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Leakage Current Paths in PV Transformer-Less Single-Phase Inverter Topology and Its Mitigation through PWM for Switching

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ABSTRACT

The Photovoltaic (PV) is a part and parcel and well known for cost-effective and easy to operatefeatures when it is used with transformer-less inverter-based grid-tied distribution generation systems. It reduces the leakage current issue that actually occurs making paths from PV penal to ground. In this paper has been addressed this issue as main problem for reducing leakage current. Moreover, here iscompared the proposed topology's results to AC and DC-based transformer-less topologies. The possibilities of larger number of leakage current paths indicatepower loss, which is the focus of work in this paper for different switching conditions. The results on leakage current paths using PSpice with different parasitic capacitance values from inverters of different topologies are compared with the simulation results of the topology proposed in this paper.

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1. INTRODUCTION

Electrical generation using coal, oil and natural gas are commonly used, however, most all of these sources haveresultedintopolluting our environment. Besides having been the main reason for many of us with environmental concerns, such kinds of production are not only despicable ratherthey areleading to having ourresources getting closer to depletion. In the case of having energy generated from renewable means, such as solar, wind, biomass, hydrogen, geothermal, ocean energies are most reliable, the sources do not suffer from the dilemma of extinction. Furthermore, it is actually environmentally beneficial and energy efficient as well. In between all of those renewable sources of energy, solar and wind are more convenient and efficient in the case of electrical power generation [1] and countries have been getting significant benefits from these two types of renewable, include Japanese, Cypriots, Chinese [2]-[4]. Ignoring the limitations of using solar (high frank cost, large area required, sunny area required, no night time functionality and so on) and wind energy needing availability of wind, killing birds, with low energy density, with turbine producing noise besides having to use large area of land, and so on), the benefits are too high and profitable as well as useable for different sectors in both developed and undeveloped counties [5].

Here, the Figure 1 is actually showing that how solar cell gets energy from the sunlight, which is pure and cost free. As a result, it can be taken as much as energy from the solar cells that actually have been getting through the ray of light. On the other hand, inside of the solar cell has photon that has p and n channel where it can possible to get electricity. After that, it can be controlled and transfered to battery as loaded.

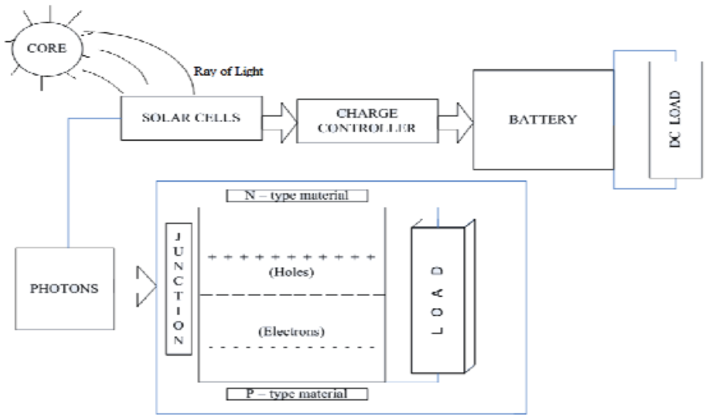

Figure 1. Solar cells are getting energy from the sun

The PV panels are used stand alone and or even connected to grid; in both of the cases, power conditioning and regulation make up the core components. Moreover, day-by-day, PV panel isbecoming a part and parcel for distribution power generation [6]-[8]. In the case of grid tied solar generation, inverters become the second core components to be used; inverter may be transformer-based or transformer-less. However, in both cases, it does very good performance and expected outcome. PV panel actually works to manage DC current that actually converted to AC through inverter, although the main concentration is clean the environment as much as possible [9], [10]. To do so, transformer is highly needed to make the system proper handed. Where the PV panel is used as for DC signal achieving, but other side of the system is connected to grid that isused for AC signal. In addition, Grid connected inverter is nowadays highly popular to get high range of power point over the system where the maximum points are developed through analog maximum or normal point tracking methods [11]. Previously isolation transformer-based topology had highly populated, although the main predicament is size, cost and efficiency. In contrast, to recover these problems, the best solution would be used no transformer-based topology for both cases single phase and three phase [8]. As for getting smaller weight, low cost and high efficiency system no transformer topology is the best solution where the galvanic isolation is not included, the main problem can be seen that is common mode leakage issue which is actually the reason of reducing the efficiency and increasing the loss [8], [12]-[13].

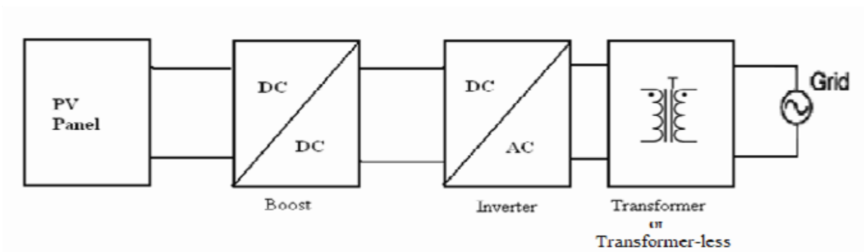

Figure 2. The overall system either transformer-based or transformer-less

On a commercial scale generation, large number of solar photovoltaic (SPV) cells is connected for making a solar panel module, and all such modules are connected in parallel as a single generation structure before tied to utility grid using power conditioner circuits as shown in Figure 2.

The common mode leakage issue is the serious problematic issue today's situation. It actually occurs in between the PV panel to ground through parasitic capacitor. However, it has different current paths such as inverter to ground, PV panel to ground, filters to ground and so on. As for reducing the leakage issue, most important and effective way is switching configuration that can be done through Pulse Width Modulation (PWM). In addition, this paper is about to finding the paths of leakage issue and to reduce the common mode leakage issue for transformer-less topology by using PWM condition.

2. PROTOPOLOGY WITH LEAKAGE PATHS

In this approach is a transformer-less topology, which is actually made by AC and DC decoupling with nine switches. AC decoupling has two switches that connect with output of inverter and DC decoupling has two switches after DC signal that control the DC signal. Moreover last switch is connected after AC decoupling which is helping to get signal for EMC filter. Here used a full bridge inverter with four switches. Figure 3 shows the approach topology with EMC filter with transfer function and related figures.

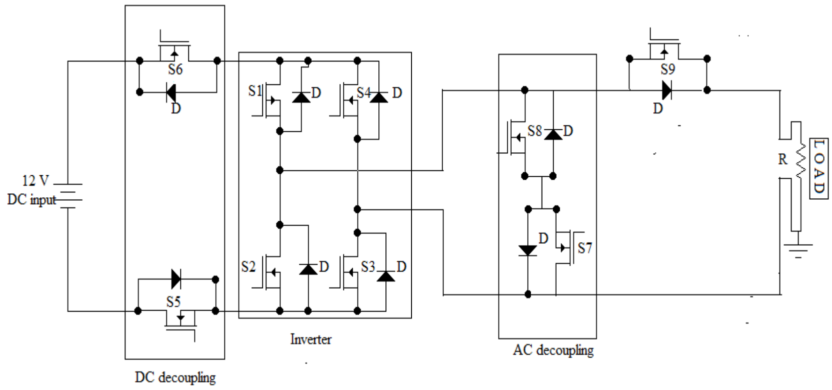

Figure 3. Approach topology

Moreover, Electromagnetic compatibility (EMC) filter [14] is used for filtering purposes. However, the transfer function of EMC filter indicates one low frequency component shownbelow with appropriate transfer function, equivalent impedance and theoretical curve as well.

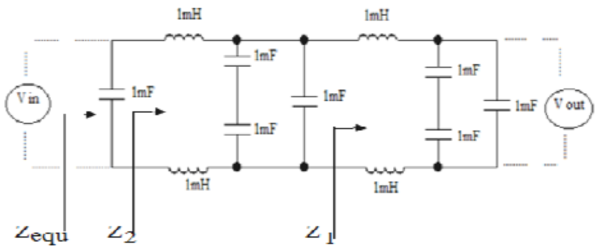

Figure 4. EMC Filter with 10V, 50Hz input [15]

In Figure 4 is shown the diagram of EMC filter, for the assumed inductance and capacitance values of a 1mH and 1mF respectively, the transfer function, H (s) =VO(s) /Vi(s), is derived as accordingly.

At afrequency is ω,and capacitance and inductance are L and C respectively, the the frequency response for the above filter is as shown:

$$Z_1 = \left(\frac{1+j^2 3\omega^2 LC}{j1.5\omega C}\right)$$

$$Z_2 = \left(\frac{1-9\omega^2 LC+9\omega^4 L^2 C^2}{\omega C(3j-4.5\omega^2 LC)}\right)$$

$$Z_{equ} = \left(\frac{1-9\omega^2 LC+9\omega^4 L^2 C^2}{9\omega^4 LC^3+9j\omega^6 L^2 C^4-4\omega^2 C^2-4.5j\omega^4 LC^3}\right)$$

Figure 5 shows the current directions of EMF filter, which is needed for find out the transfer function. The overall current by Ohm's law is given:

$$I = \frac{V_{in}}{Z_{equ}}$$

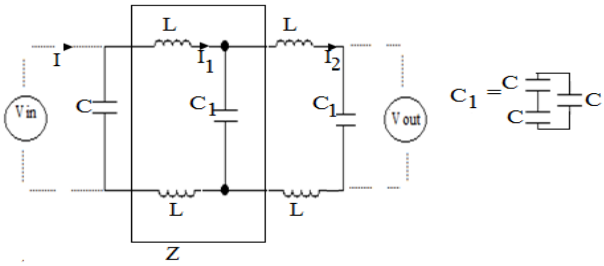

Figure 5. Current directions for finding transfer function

Now using the Kirchhoff's circuit laws below shows the divided two current values where impedances values are shown above.

Current, $I_1 = \frac{\frac{1}{j\omega C} * I}{\frac{1}{j\omega C} + Z_1} = \frac{I}{1+j\omega CZ_1} = \frac{V_{in}}{Z_{equ}(1+j\omega CZ_1)}$

and Current , $I_2 = \frac{ZV_{in}}{Z_{equ}(Z+Z_1)(1+j\omega CZ_1)}$

Now the output Voltage is $V_{out} = \frac{ZV_{in}}{Z_{equ}(Z+Z_1)(1+j\omega CZ_1)} * C_1$

Now the Transfer Function (TF):

$H(j\omega) = V_{OUT}/V_{IN} = \frac{ZC_1}{Z_{equ}(Z+Z_1)(1+j\omega CZ_1)}$

Now in the case of impedance of using EMC filter is in below Figure 6 where $X_L$is the inductor impedance while X_C is the capacitance impedance and the equivalent impedance isZ_{equ}.

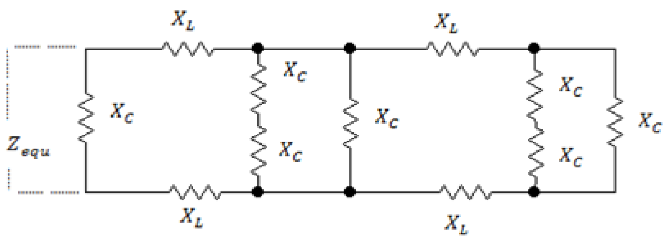

Figure 6. Equivalent impedance of EMC Filter

Now,

$$Z_{equ} = \left(\left(\begin{matrix} 3.1416 + 3.1416)||3.1416) + (0.31416 + 0.31416))| \\ |(3.1416 + 3.1416)||3.1416)) + (0.31416 + 0.31416) \end{matrix} \right) || + 0.31416 \right)$$
$$= 0.26774 \text{ ohm}$$

On the other hand, the theoretical waveform plot of the EMC filter is as shown in Figure 7 where the input voltage of 5V at 50Hz is used. The input switching at 50Hz is making the current to make and break through the series inductances, producing a kind of voltage boosting phenomenon, which is supported by the parallel capacitances. As for using this type of inductances and capacitances based EMC filter the 5V amplitude is increased to a value at around 23.932V peak value.

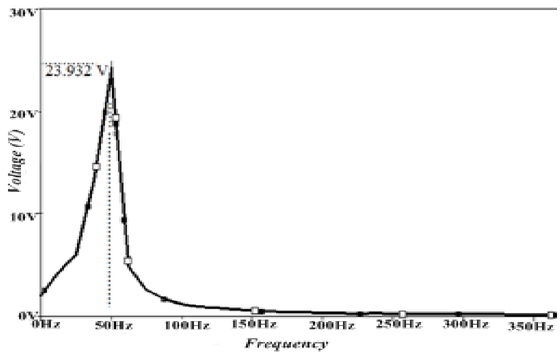

Figure 7. Plot of EMC Filter for 5V input with 50Hz frequency

Leakage currents occurring at different points along the path from PV Panel to grid areas shown in Figure 8, including PV panel, switches, and filter and load as well. Actually leakage current flows in from both sides of PV panel through Parasitic Capacitance (PC) [16]. Here the using inverter is full bridge where four switches are connected with inverting manner and leakage current flows in between two switches. One path is in between M1 and M2 while another path is in between M3 and M4. Here is drawn the diagram where shows the different paths and current flowing direction. Moreover, itshows the place where the common mode valotage (CMV) is developed in the transformer-less inverter based topology in PV-grid tried system.

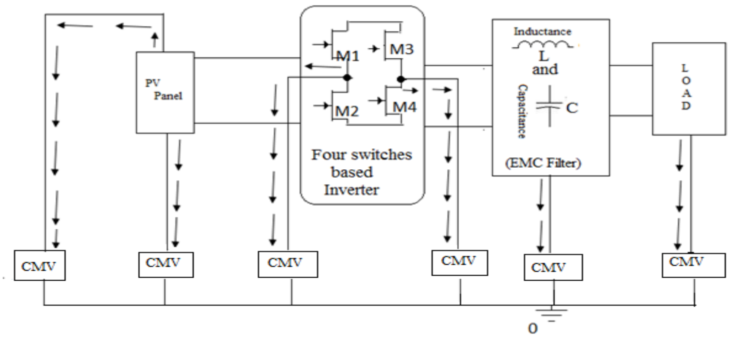

Figure 8. Different leakage current paths

3. LEAKAGE CURRETNT MITIGATION SIMULATION DETAILS

In Figure 9 below is a DC-decoupling based transformer-less inverter topology which is helped to switch the DC value and below use the Duty Ratio to see the effect of switches in the system which can be verified by output voltage and also changes of Leakage current where only one path (PV panel to ground)is consider.In the case of 50% duty cycle in Table 1 when switch S1 and S3 is in on S2 and S4 is in off mode that works is in opposite direction and S5 and S6 is the DC decoupling switches. After using the six switches in 50% duty ratio, output voltage can be got more than 10.5V, but the leakage current is occurred more that varies from 110.309uA to 1.1523mA. Here selected only one leakage path.

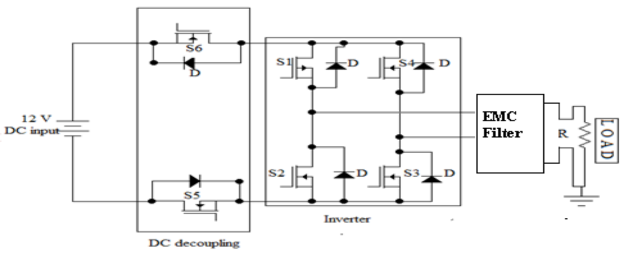

Figure 9. DC-decoupling based transformers-less inverter topology [17]

Table 1. 50% duty cycle of inverter switching condition uses for DC decoupling topology

S1	S2	S3	S4	S5	S6	Vout	LC (A)
ON	OFF	ON	OFF	ON	OFF	10.546V	1.0789m
OFF	ON	OFF	ON	OFF	ON	10.546V	1.0727m
ON	OFF	ON	OFF	OFF	ON	10.538V	110.309u
OFF	ON	OFF	ON	ON	OFF	10.538V	1.1523m

In the case of 75% duty cycle when leakage current has occurred throughonepath that has been shown in Table 2 for DC decoupling, when switch S1 and S3 is in on mode than the switches S2 and S4 is in off mode that works is in opposite direction and S5 and S6 is the DC decoupling switches that fixed in 50% duty ration and after using the inverter switches in 75% duty ration and rest of the two switches which are DC decoupling switches are fixed in 50% duty cycle, output voltage can be got more than 10.5V which is approximately similar with 50% duty ration but the leakage current is occurred which is reduced from the 50% duty ration that varies from 129.09u to 1.1869m Amp.

Table 2. 75% duty cycle of inverter switching condition uses for DC decoupling topology

S1	S2	S3	S4	S5	S6	Vout	Lekage Current
ON	OFF	ON	OFF	ON	OFF	10.526V	129.09uA
ON	OFF	ON	OFF	OFF	ON	10.531V	12.922uA
ON	OFF	ON	OFF	OFF	ON	10.521V	2.2429uA
OFF	ON	OFF	ON	ON	OFF	10.538V	1.1869mA

In below Figure 10 is an AC-decoupling based transformer-less inverter topology which is helped to switch the AC value and below use the Duty Ratio to see the effect of switches in the system which can be verified by output voltage and also changes of Leakage current where only one path (PV panel to ground) is consider.

In the case of 50% duty cycle in Table 3 when switch S1 and S3 is in on and S2 and S4 is in off mode that works is in opposite direction and S5 and S6 is the AC decoupling switches. After using the six switches in 50% duty ration, output voltage can be varied from 9.35V to 10.283V, but the occurring leakage current is occurred more compared to using DC-decoupling system that varies from 1.47m to 75.843m Amp.

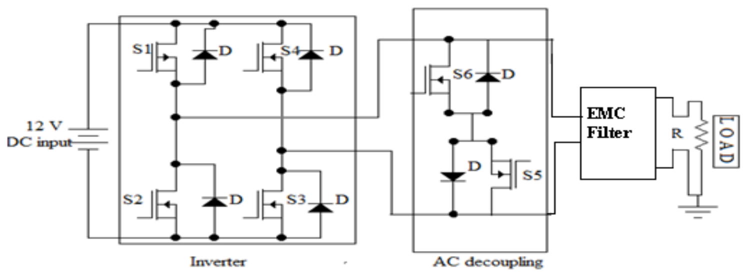

Figure 10. AC-decoupling based transformers-less inverter topology [18]

Table 3. Duty Cycle of 50% of inverter and different switching conditions are used for AC decoupling topology

S1	S2	S3	S4	S5	S6	Vout	Leakage Current
ON	OFF	ON	OFF	ON	OFF	9.3485V	1.5209mA
OFF	ON	OFF	ON	OFF	ON	10.283V	1.9483mA
ON	OFF	ON	OFF	OFF	ON	9.750V	1.4732mA
OFF	ON	OFF	ON	ON	OFF	9.982V	75.843mA

The case of 75% duty cycle in Table 4 for AC decoupling, when switch S1 and S3 is in on mode than the switches S2 and S4 is in off mode that works is in opposite direction and S5 and S6 is the AC decoupling switches that fixed in 50% duty ration and after using the inverter switches in 75% duty ration and rest of the two switches which are AC decoupling switches are fixed in 50% duty cycle, output voltage can be got more than 9.5V which is approximately similar with 50% duty ration of AC-decoupling based system but in the case of leakage current that shows more than 39m Amp.

Table 4. 75% duty cycle for inverter and different switching conditions are used for AC decoupling topology.

S1	S2	S3	S4	S5	S6	V out	Leakage Current
ON	OFF	ON	OFF	ON	OFF	9.3486V	1.5209mA
ON	OFF	ON	OFF	OFF	ON	9.745V	39.604mA
ON	OFF	ON	OFF	OFF	ON	9.745V	39.532mA
OFF	ON	OFF	ON	ON	OFF	9.986V	73.782mA

In below in Figure 11, shows the leakage paths of our proposing topology where has been shown the different paths that actually flows from inverter, PV panel in both sides, EMF filter, load and all are flowed through ground.

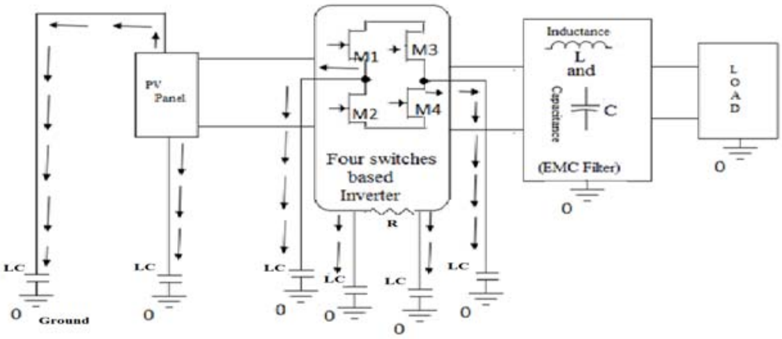

Figure 11. Approach topology where leakage paths are shown

Now in below, shows the switching conditions of approaching topology in tabular form in Table 5 and 3.6 for 50% and 75% duty ratio respectively.

Table 5. 50% duty cycle of inverter and different switching conditions are used for Approach topology

.S1	S2	S3	S4	S5	S6	S7	S8	S9	Vout	Leakage Current
ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	8.32V	-646.21nA
OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	8.32V	373.997pA
ON	OFF	ON	OFF	OFF	ON	ON	OFF	ON	8.81V	-153.45nA
OFF	ON	OFF	ON	ON	OFF	OFF	ON	OFF	8.81V	-541.75fA

Here in Table 5 and 6 are shown some switching conditions where inverter switches are fixed 50% and 75% duty ratio respectively while the other switches are conducted in 50% duty ration, hence it is clear to observe that in my approaching circuit output voltage is around 8.5V and the occurring leakage current is very small amount in pico and nino range and 75% duty cycle shows reducing leakage current compared to 50% duty ration. Indeed, in both cases leakage current shows very small range.

Table 6. 75% duty cycle of inverter and different switching conditions are used for Approach topology

S1	S2	S3	S4	S5	S6	S7	S8	S9	V out	LC (A)
ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	8.3152V	99.474n
ON	OFF	ON	OFF	OFF	ON	OFF	ON	OFF	8.3188V	373.997p
ON	OFF	ON	OFF	OFF	ON	ON	OFF	ON	8.319V	-692.7n
OFF	ON	OFF	ON	ON	OFF	OFF	ON	OFF	8.8010V	-41.75f

4. RESULT AND DISCUSSION

Leakage current has occurred in different places and when it issimulated after constricting together the value of leakage current for PV panel to ground is changed from when we consider in one path that has been shown in above in a tabular form. Below is shown five considering paths where leakage current is occurred. Meanwhile, these leakage current wave shapes are shown for both 50% and 75% duty cycle as well. In Figure 2-6 is shown the different paths of occurring leakage current in a transformer-less system where load and filter is grounded and inverter leakage current is flowed from two side one side is considered as before tiny resistance when R=10Ω and another one is after using this resistance as well.

Below has been shown the simulations of using two duty cycles (50% and 75%) for proposed transformer-less topology.

4.1. 50% Duty Cycle

a) PV Panel to Ground:

The leakage current shows in Figure 12(a) where it occurs in between PV panel to ground when all leakage current is flowed by different paths where leakage current flows around -3.4048ηA to 291.856µA and it shows fluctuation in negative direction as well.

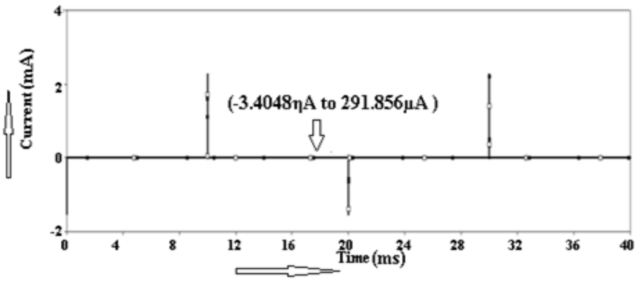

Figure 12(a). Leakage current in between PV panel to ground

b) Inverter Side Before and After Using Tiny Resistance:

Leakage current has been shown on the inverter side and it shows very high before using a tiny resistance. Here we haveused 100 Ωohm resistance to see the effect of leakage current in the inverter, hence in Figure 12(b) shows the leakage current in inverter without any effect of resistance that got -578.8p A to 8.633n A, however, this value can be reduced after using a 100 ohm resistance that shows in Figure 12(c) and the range is around -76.977fA to 4.6677nA.

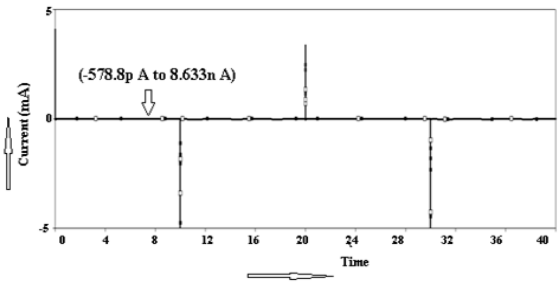

Figure 12(b). Leakage current of an inverter

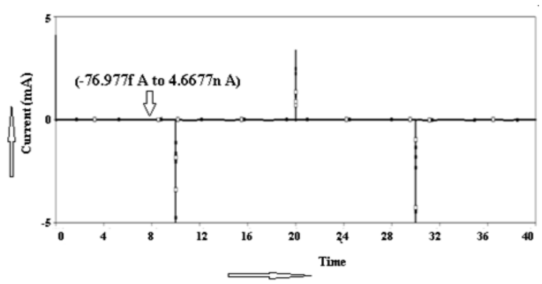

Figure 12(c). Leakage current of an inverter after using tiny resistance

c) In Between Switches S1 and S2:

In between Switch S1 and S2, the leakage current flows in -193.42n A to 215.619uA range, however, in the switching on/off time leakage current occurred highly. In Figure 12(d) shows the leakage current of this point that show for two full cycles.

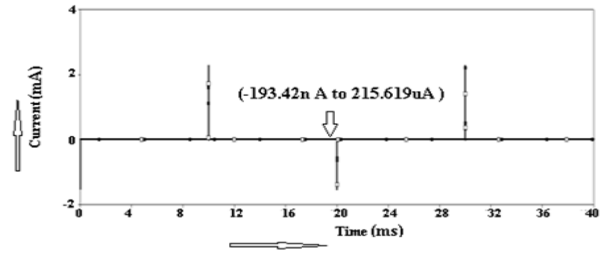

Figure 12(d). Leakage current in between switch S1 and S2

d) In Between Switches S7 and S8:

The leakage current is also occurred in between AC decoupling switches M7 and M8, in additionally, this flowing current is fluctuated and varying from -248.224p A to 78.739u A and in switches on and off both time it flows around 0.5m A that shows in Figure 12(e).

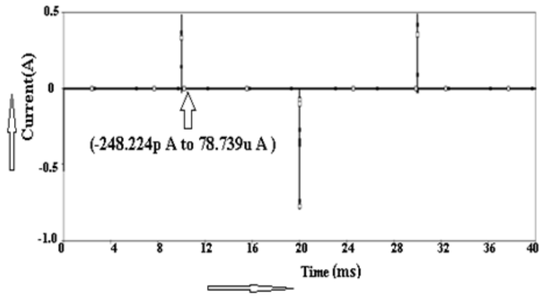

Figure 12(e). Leakage current in between AC decoupling switches

4.2. 75% Duty Cycle

a) PV Panel to Ground:

The PV panel to ground has been flowed the leakage current which is different from the 50% duty cycle. Here the leakage current is varying from -773.21ηA to 235.63µA whereas it had around -3.4048ηA to 291.856µA range. Here the leakage current fluctuates but one few seconds it is shown in milli range current, on the other hand, the maximum current flows in negative side which is shown by Figure 13(a).

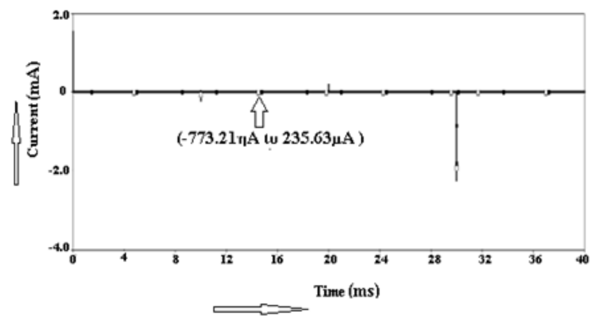

Figure 13(a). Leakage current in between PV panel to Ground

b) Inverter Side Before and After Using Tiny Resistance:

Inverter actually used to inverter the DC signal to AC signal, to do so the leakage current is occurring in the inverter side and this current is -110.44n A to 606.701p A, however, this value can be minimized through using a resistance, hence this values goes down to 1.1618η A to 15.547pA. In Figure

13(b) and Figure 13(c) are shown the waveform of the leakage current that actually occurred in the inverter and after using tiny resistance respectively.

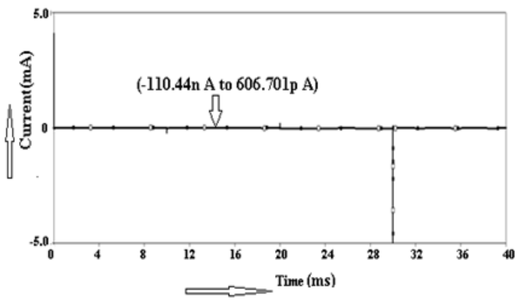

Figure 13(b). Leakage current shoes in the inverter

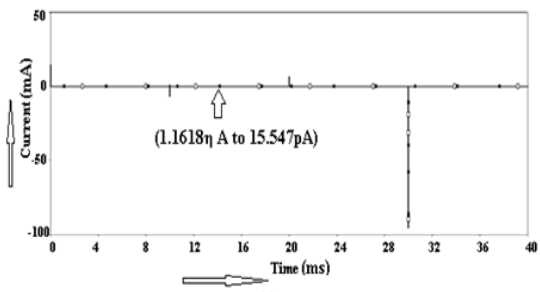

Figure 13(c). Leakage current of an inverter after using 100 ohm resistance

c) In between switches S1 and S2:

Switches S1 and S2 are added on one side of the inverter where the leakage current is occurred in between these two switches and this value is 994.2ηA to 19.375µA, hence the leakage current is very small amount compared to 50% duty cycle as well. In Figure 13(d) shows that leakage current by wave form.

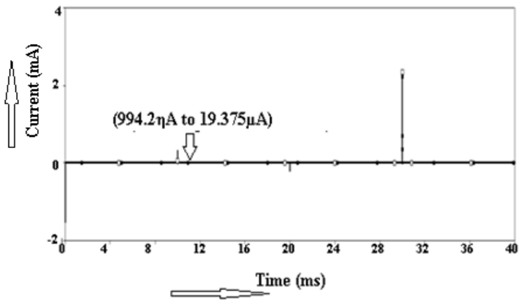

Figure 13(d). Leakage current in between switch S1 and S2

d) In Between Switches S7 and S8:

In AC decoupling of my approaching system can be seen that the leakage current is very small amount and that also small compared to 50% duty cycle. Moreover this range is varying from -321.162p A to 796.077u A that shows in Figure 13(e).

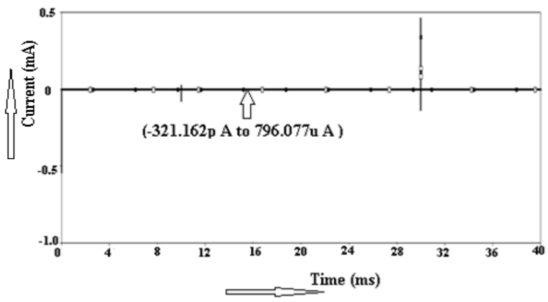

Figure 13(e). Leakage current in between AC decoupling switches in 75% duty ration

5. CONCLUSION

Transformer-less topology is well known for cost-effective and easy to operate in inverter-based grid-tied distribution generation systems. It is reduced in size and weight, which is its advantage but is associated with the problem of common mode voltage development; hence leading to having leakage current and power loss as a result, this is a power loss component as well safety concern. In this paper has been addressed the issue of leakage currents, and to show how such current can be reduced by using PWM of varying Duty Cycle for switching devices. Hence, here compared the proposed topology's results to AC and DC based transformer-less topologies. The possibility of larger number of leakage current paths and how such currents are making power losses are elaborated to show how such current paths develop many switches and the ground. A hybrid of AC decoupling and DC-decoupling is proposed in a suggested inverter topology. This topology is tested for varying Duty Cycle values of PWM to show how the suggested topology has been effective in having leakage current reduced in nano, pico and fico range where as other two topologies are in milli and micro range.

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