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Evaluation of Transformerless Inverters for Single Phase Photovoltaic Systems

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Abstract: The transformerless inverter topologies have gained more attention in photovoltaic generation system since they feature high efficiency and low cost. Unfortunately, it has problems on the galvanic isolation between photovoltaic systems to the grid, which leads to high leakage current. So in order to meet the safety requirement, leakage current must be tackled carefully in the transformerless inverters. In order to avoid the leakage current, various transformerless inverters have been proposed using different topologies to keep the common mode voltage constant. This paper focuses on the latest development of the inverters for the photovoltaic grid. Their performances are compared and analyzed.

Keywords: photovoltaic systems, leakage current, transformerless inverters, parasitic capacitance, common mode voltage.

I. INTRODUCTION

An inverter is a device that converts dc power into ac power. Means we can convert a dc input voltage to a symmetrical ac output voltage of desired magnitude and frequency. The inverters for the photovoltaic applications are gaining more and more visibility; also power demand of world is increasing day by day. But the cost of photovoltaic system is the major issue, so due to this not many photovoltaic systems are put into grid due to higher cost. Thus the cost of photovoltaic panels is the major contributions to these systems.

The inverters are needed for two functions: The first is to amplify the low dc voltage that is generated by the modules to the high level ac voltage in the grid. And the second is the power delivered from PV modules is very sensitive to point of operation and inverter must incorporate a function for the purpose of maximum power point tracking. Today we need more and more energy due to skyrocketing population and also the industries. Hence the renewable energy plays a vital role in ensuring the better future. Solar energy has the major role in empowering the world, because it is pollution free and green [1].

Photovoltaic systems with grid connected may be with transformer or without transformer [2]. For the lower power applications, single phase converter is normally used with low or high frequency transformer. The design of highly efficient low cost and small size inverters becomes a difficult task.

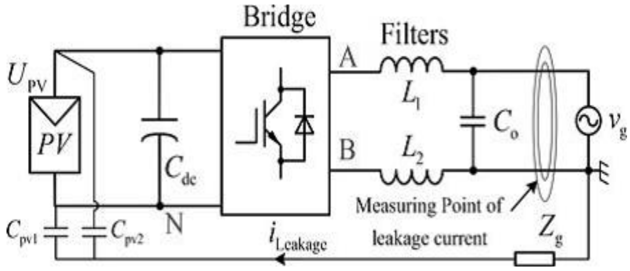


Fig. 1: Leakage current path for transformerless PV inverters.

The inverter with transformers also called isolated inverters and without transformer is called non-isolated transformers. On the other hand, it is possible to design the inverter without transformer to minimize the losses, size and cost of these systems. However after removing the transformer, the galvanic connection between the grid and the PV array introduces the ground leakage current path due to parasitic capacitance [3]. As a result the leakage current gives rise to EMC problems and therefore increase the harmonic injected into the grid. If the ground current exceeds the prefixed limits, there is disconnection of PV array from the converter. However harmonic content and its amplitude depend on converter topology and parameters of resonant circuit.

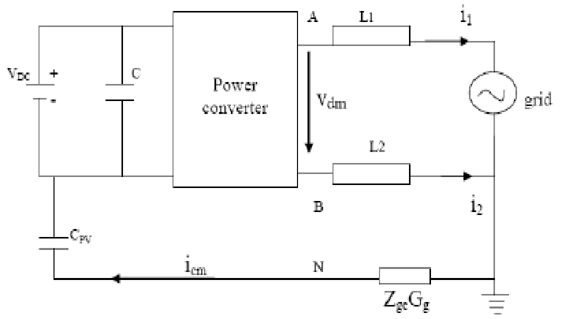
In order to overcome these problems, many solutions have been proposed, most of the efforts are to limit leakage current up to 300mA to meet standard requirements [4]. Some of the solutions are to keep the CM voltage constant or varied at low frequency such as 50 Hz or 60 Hz. According to this the conventional solution is a half bridge inverter [5]. However the dc voltage utilization of half bridge topology is half of the full bridge topology. The input voltage requires is half of the half bridge inverter.

The diagram 1 shows the leakage current path for the transformerless PV inverters.

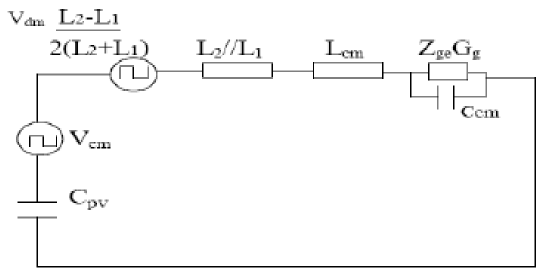
II. COMMON MODE VOLTAGE AND LEAKAGE CURRENT ANALYSIS IN TRANSFORMERLESS INVERTER

When transformer is removed in a isolated inverter, galvanic is created in a resonant circuit through parasitic capacitance, filter inductance, grid includes leakage current flowing through ground as in figure 1.To understand the system, common mode voltage, differential mode voltage behavior must be taken into consideration.

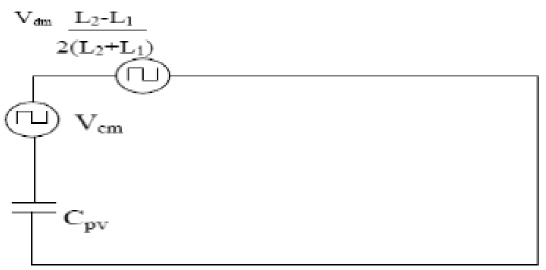
In case of single phase system, common mode and differential mode voltages are derived from the two phases with respective to neutral [6]. The common mode voltage is the average sum of voltages between output and common reference N, The differential voltage is difference between two phases with respect to neutral.



a) System full model



b) Detailed common model



C) Simplified common mode model

Fig. 2: Different models of transformerless PV grid tied inverters.

The voltage between converter output points and reference N can be expressed as,

$$VAN = Vdm\text{-}AB + Vcm\text{-}AB/2 \quad (1)$$

$$VAN = Vdm\text{-}AB + Vcm\text{-}AB/2 \quad (2)$$

And common mode current is given by,

$$icm = i1 + i2 \quad (3)$$

III.DIFFERENTTYPES OF TRANSFORMERLESS PV INVERTERS

A. Full bridge inverter:-

The figure shows the FB inverter [7-8]. These inverters can be either unipolar or bipolar modulation technique.

In the unipolar modulation technique, switch S1, S2 and switch S3&S4 switched with high frequency with mirrored sinusoidal reference. And zero output voltages stages are possible.

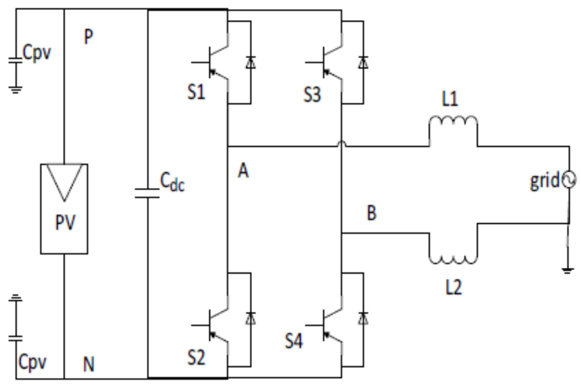


Fig. 3: Single phase full bridge Inverter

Therefore, S1, S3 =ON & S2, S4 = ON

With the use of this unipolar technique, the implementation is more feasible and popular. However, high CMV appears and leads to high leakage currents. In the bipolar modulation both the pairs of switches i.e. S1, S3 &S2, S4 are switched simultaneously i.e. in the positive half cycle S1& S3 are ON and negative half cycle S2 &S4 are ON.

Due to use of bipolar modulation technique the CMV is constant, which eliminates the leakage currents. But, in this modulation technique causes large ripple currents &which affect power quality and efficiency.

B. DC bypassed method

In the dc bypassed method, the inverter gets disconnected from the grid in the dc side. The galvanic isolation can be feeded in the freewheeling state with the use of proper modulation technique [9].

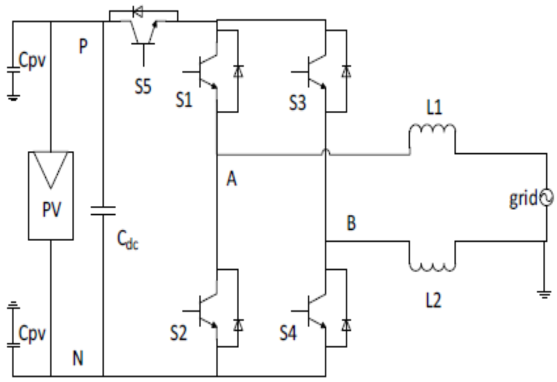


Fig. 4: H5 topology.

This topology adds extra switches on the dc side as a decoupling switch such as H5 topology When switch S5 is off ,then leakage current path is cut off, zero v voltage vectors appears when S5 is off. During the positive half cycle, freewheeling path is created via switch S1 & S3and for the negative active state , the freewheeling path is created via the switch S3 & antiparallel diode of S1.For eliminating the leakage current, the common mode voltage must be kept constant. But, the dc bypassed method such as H5 is not able to maintain the CMV at Vdc/2.So the leakage current still flows through the parasitic parameters of the circuit. Also this topology has higher conduction loss, due to more switches in the conduction path.

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C. AC bypass method
As the name suggests, switches or diodes are added on the ac side to create the freewheeling path. The HERIC (Highly Efficient Reliable Inverter Concept) is implementing this method. The advantages of both unipolar and bipolar modulation techniques are combined in this topology [10]. In this method, the switches in the conduction path are less than the dc bypassed method. So as mentioned earlier, to eliminate leakage current, the CMV must be constant. So this topology also fails to generate the constant CMV.

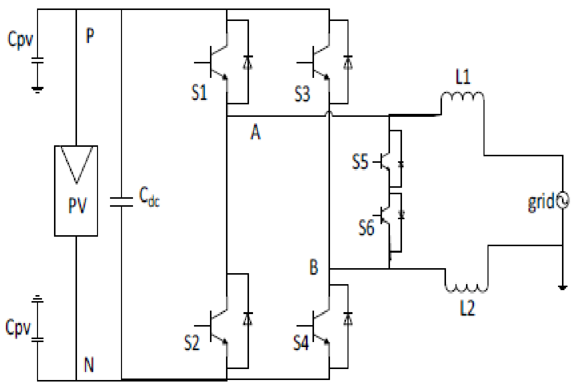

Fig 5: HERIC topology

D. Clamping Method
In this method, one clamping branch [11-12] is connected to the midpoint of the dc link to realize the constant CMV; hence it improves the common mode behavior of decoupling method. [H6]. The figure shows the topology which uses clamping method.

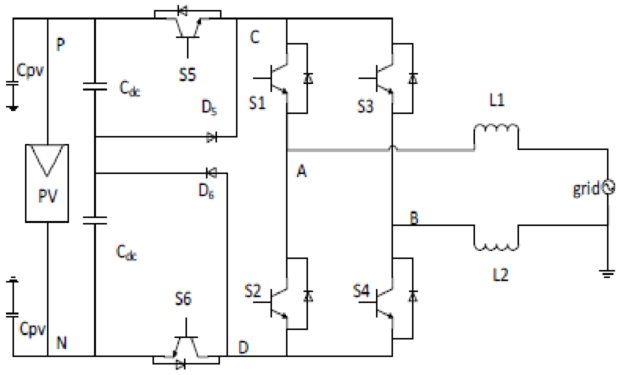

Fig. 6: H6 topology.

The positive active state, switches S1, S4 are on. During this period S5&S6 commutate at the switching frequency. At negative active state, S2 & S3 are ON and S5 & S6 commutate at the switching frequency. Zero voltage vectors occur when S5 & s6 are OFF. So VAB & VCD tends to zero and to overcome this issue two additional diodes D5 &D6 are used to fix freewheeling path at Vdc/2. The CMV is clamped at constant with the help of the FB-DCBP (H6) topology generates unipolar output voltage [15]. Therefore it has high efficiency and becomes very attractive solution for the transformerless PV inverters.

The recently proposed topology is HBZVR-D (H bridge zero voltage state rectifier diode) as in the figure 8 [16].

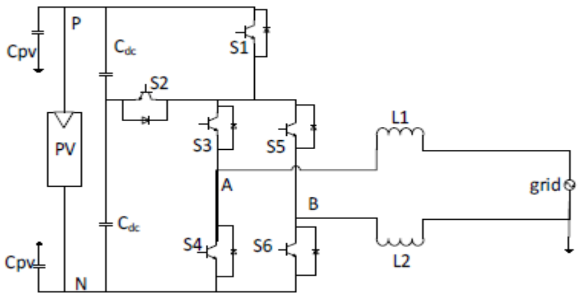

Fig. 7: oH5 topology

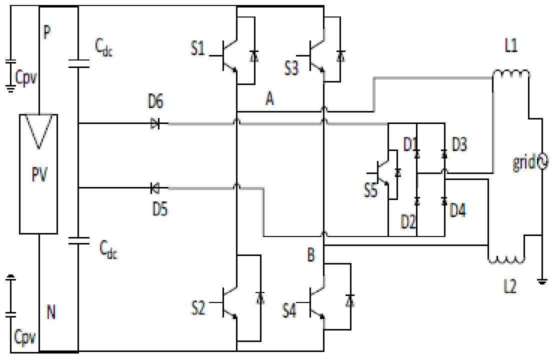

Fig. 8: HBZVR-D topology

In this topology in the freewheeling period protection circuit is formed by one active switch and diode. But the main drawback of this topology is bipolar output voltage due to dead time between conduction and freewheeling mode. To overcome this drawback, the proper setting of dead time period must be done. The topology that uses clamping is oH5 [11] as in figure 7. In this topology, clamping is done using switch S1 & S2. But it has high conduction loss due to use of more switches as compared to HBZVR-D topology. But drawback of this method is the voltage balancing on the capacitors due to dispersion due to parasitic parameters of component. This effect can be minimized by using simple resistor across the switch or capacitor. From the above discussed topologies, the clamping method topologies are FBDCBP, HBZVR-D, oH5 are very attractive solutions for the transformerless PV inverters than the dc & ac decoupling methods due to improved common mode voltages & minimum approximately zero voltage leakage current.

IV.SIMULATIONS AND DISCUSSIONS

For the performance analysis the simulation of different transformerless PV inverters was done using the MATLAB software with the parameters as in table 1 [16]. The section describes the comparison of different parameters such as output voltage, common mode voltage, leakage current & current total harmonic distortion (THD) of various topologies.

Table I: Parameters

Filter inductanceL1,L2	1.8 mH
Filter capacitance C_f	2 µF
Load resistance	15 Ω
Input DC voltage VDC	400 V

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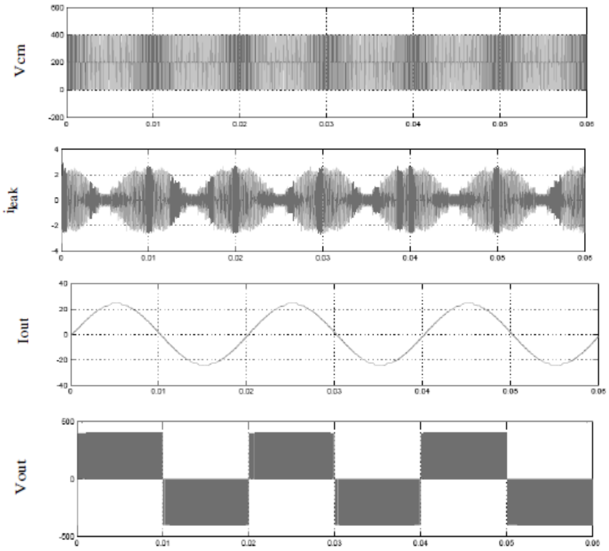
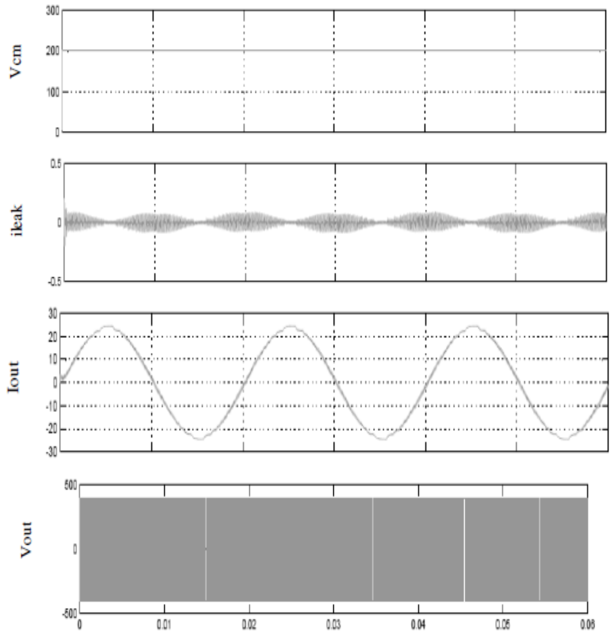
DC link capacitor C_{dc}	250 µF
Parasitic capacitance of the PV array C_{pv}	100 nF
Switching frequency F_{sw}	10 KHz

The full bridge inverters with the unipolar modulation have three level output voltage as well as good efficiency. But it generates varying common mode voltages & also high leakage current, so it is not suitable for transformerless PV inverters.

For the bipolar modulation, it has two level output voltage. Unlike unipolar modulation, it does not generate the varying CMV, so leakage current is reduced significantly as shown in figure10. But it generates high current % THD such as current ripples & switching losses.

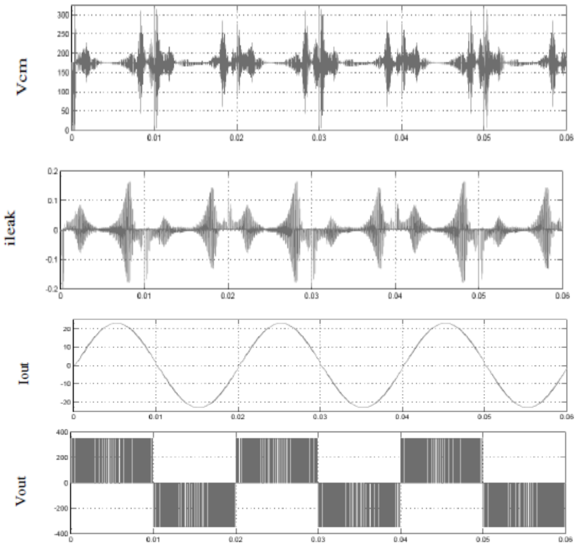


Time in Sec (a)



Time in Sec (b)

Fig. 9: Common mode voltage (CMV), leakage current (ileak), output current (Iout) and output voltage (Vout) for full bridge unipolar and bipolar PWM.



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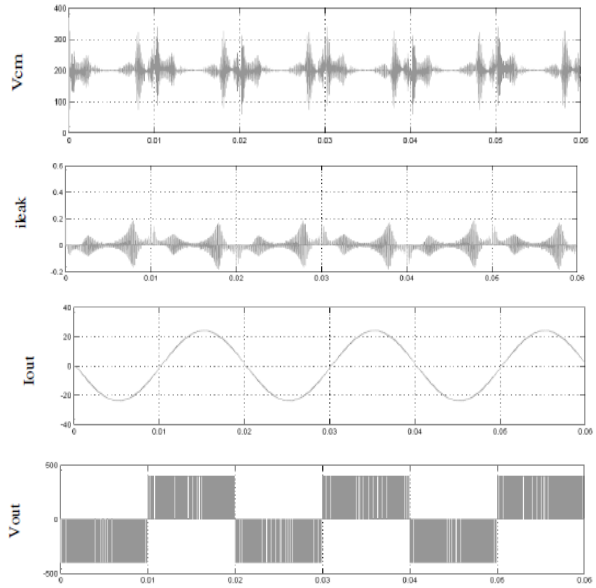

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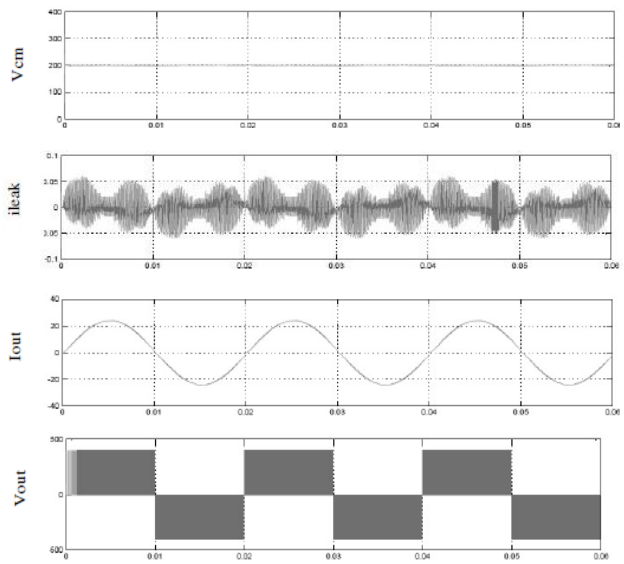

Time in Sec (c)

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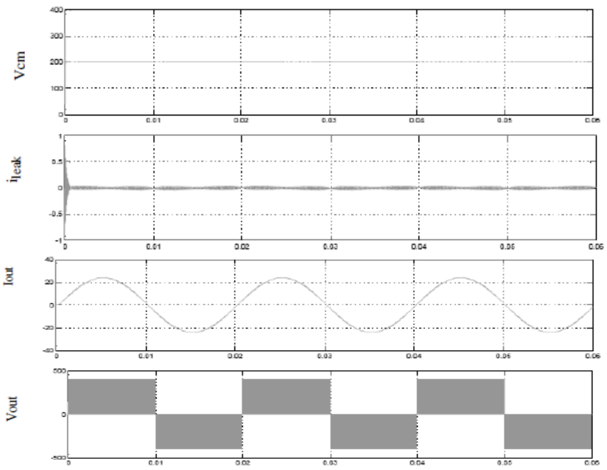

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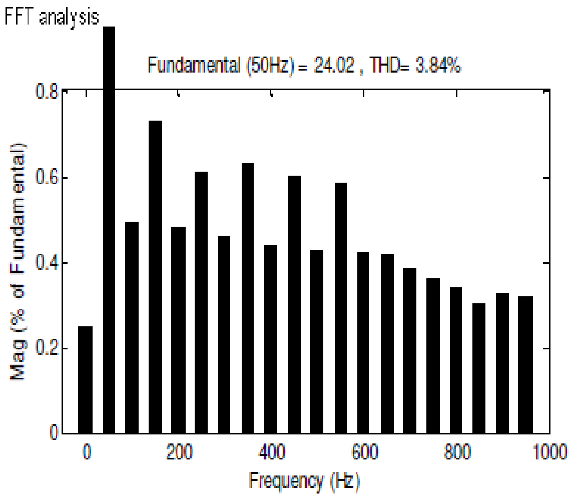
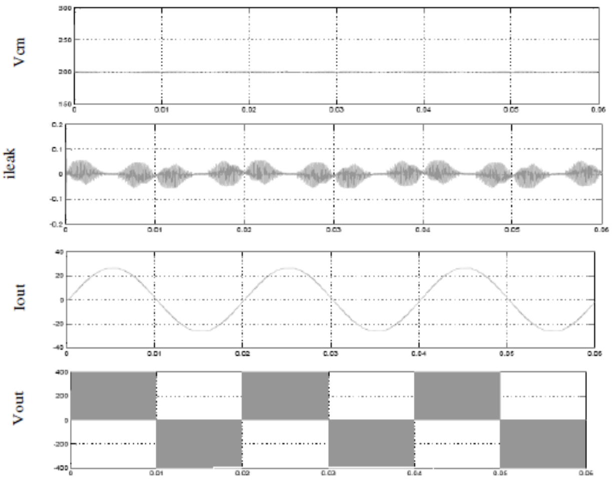




Time in Sec (e)

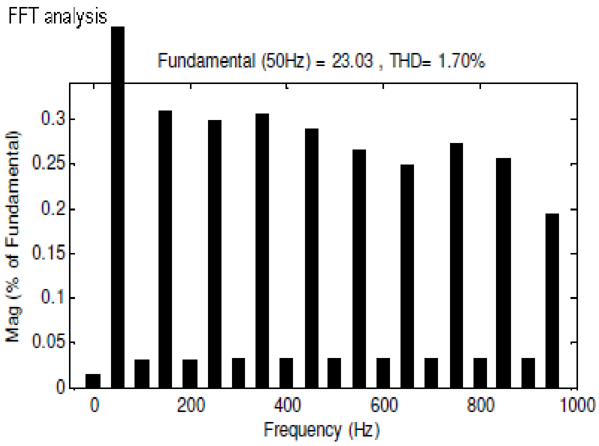
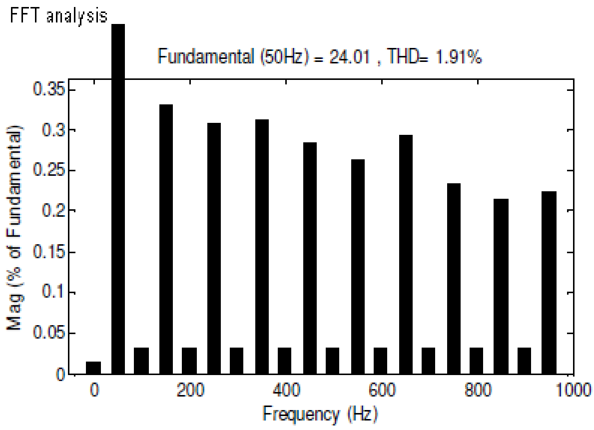
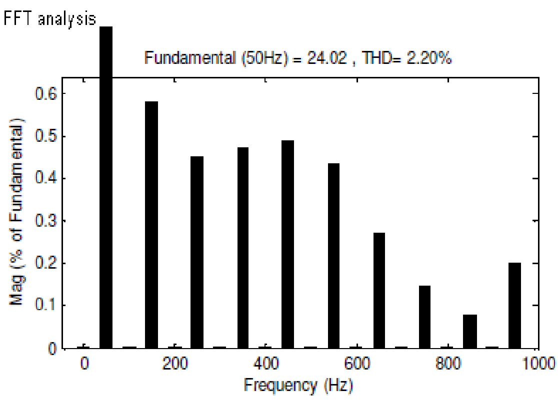


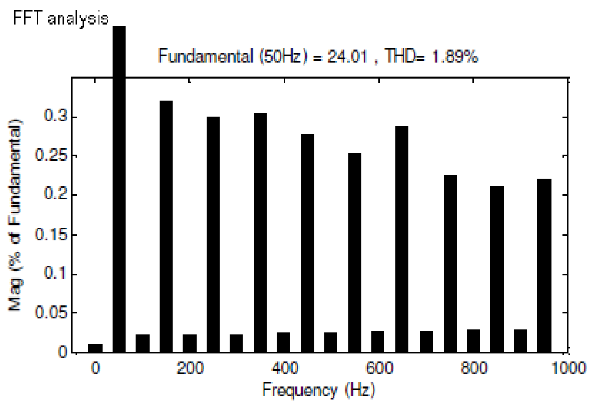
Fig. 10 : The performance analysis for (a) H5, (b) HERIC, (c) FBDCBP, (d) oH5, (e) HBZVR-D.

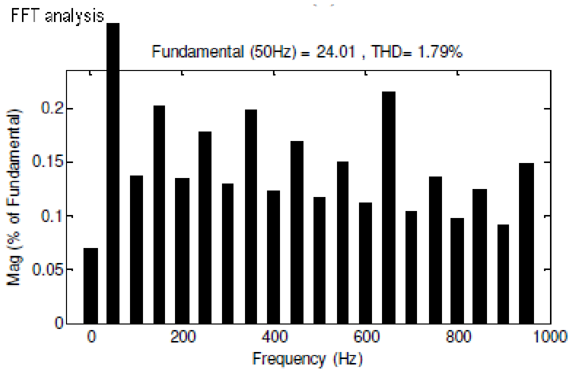


The performance analysis of topologies using clamping (FBDCBP, HBZVR-D, and oH5), dc bypass family and ac bypass family are as shown in figures (a-e) respectively as shown above. Figure (a) & (b) fails to generate constant CMV. But the % current THD are increased because this injects the ripple to the grid current. On the contrary, FBDCBP, HBZVR-D & oH5 topologies improve the common- mode behavior by introducing CMV clamping branch. So leakage current is eliminated as in figure11 (c) to (e) [16].



(a)





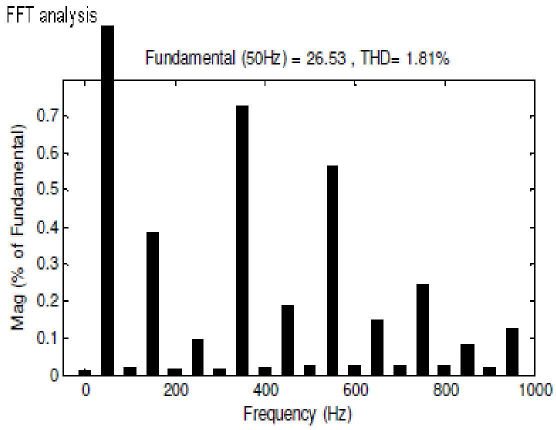


Fig. 11.The Harmonic analysis for (a)FB-Unipolar,(b)FB-Bipolar,(c)H5,(d)HERIC,(e)FBDCBP,(f)oH5,(g)HBZVR-D

Table II

Evaluation methods with topologies	Advantages	Disadvantages
FB-Unipolar	Three level output voltage, High efficiency	High leakage current
FB-Bipolar	Constant CMV,Low leakage current	large current ripples
H5(DC bypass)	Three level output voltage, low current ripple	Higher conduction losses, variable CMV
HERIC(AC bypass)	Three level output voltage, high efficiency	Injection of reactive power into the grid [12], Floating CMV
FBDCBP (H6) (Clamping)	Constant CMV,low leakage current	Higher conduction losses, variable CMV
HBZVR-D	Constant CMV, Very low leakage current, high efficiency	Bipolar output voltage in dead time period
oH5	Very low leakage current	Voltage balancing

So among recently proposed topologies, CMV clamping topologies are the best solution for the transformerless PV inverters. Table 2 summarizes the evaluations of different methods including advantages and disadvantages [17].

V. CONCLUSION

When the line transformer is removed in a PV system, galvanic isolation problems occur between the PV to the grid. This emerge a leakage current in the parasitic elements of the resonant circuit. This leakage current can be minimized using different transformerless PV inverter topologies with different operating principles, which has to minimize the critical issues on common mode voltage and leakage current. All the topologies developed are designed by basic full bridge inverter. In H5, HERIC topologies we have to disconnect switches from dc, ac sides in the freewheeling modes. Also clamping topologies clamp the voltage at constant level using different clamping branches, which includes FBDCBP, HBZVR-D & oH5. In the simulation results, full bridge topology with unipolar & bipolar modulation, are not suitable for the transformerless PV inverters, because of high leakage current & conduction losses. Ac bypass method is efficient than dc bypass method, but still there is leakage current flowing in both the topologies, such as FBDCBP, HBZVR-D, oH5 have minimized the leakage current approximately to zero with improved common mode voltages.

Further in the simulation results, the clamping topologies such as, HBZVR-D & oH5 are very attractive solution for the transformerless systems. The HERIC topology has maximum efficiency but common mode behavior is not so good. The same problem is raised in the H5 topology

So this paper analyses & compares the performance of various evaluation methods of the single phase transformerless PV inverters which do not eliminate but minimize the leakage current. It contains the working principles and their control strategies as well validated by their simulation using MATLAB.

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