the standard grid frequency is 50 Hz. The CEA has mandated the system to be equipped with protective functions for over and under frequency trip functions, if the frequency reaches 50.5 Hz or 47.5 Hz with a disconnection time up to 0.2 seconds. Only after the frequency is in the prescribed limits and is stable for 60 seconds, reconnection is allowed.

2.1.3 Power Quality

2.1.3.1 Harmonics

Harmonic currents can cause a voltage drop and result in distortion of the supply voltage. India has adopted IEEE 519 on the lines of USA and Australia. IEEE 519 addresses current and voltage limitations through individual harmonic limit and total harmonic distortion limit. The voltage distortion limit established by the standard for general systems is 5% THD.

2.1.3.2 Flicker

Random or repetitive variations in the root mean square (RMS) voltage between 90% and 110% of nominal voltage can be generated by the solar system and produce a phenomenon known as 'flicker'. India adopts the IEC 61000, standards to control flicker. To control flicker, the IEC 61000-3-3 and IEC 61000-3-11 standards are globally followed. The IEC 61000-3-3 provides the flicker limits for LV equipment (<16A) and IEC 61000-3-11 provides the flicker limits for LV equipment (≤75A). India also adopts the IEC 61000-3-3,-3-11 standards to control flicker.

2.1.3.3 DC current injection

DC current within the low voltage ac network could cause significant disturbances within distribution and measurement transformers. The most prominent phenomenon being "half cycle saturation", where a transformer, which normally operates with a very small exciting current, starts drawing as much as a hundred times the normal current. This results in the transformer operating beyond the design limits. In India CEA has regulated the DC current injection limit in accordance with IEEE 1547, where maximum permissible level for dc injection is 0.5% of the full rated output at the interconnection point.

2.1.4 Anti islanding function

If a solar system continues to supply a load even if grid power is absent then this condition is termed as islanding. The inverter in the PV system should be able to detect this condition and stop supplying power if the grid is down which is called anti-islanding. Under CEA's, "Technical Standards for Connectivity of the Distributed Generation Resources', 2013, strictly all inverters have to adhere to this technical requirement.
The MNRE also has mandated the IEEE 1547 for antis-landing protection for utility scale projects commissioned under the Jawaharlal Nehru National Solar Mission (NSM).

2.2 Synchronization

The current to be injected in the grid must be synchronized with the grid voltage. A good synchronization technique should respond instantly and accurately as soon as the fault occurs, e.g. voltage drop, phase jump, frequency jump and good harmonic rejection ability [22]. Since the voltage fault occurs for a very short period of time the fast synchronization technique ensures reliable performance of the entire PV system with the grid [23]. The synchronization techniques can be classified as:

- Mathematical analysis methods e.g. Fourier series methods.
- Phase locked loop (PLL) techniques. The basic structure of a PLL consists of a Phase Detector (PD), a Proportional Integrator (PI) based filter and an oscillator. The main difference among various PLL methods lies with the configuration of PD.

3. GRID CONNECTED PV SYSTEM

Grid connected PV system are of two types,

1. With transformer,
2. Without transformer.

3.1 PV system with transformer

For the first type the transformer can be either of low frequency present on either grid side or high frequency as shown in fig 1 and fig 2. These systems have efficiency in the range of 93-95% [3].

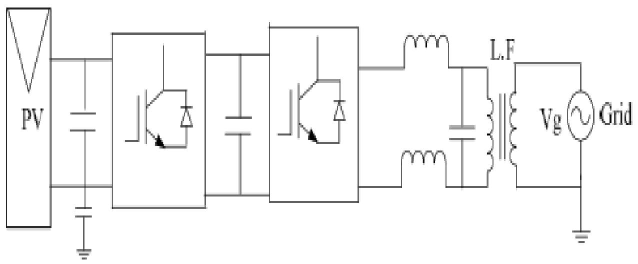

Fig -1: Single phase grid connected PV system with low frequency transformer.

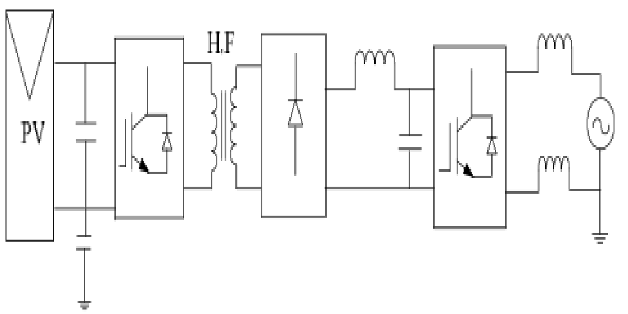

Fig -2: Single phase grid connected PV system with high frequency transformer.

3.2 PV system without transformer

From galvanic isolation point of view either high frequency or low frequency transformers can be used but the disadvantage is the increased cost and system volume. Hence, the trend is shifting towards transformer-less configurations from the efficiency point of view [4-5].In earlier works presented , the common mode voltage that is generated by a topology and modulation strategy has influence on ground leakage current which actually flows through parasitic capacitance of PV array[35-36]. The efficiency of these devices is defined by (1).

$$n = \frac{P_{dc} - Loss}{P_{dc}} \quad (1)$$

Where, Pdc is the input DC power.
Since the losses are mostly due to internal power dissipation of switches. In real time applications, to consider different levels of efficiency at different levels of input power, the efficiency commonly used is European efficiency and is given by (2).

$$\eta Euro = 0.03.\eta 5\% + 0.06.\eta 10\% + 0.13.\eta 20\% + 0.10.\eta 30\% + 0.48.\eta 50\% + 0.2.\eta 100\% \quad (2)$$

Where, ηi % is the conversion efficiency at i% of inverter input power [38].

3.2.1 Full Bridge inverter

The most commonly used full bridge topology is shown in fig.3. Two modulation strategies are applicable to this inverter a) unipolar b) bipolar modulation. With unipolar both legs, A (S1, S2) and leg B (S3, S4) are switched with high frequency. The output voltage states S1, S3-ON and S2, S4- ON are possible. Due to lack of galvanic isolation high leakage currents may be induced in these inverters and high common mode voltage (CMV) appears. To prevent this common mode voltage must be maintained constant [35-37].

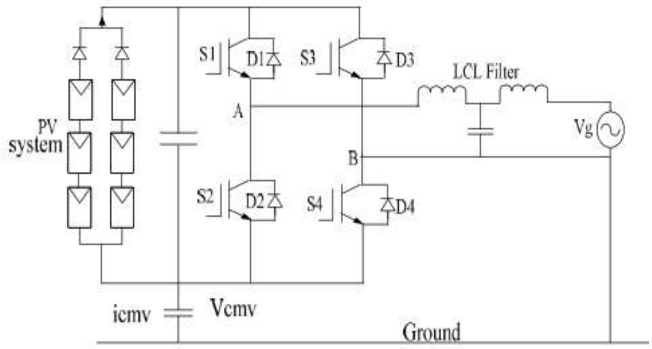

Fig -3: Full Bridge connected converter.

3.2.2 DC Bypass method

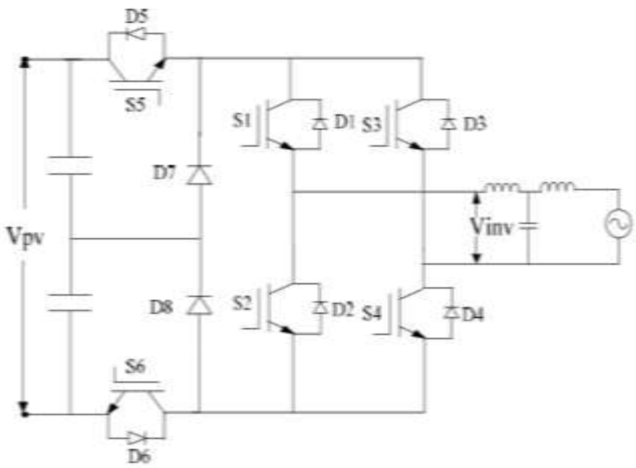

Fig -4: Full Bridge with DC Bypass.

The full bridge with DC bypass is shown in fig 4.The inverter is disconnected from the grid in this method. The H5 topology patented by SMA [33] disconnects the PV panel from the grid during the current freewheeling periods and thus can have constant common mode voltage. Fig 4 shows four switches (S1, S2, S3, S4) and a DC bypass switch. The switches S1 and S2 are operated at grid frequency and S3, S4 and S5 are operated at high frequency. During current freewheeling period the S5 switch is open and thus it disconnects PV panels from the inverter full H-bridge [36]. H5 inverter in fig 5 cannot maintain CMV constant. The leakage currents flow with respect to parasitic parameters of resonant circuit. Besides floating CMV another disadvantage is that of higher conduction loss due to more switches in conduction path [36-37].

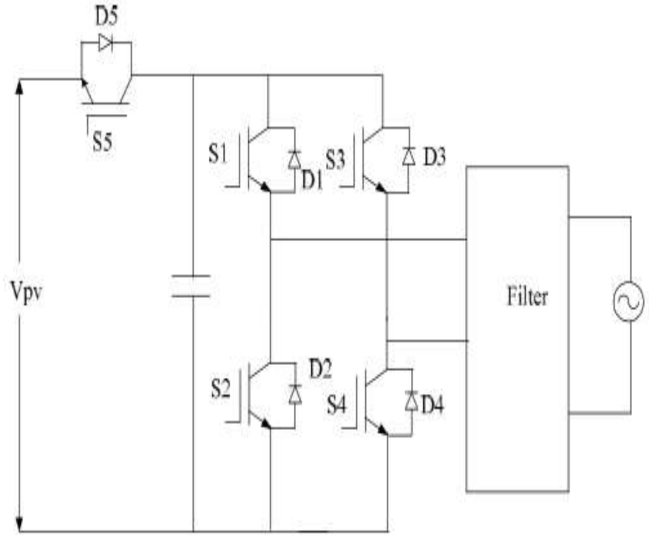

Fig -5: H5 Inverter.

3.2.3 AC Bypass method

To create a freewheeling path on the ac side so as to reduce the leakage current, switches are added in this method. HERIC (High efficient and reliable inverter concept) inverter shown in fig 6 has advantages of both unipolar and bipolar modulation techniques [37]. The PV system having HERIC inverter produces more annual energy yield than FB and H6 inverter shown in fig 7.

HERIC topology avoids a fluctuating potential on the DC side terminals of PV generator. This topology generates a constant mode voltage, by disconnecting the PV from the grid when the output of inverter is short circuited. As a result the common mode voltage acting on the parasitic capacitance of the PV array remains constant with respect to time which ensures that leakage current are kept at low values [40-41].

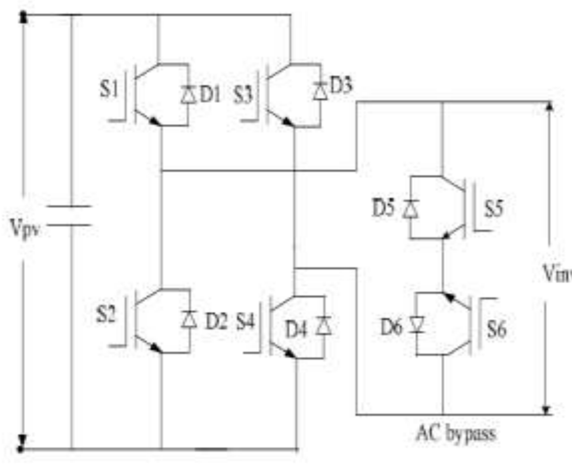

Fig -6: HERIC Inverter.

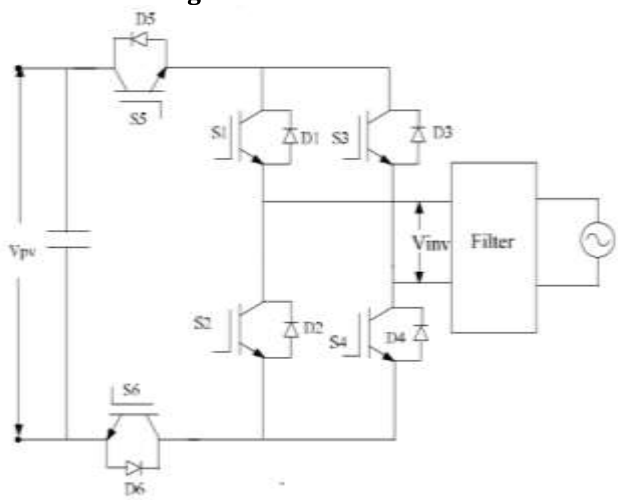

Fig -7: H6 Inverter.

4. PROBLEMS ASSOCIATED WITH TRANSFORMER-LESS INVERTERS

The galvanic connection in transformer-less inverters allows leakage current to flow. For full bridge inverter with unipolar modulation technique, though two zero output states are possible but high common mode voltage appears which leads to high leakage currents. The bipolar modulation on the other hand offers constant common mode voltage eliminating leakage currents, but this technique causes large ripple currents deteriorating the power quality. HERIC inverter has good efficiency but its performance is hampered when considering common mode behavior. H5 and HERIC focus only on providing galvanic isolation. H6 eliminates the leakage currents by using galvanic isolation and common mode voltage clamping but the efficiency of the system is reduced [36-40].

5. CONCLUSIONS

This review paper studies different Synchronization technique as well the grid regulations as defined by the CEA. Numerous techniques are available in literature for implementing good grid synchronization which can be classified as zero crossing detector (ZCD), discrete Fourier transform (DFT), Kalman filter (KF). The different PLL methods considered are T/4 delay, enhanced PLL (EPLL), adaptive PLL (APLL) [20, 23, 25, 34]. A comparison of these methods is given in the table 1.

In comparison to transformer-less PV inverter systems the PV systems with transformer have less efficiency and that they have galvanic isolation. The common mode behavior influences ground leakage current. The problem associated with common mode voltage behavior is dependent on topology structure. The leakage current is influences through stray capacitance due to the variation in common mode voltage. The performance of different transformer-less inverters for specific topologies are carried out based on the comparison of efficiency, leakage current, common mode voltage and switching frequency is studied and presented in table 2. Due application of proper modulation techniques and the addition of only few power devices the performance of inverters with regards to efficiency can be improved. Also HERIC and H5 can comply with the standards laid down with regards to maximum leakage current levels that are allowed.

Table -1: Comparison of synchronization techniques.

Synchronization Method	Harmonic Immunity	Adaptation to frequency	Dynamic Response	Computational Cost	Complexity
ZCD	Low	Medium	Slow	Low	Low
DFT	High	High	Slow	High	High
T/4 Delay	No	Medium	Medium	Medium	Low
KF	--	Medium	--	Very High	Very High
PLL	Medium	Medium	Medium	Low	Low
EPLL	High	High	Medium	Medium	Low
APLL	Medium	Medium	Fast	Medium	Medium

Table -2: Comparison of different inverter topology according to several parameters.

Parameters	Inverter Topology			
	Full bridge Bipolar Inverter	***H5 Inverter***	***H6 Inverter***	***HERIC Inverter***
No. of power devices	4	5	6	6
No of switches conducting in each period	2	3	4	2
Leakage current	High	Low	Very low	Very low
Efficiency (%)	High	High	High	Highest
CMV	Constant	Floating	Constant	Floating
Device current stress	S1 - 4: Moderate	S1 - 4: Moderate SD5 - 6: high	S1 - 4: Moderate SD5- 6: very high	S1 - 4: low SD5- 6: very low
Switching frequency	S1 - 4: high	S1- 4:Line frequency S5 : high	S1-4:Line frequency S5 - 6: high	S1 - 4: High S5- 6: line frequency

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