

Quantitative Leakage Current Assessment in Grid-Tied Photo Voltaic Inverters

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ABSTRACT: Photo Voltaic energy has replaced the fossil based fuels in many fields. An exodus drift from carbonic fuels to photo voltaic energy is observed. At its infant stages solar energy was comprised of isolated generating units. Rampant developments led to the emerging of grid tied systems. Protocols issued by authorities, technical and non-technical constraints altogether possess severe threats to grid tied systems. Leakage current, harmonics, electromagnetic interference, dead time, reactive power compensation etc put the system in swirls of crisis. Ostensibly leakage current is the prime impediment for the grid connected systems. Rapid variation in common mode voltage and parasitic capacitance are the root causes for leakage current. Damage of PV array, harmonic distortion in grid, safety disasters, losses, false tripping of protective devices, malfunction of power conditioning system etc are major outrages caused by leakage current. The causes, magnitude, path, detrimental, point of measurement and preventive measures of leakage current are analysed. Advanced power electronic circuits namely H5, HERIC and H6 topology of inverters can restrict leakage current to safe limits. A comparative analysis of these inverters are performed with regard to leakage current and overall efficiency. Theoretical arguments are substantiated by MATLAB simulations. H5 topology gave the best leakage current results.

KEYWORDS: Leakage current, parasitic capacitance, common mode voltage, differential mode voltage, unipolar modulation.

I. INTRODUCTION

In the backdrop of hazards intrigued by the carbonic fuels solar energy is widely promoted. Photo voltaic energy is admired in due of its merits like ubiquity, abundance, sustainability, cheapness, eco friendliness etc. Solar systems could devocalise the environmental queries raised by the fossil based energy sources. It envisages energy security and provide energy at affordable price. During the primitive periods isolated generation units were installed in rural areas which were not electrified. Recently grid tied photovoltaic systems are emerged in urban as well as rural areas. At present solar energy is utilized for commercial and domestic uses.

Large scale grid connected photo voltaic plants have been installed in different parts of the world [1]. Many of these are associated with industries. Bilateral power transfer exist between grid and these projects. Roof-top grid tied plants exclusively intended to feed grid are set up in different places. Apart from the stringent formalities demanded by the authorities, these plants face technical as well as non-technical challenges. Monsoon and rugged topography are major non-technical constraints. In technical domain leakage current, harmonics, electromagnetic interference, dead time, reactive power compensation etc are major pitfalls. Of these leakage current is a severe problem. It is a current following through undesirable path. This current can cause severe damage to grid property and deteriorate the quality of power supplied.

Transformers provide galvanic isolation and can solve the misery of leakage current. However the presence of transformer makes the system more bulky, multiple conversion stages decreases the overall efficiency. Transformer less inverters are favoured due to less weight, simple circuitry, mobility, high efficiency etc. Transformer less inverters are struck with leakage current as isolation is not possible. Recent advances in power electronics is capable of providing isolation between grid and panel during adverse conditions. These topologies facilitate AC and DC decoupling, which can separate the panel from grid connections. H5, HERIC and H6 are well versed transformer less topologies that could mitigate leakage current and can ensure more safer grounds of operation [2]. These topologies are derived from conventional H-bridge inverter by inserting additional switches. The leakage current profile of these inverters are compared with MATLAB simulations.

In this paper grid connected inverter system with conventional H bridge, H5 topology, HERIC topology and H6 topologies are studied in detail. MATLAB simulations are created for each topology. The system comprises of solar module, dc-dc converter, filter and inverter circuits. Cuk converter is employed for dc to dc conversion, LLCL filter reduces the harmonic content to standard levels. Leakage current profile of each topology is analysed. Leakage current was less pronounced in H5 topology. The paper is organised as Section II describes the leakage current in grid tied photovoltaic inverters, Section III illustrates various transformer less topologies, Section IV compares the simulation results and Section V concludes the paper.

II. LEAKAGE CURRENT ANALYSIS

Grid-Tied systems are abide to follow certain code of practice, which demand earthing of PV panels. Earthing leads to the development of parasitic capacitance between the metallic frame and earth. This capacitance develop a high voltage potential between the panel and ground. Parasitic capacitance depends on the area of solar array, height of panel above the ground, atmospheric conditions, etc. The average of individual inverter leg voltages is called common mode voltage given in equation (1)

$$V_{CM} = \frac{V_{AN} + V_{BN}}{2} \quad (1)$$

Where,

V_{AN} = Potential between “A” and “N” , V_{BN} = Potential between “B” and “N”

At high frequency of operation common mode voltage varies rapidly [3]. The rapidly varying common mode voltage generates high potential between the inverter output port and ground. When a grounded load is connected to inverter, a closed path is created and common mode leakage current flows through it. Fig.1 illustrates the path of leakage current. The parasitic capacitance is denoted by C_{pv} .

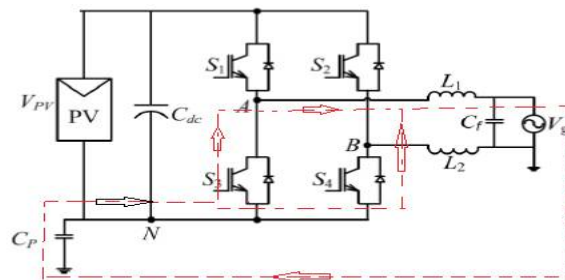


Fig.1. Leakage current path in a transformer less inverter.

Leakage current is alternating current flowing through the inverter legs, grid and ground. This leakage current cause shock hazards to consumers, initiate radiated interference on sensitive loads, super impose with grid current leading to harmonics, false tripping of residual current devices (RCDs), damage PV cells and malfunction of Power Conditioning System. The preventive strategies can be proposed after analysing the equivalent diagram of grid connected inverter. The photovoltaic system can be simplified and studied by using different theorems and principles of circuit theory. Equivalent circuit diagram of photo voltaic inverter is shown below.

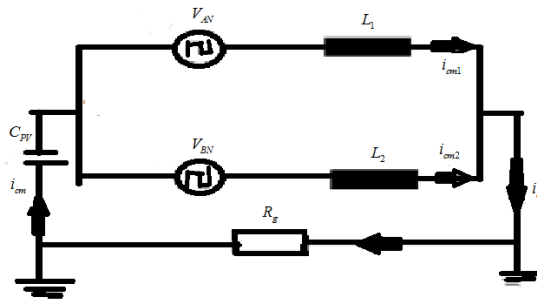


Fig.2. Equivalent circuit diagram of PV grid tied inverter

The differential mode voltage, V_{DM} can be expressed as

$$V_{DM} = \frac{V_{AN} - V_{BN}}{2} \quad (2)$$

The individual bridge voltages can be expressed in terms of common mode voltage V_{CM} and differential mode voltage V_{DM} as

$$V_{AN} = V_{CM} + 0.5V_{DM} \quad (3)$$

$$V_{BN} = V_{CM} - 0.5V_{DM} \quad (4)$$

These voltage equations together with the application of Millmanns theorem reduce model shown in Fig.3 as below.

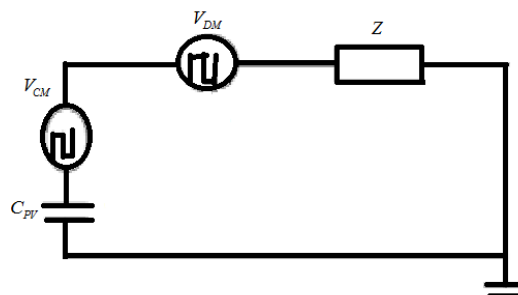


Fig.3.Simplified circuit diagram of PV grid tied system

The common mode impedance is represented by Z. Circuit theory analysis brings out four methods to reduce common mode leakage current. They are (i) Maintaining high impedance during high frequency variation of common mode voltage, (ii) Employing appropriate Sinusoidal Pulse width modulation techniques to keep V_{CM} constant, (iii) Keeping both V_{CM} and V_{DM} constant by matching circuit parameters and decreasing parasitic capacitance by placing a series capacitor in series to it. Strategy (i) is found to be the most feasible solution for obstructing leakage currents to perpetual safe levels. High impedance is created by decoupling the inverter from grid at intervals of leakage current flow. AC decoupling is employed in HERIC topology and DC decoupling is used in H5, H6 etc.

III. DECOUPLING TOPOLOGIES

With regard to the various problems caused by leakage current, its elimination is of great importance. The common mode impedance can be made high by the electrical decouple between the grid and panel. Transformer is the best

option for isolation. There are many demerits for inverters with transformers like bulkiness, high cost, multiple power conversion stages, increased losses etc. Transformer less inverters employing advanced power electronic circuits can provide electrical decoupling at predetermined intervals. These circuits can be easily interfaced with grid tied systems. Different power electronic circuits have their own distinct characteristics. Selection is done on the basis of various constraints like efficiency, switching loss, compactness, etc. Some of the most efficient topologies capable of limiting leakage current are briefed below.

(a) HERIC Topology (HIGHLY EFFICIENT AND RELIABLE INVERTER CONCEPT)

The topology generate high common mode impedance by AC decoupling technique. The circuit consists of two opposite switches placed in parallel to the load. Each switch placed in the shunt branch is active during one whole half period of grid waveform. Freewheeling of current occur through this branch preventing the internal flow of reactive power, allowing additional voltage level and limiting leakage current. The operating modes are explained below.

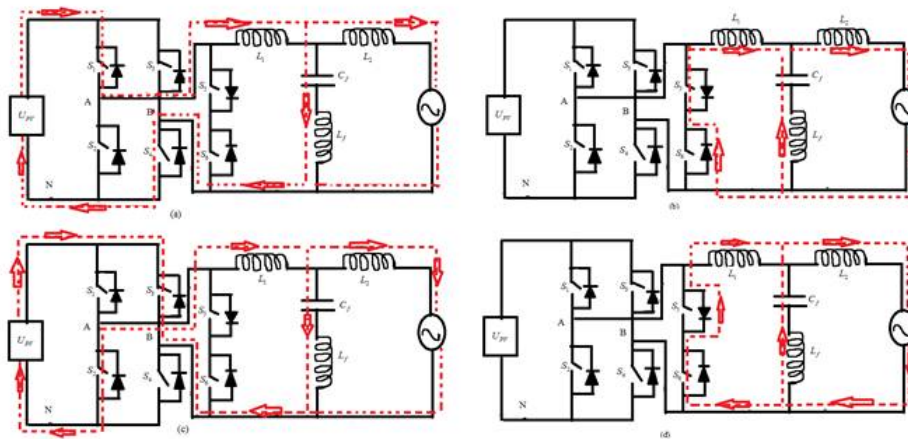


Fig.4 (a)Current path during mode-1 operation b) Current path in mode-2 operation,(c) Current path during mode 3 operation, (d)Current path during mode4 operation

Mode1: Active period of positive half cycle

During this mode switches S_1 , S_4 and S_5 conducts, all other switches are turned OFF, current flows from inverter to grid through filter. The voltages are: $V_{AN} = U_{PV}, V_{BN} = 0, V_{CM} = 0.5U_{PV}$

Mode2: Freewheeling period in positive half cycle

During this mode S_5 is ON, all other switches are turned OFF. Current from grid freewheels through S_5 and anti-parallel diode D_6 . Freewheeling current flows through the shunt branch, filter and grid, it never enter the inverter circuit. The voltages are:

$$V_{AN} = U_{PV}, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

Mode 3: Active period during negative half cycle

During this mode switches S_2 , S_6 and S_3 are turned ON, all other switches are turned OFF. Current is fed from inverter to grid through filter. The voltages are:

$$V_{AN} = 0, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

Mode4: Freewheeling period during negative half cycle

During this mode switch is turned ON, all other switches are turned OFF. Current freewheels though S_6 and diode D_5 and never enter the inverter circuit. The voltages are:

$$V_{AN} = U_{PV}, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

Study reveals that the path for leakage current is broken during freewheeling period. Freewheeling current never enter the inverter-photo voltaic panel system. In all modes of operation common mode voltage is maintained constant at $0.5U_{PV}$.

(b) H5 Topology

H5 inverter consists of an additional switch to the conventional H bridge inverter. The topology has well defined sequential switching action which can mitigate leakage current to a great extent. The switching cycle includes two periods: active period and freewheeling period. The operating modes is illustrated below

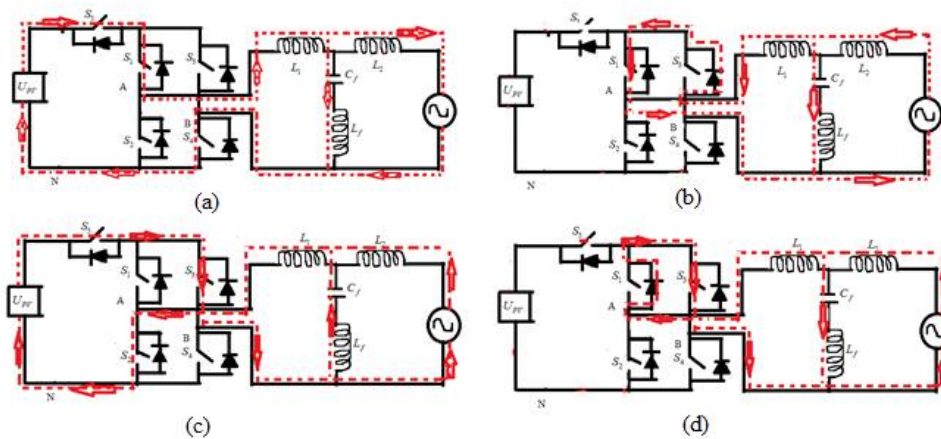


Fig.5 (a)Current path during mode-1 operation b) Current path in mode-2 operation,(c) Current path during mode 3 operation, (d)Current path during mode4 operation

Mode1: Active period of positive half cycle

During this mode switches S_5, S_1 and S_2 conduct, all other switches are turned OFF, current flows from inverter to grid through filter. The voltages are:

$$V_{AN} = U_{PV}, V_{BN} = 0, V_{CM} = 0.5U_{PV}$$

Mode2: Freewheeling period in positive half cycle

During this mode S_1 is ON, all other switches are turned OFF. Current from grid freewheels through S_1 and anti-parallel diode D_3 . The voltages are: $V_{AN} = U_{PV}, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$

Mode 3: Active period during negative half cycle

During this mode switches S_5, S_3 and S_4 are turned ON, all other switches are turned OFF. Current is fed from inverter to grid through filter. The voltages are:

$$V_{AN} = 0, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

Mode4: Freewheeling period during negative half cycle

During this mode switch S_3 is turned ON, all other switches are turned OFF. Current freewheels through S_3 and diode D_1 . The voltages are:

$$V_{AN} = U_{PV}, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

From above analysis it is evident that the PV array can be disconnected from the utility grid when the output voltage of inverter is at zero voltage level and the leakage current path is cut off. The CM voltage of the proposed topology in each operation mode is equals to $0.5U_{PV}$, and it results in low leakage current profile.

(C) H6 Topology

H6 topology is derived from H5 topology by emphasising on the switching losses. Additional switch S_6 is added to H5 topology, this switch can bypass the input supply during negative half cycle so that the number of devices in conduction decreases. The sequential mode of operation is briefed below.

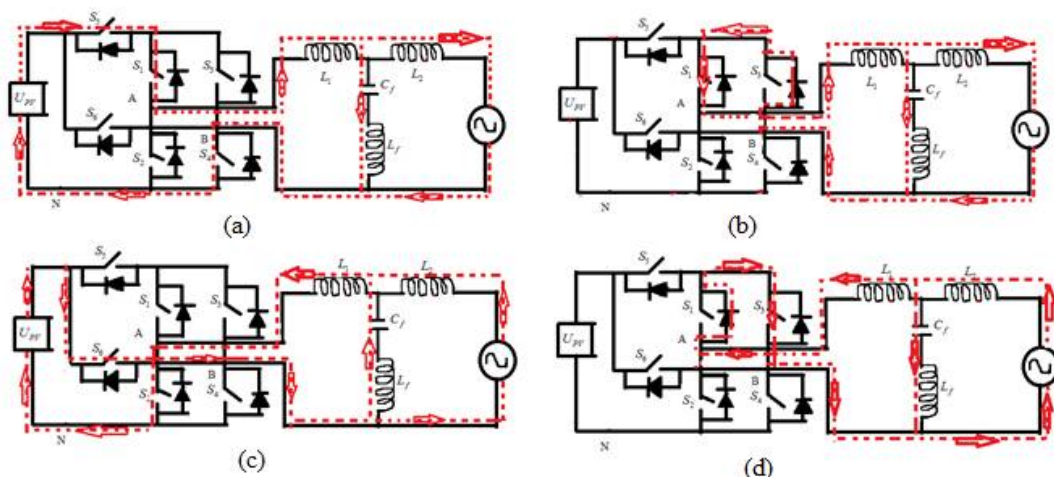


Fig.6 (a)Current path during mode-1 operation (b) Current path in mode-2 operation, (c) Current path during mode 3 operation, (d)Current path during mode4 operation

Mode1: Active period of positive half cycle

During this mode switches S_1 , S_4 and S_5 conduct, all other switches are turned OFF, current flows from inverter to grid through filter. The voltages are

$$V_{AN} = U_{PV}, V_{BN} = 0, V_{CM} = 0.5U_{PV}$$

Mode2: Freewheeling period in positive half cycle

During this mode S_1 is ON, all other switches are turned OFF. Current from grid freewheels through S_1 and anti-parallel diode D_3 . The voltages are:

$$V_{AN} = U_{PV}, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

Mode 3: Active period during negative half cycle

During this mode switches S_6 and S_2 are turned ON, all other switches are turned OFF. Current is fed from inverter to grid through filter. The voltages are

$$V_{AN} = 0, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

Mode4: Freewheeling period during negative half cycle

During this mode switch S_3 is turned ON, all other switches are turned OFF. Current freewheels through S_3 and diode D_1 . The voltages are:

$$V_{AN} = U_{PV}, V_{BN} = U_{PV}, V_{CM} = 0.5U_{PV}$$

Analysis points out that the circuit is capable of maintaining constant common mode voltage $0.5U_{PV}$ during all the four modes of operation. The AC component of common mode voltage is constant therefore leakage current is of requisite amount.

HERIC topology employs AC decoupling for isolation whereas H5 and H6 uses DC decoupling. AC decoupling is found to have complex circuit and more losses. However it is unable to process the reactive power. H5 and H6 topologies are interrelated, they possess similar modes of operation. In H6 topology even though the number of switches increases but the conduction period of switches is drastically reduced. On theoretical basis three topologies are capable of eliminating leakage current, their efficacy is compared through simulations in section IV.

IV. SIMULATION AND RESULTS

To validate the theoretical analysis simulations are done in Simulink and results are verified. HERIC, H5 and H6 topologies are connected to grid and were simulated individually. The block diagram of grid-tied system is shown in Fig-7. The system composed of a solar module, DC-DC converter, MPPT, inverter, filter and grid. Inverter is connected to grid through a filter. Solar module provide dc voltage, in real systems there is slight possibility of variations in solar output. To regulate the solar output proper tracking is required. Maximum power point tracking is implemented through perturb and observe algorithm. MPPT system modulate the switching frequency of cuk converter to facilitate constant input for inverter. LLCL filter is used to interface inverter to the grid. This filter can eliminate harmonics to a great extent. Conventional practice is to use boost converter, cuk converter has several advantages over boost converter. Cuk converter provide continuous input current, reduce ripples in output, minimize switching losses, output can be less than or greater than input etc

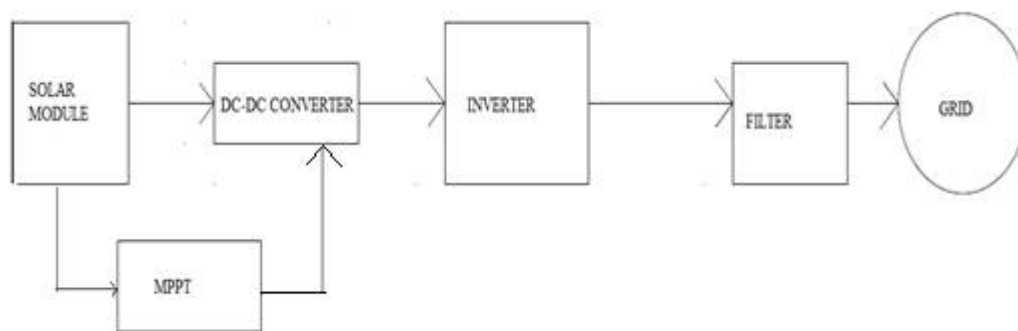


Fig.7. Block diagram of grid tied system

The simulation parameters for each block is determined on the basis of design equations. Parasitic capacitance depends on various atmospheric conditions. Internationally accepted codes specify parasitic capacitance to be taken as $0.1\mu f$. Solar module is modelled by mathematical modelling, the output from solar module is $V_{oc} = 100$ V and $I_{sc} = 2.5$ A. Cuk converter is designed with following equation:

$$\frac{V_{dc}}{V_{PV}} = \frac{-D}{1-D} \quad (5)$$

Parameters of cuk converter are $V_{dc} = 300V$ and $V_{PV} = 100V$. LLCL filter is designed on the basis of its resonant frequency and quality factor.

$$f_r = \frac{1}{2\pi\sqrt{L_f C_f}} \quad (6)$$

$$Q = \frac{1}{R_f} \sqrt{\frac{L_f}{C_f}} \quad (7)$$

$$f_r = 7.6 \text{ KHz}, Q = 20, L_1 = 0.026\text{mH}, L_2 = 0.22\text{mH}, C_f = .00079 \mu\text{f}, L_f = 32 \mu\text{H}$$

For the inverter side design, Switching frequency = 1 KHz

Grid voltage = 230V

Grid reference current = 10 A

Different inverter topologies are simulated to plot the leakage current. The three level inverter output voltage, grid voltage, grid current and leakage current are plotted. Unipolar pulse width modulation is used for generating gate signals. The output waveforms of H5 inverter is shown in Fig-9. Square wave output was obtained from inverter. The inverter is tied with grid through a filter. The grid voltage and current was found to be of sinusoidal nature. Leakage current was observed to be of alternating nature.

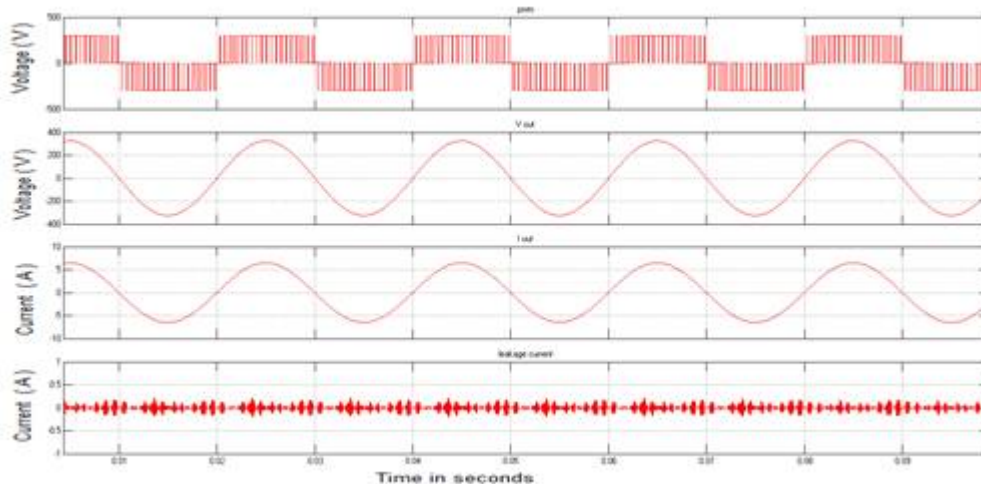


Fig.8 (a) Inverter output voltage b) Grid voltage (c) Grid current, (d) Leakage current

Leakage current profile of conventional H-bridge inverter is also simulated. The leakage current waveforms of H4, HERIC and H6 are shown in Fig-10. Inverter output which is a square waveform was similar for all topologies.

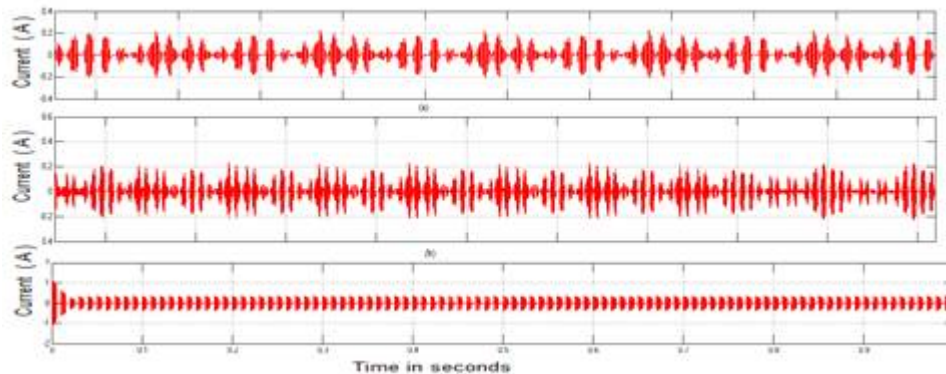


Fig.9 Leakage currents (a) H4 topology,(b) H6 topology,(c) HERIC topology

The leakage current was observed to be alternating. The nature of waveform was similar for conventional H-bridge and DC decoupling topologies. The waveform of HERIC topology showed a different pattern. The observations are assembled in Table-1

Table-1 Simulation Results in different topologies

TOPOLOGY	CONTROL	INPUT DC	GRIDAC VOLTAGE	SWITCHING FREQUENCY	LEAKAGE CURRENT
H-Bridge	Unipolar PWM	300V	230V,50Hz	1 KHz	472mA
H5					24mA
H6	Square Pulse			50Hz	92mA
HERIC					132mA

Simulations were performed to trace out the deterministic factors of leakage current. Many variations were made two of them were found worthy. The leakage current was found to vary with input DC voltage. Leakage current is directly proportional to solar output voltage and is independent of grid voltage. Parasitic capacitance was varied to find the leakage current behaviour. Leakage current increased with increase in parasitic capacitance. Leakage current varied inversely to increment in switching frequency. Results are illustrated in Table-2 and Table-3

Table- 2 Parasitic Capacitance C_{pv} and Leakage Current

Parasitic Capacitance C_{pv}	Leakage Current
0.1×10^{-6} F	0.0539A
0.1×10^{-5} F	0.2389A
0.1×10^{-4} F	0.6094A
0.1×10^{-3} F	0.9234A
0.1×10^{-2} F	2.092A
0.1×10^{-1} F	2.468A

Table- 3 Switching Frequency and Leakage Current

Switching Frequency	Leakage current
1KHz	.0539A
2KHz	0.0435A
5KHz	0.0124A
10KHz	0.0010A
25KHz	0.0009A
50KHz	0.0004A
100KHz	0.0003A

The inverter output, grid voltage and grid current was found to be similar in all topologies. Leakage measured was in H4, HERIC, H6 and H5 topologies. The inverter output, grid voltage and grid current followed the same pattern in all topologies. There occurred noticeable changes in the magnitude of leakage current. H5 topology offered the minimum leakage current. Cuk converter at input side could eliminate ripples in the input voltage. LLCL filter could eliminate harmonics and gave a far better THD.

V. CONCLUSION

Leakage current in different transformer less topologies were compared. Impetus variations in common mode voltage and parasitic capacitance were the root causes for leakage current. Leakage current was found to be of hefty magnitudes and much more enough for derailing the normal Power Conditioning System. H5 topology gave minimum leakage current. The system could reduce potential variations of bridge voltages with respect to ground. Leakage current obtained was within the safe limits. The leakage current profile obtained satisfies standards pertaining leakage currents. There exists topological relation between DC coupling circuits, they gave better results than AC decoupling circuit. Even though H6 has more number of switches than H5, conduction period is small hence losses are fewer comparing with H5. Articulation of LLCL filter and cuk converter make the system intractable for harmonics as well as ripples. When overall efficiency is considered H4 is the best as it has least losses. However in leakage current perspective H5 is the best.

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