Common Mode Leakage Current Analysis of 1-Φ Grid-Tied Transformer Less H-Bridge PV Inverter

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***Abstract*-Grid-connected applications of renewable energy sources (solar energy) are increasing day by day. For these applications, transformers play an important role in facilitating galvanic isolation and suitable voltage ratio for interconnection between grid and inverter. However, the omitting of the transformers from the complete power conversion system becomes inevitable because of having large size/weight and cost. Hence transformerless inverters are replacing conventional inverters for grid-connected PV systems at a rapid pace. It has been observed that a transformerless grid-connected H bridge inverter established a common mode resonant circuit with the formation of parasitic capacitance between PV terminals and grounded frame and hence, consequently, leakage current induced in the system. In this paper, a mathematical model has been derived by using source transformation approach for the common-mode resonant circuit of H bridge grid-connected PV inverter, and further, it has been analyzed for both unipolar and bipolar modulation strategies. Finally, a 1 kW grid-connected single-phase H bridge PV inverter has been simulated on Matlab and verified with satisfactory results.**

Index Terms-- **PV inverter, transformerless PV inverter, VSI, CMV, Leakage current, UPPWM, BPPWM etc.**

I. Introduction

Renewable energy is dominating over conventional energy sources because of having various advantages such as an infinite source of energy, free of cost, pollution-free, no running cost, and requires minimum maintenance, etc. [1]. Amongst all renewable energy sources; solar energy is very popular because of it's availability with free of cost and can be utilized at the consumer end with the help of solar panel and suitable power converter. The most costly part of grid-connected PV system is solar panel, while inverter cost is only 10 to 20 % cost of the total system[2]. PV inverters require regular maintenance in every 5-year block period that is not economical for users. So PV inverters should be designed in such a way that it has low cost, highly reliable, highly efficient, less leakage current, less DC injection in grid current, smaller in size and weight[3][4].

Grid-connected PV inverter has two types depends on the conversion stages from DC generated by a solar panel to the AC utility grid; are Single stage and two stages. In a single-stage conversion system, the PV panel is connected to grid utility by utilization of an inverter, and generated DC power from the PV panel has to be converted into AC directly. This technique is popular because of minimum converter losses, and reduced complexity of control compare to two stages [5]. In this technique, inverter requires high DC-link voltage, and that can be fulfilled by connecting many PV panels in series form; however, this technique has one drawback that of not getting proper high DC voltage if any panel gets damaged or affected by shadowing effect. In the case of two stages of power conversion, two converters are used; one is DC/DC boost converter to boost the DC-link voltage, and the other one is DC/AC inverter, which maintains a good quality of sinusoidal voltage that should be matched with grid voltage phase and frequency. In both conversion cases, viz: single stage and two stages, there have been two possibilities; a grid-connected PV system with a transformer and a grid-connected PV system without a transformer. Mostly, these transformer's primary windings are connected with the inverter output terminal, and secondary is connected with the grid. They operate at 50/60 Hz low power frequency; hence the system

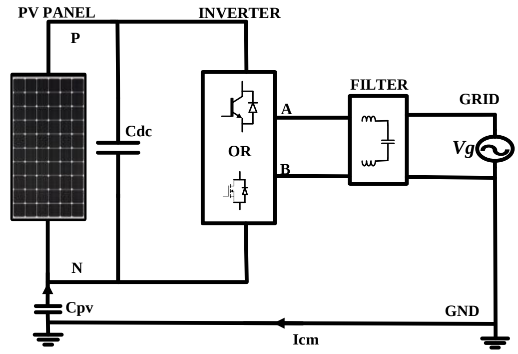

Fig .1. Block diagram of single phase GCTLPVI

becomes bulky, costly, and less efficient and needs more space for installation. To overcome these drawbacks of using LF transformer, HF (high frequency) transformers have been introduced with DC to DC isolated converter to boost DC-link voltages before feeding power to the inverter, in a grid-connected PV system. However, the implementation of HF transformer increases complexity to control the DC/DC converter.

Use of transformers becomes necessary in either AC side (between inverter filter and grid) or DC side (in isolated DC

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to DC converter) because of the following reasons:
1) To match inverter terminal voltage with grid voltage;
2) To provide galvanic isolation between PV and grid;
3) To provide safety for the living body including human being;
4) To prevent DC injection into grid.

However, when we remove the LF transformer from the single-stage conversion system, the requirements mentioned above must be fulfilled by the inverter. But as soon as we remove transformers from the system, then a galvanic connection takes place between grid and PV, and forms a resonant circuit through the formation of parasitic capacitance between PV terminals and grounded frame. That resonant circuit provides the path for a leakage current that will flow from grid to PV panel, through parasitic capacitance. The induced leakage current causes various issues like human safety, increased THD in grid current, reduces the efficiency of the system, and generates conducted EMI, which can affect the performance of the connected nearby devices[6].

German VDE-0126-1-1 standard that specifically deals with transformerless PV systems regarding fault and leakage current levels. According to that German standard, three different currents have to be monitored[7]:

• Ground Fault current, which happens in case of insulation failure when the current flows through the ground wire;

• Fault current, which represents the sum of the instantaneous values of the main currents, that in normal conditions leads to zero;

• Leakage Ground currents, which is the result of potential variations of capacitive coupled parasitic elements.

The monitoring is typically done using a Residual Current Monitoring Unit(RCMU), which measures the fault and leakage current of the whole system. The standard states that disconnection from the grid is necessary within 0.3 s in case if the peak of leakage current reaches 300 mA[7]. Furthermore, it recommends a table detailing the Root Mean Square (RMS) value of the fault/leakage current jumps and their respective disconnection times, as summarized in Table I.

TABLE I
RELATION BETWEEN LEAKAGE CURRENT RMS VALUE AND DISCONNECTING TIME OF PV SYSTEM FROM THE GRID (DIN VDE 0126-1-1)

Leakage current (mA)	Disconnecting time (S)
30	0.3
60	0.15
100	.04

For example, from the Table I, in case where the RMS value of the leakage current reaches by 30 mA, then disconnection of PV panel from grid is mandatory within 0.3 S. This way in case of a fault, or severe flow of leakage ground current crosses the limits, the system should be disconnected and de-energized.

In this paper, common-mode resonant circuit modeling of H-bridge inverter using source transformation approach has been performed in section II. In section III, simulation parameters of the system are tabulated and results are discussed, and finally, the conclusion is summarized in section IV.

II. COMMON-MODE RESONANT CIRCUIT MODELING

For the circuit diagram as depicted in Fig. 2, full-bridge (H-bridge) inverter is VSI, which is converting DC power from the PV panel to AC power grid utility. Parasitic capacitance forms between the positive and negative both terminal of PV with respect to the grounded frame of the panel. However, here both capacitances are combined and represented as Cpv to show their cumulative effect on the leakage current. This

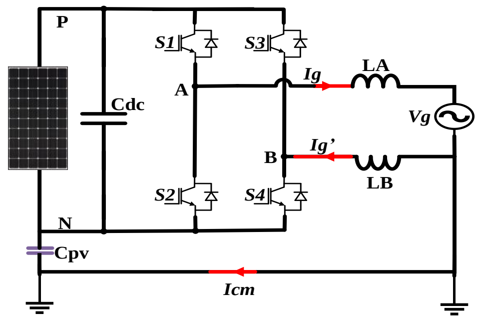


Fig .2. Flow of leakage current in single phase H-bridge GCTLPVI

value of Cpv may be in the range of 50-150 nF/kW for normal weather conditions. Therefore, for experimental purpose an approximate value of 100 n*F* has been taken as emulated parasitic capacitance for 1 kW prototype system. A full-bridge inverter has been connected between the PV panel and utility grid, as shown in Fig. 2. There are two pole voltages V_{AN} and V_{BN}, and their values depend on the switching states produced by the PWM modulation techniques. If the upper switch is on, the pole voltages will be +Vdc volt, and if the lower switch is on, then pole voltages will be zero volts. These states alter at switching frequency. The path of leakage current I_{cm} has been shown in Fig. 2, which circulates clockwise in both phase and neutral wire of inverter's connection.

Any inverter requires to have better common-mode characteristics as well as better differential mode characteristics. The sufficient condition to show better CM characteristics is to maintain constant CM voltage and induce zero leakage current in steady-state. DM characteristics are said to be better if the DM voltage has three or more levels for a grid cycle.

The equivalent resonant circuit of Fig. 2 in the form of pole voltages can be represented after simplification as in Fig. 3.

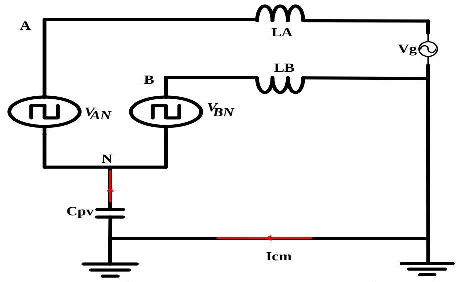


Fig .3. Resonant circuit of H-Bridge GCTLPVI in the form of pole voltages

The pole voltages of the inverter can be represented by CM voltage and DM voltages as below;
Common mode(CM) voltage is the average value of both pole voltages and can be expressed as

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

Differential mode(DM) voltage is the difference value of both pole voltages and can be expressed as

$$V_{DM} = V_{AB} = V_{AN} - V_{BN} \qquad (2)$$

Now from (1) and (2) pole voltages V_{AN} and V_{BN} can be written in terms of V_{CM} and V_{DM} as below

$$V_{AN} = V_{CM} + \frac{V_{DM}}{2} \qquad (3.A)$$

$$V_{BN} = V_{CM} - \frac{V_{DM}}{2} \qquad (3.B)$$

So again, the equivalent circuit represented in Fig. 3 can be converted in the form of CM and DM voltages, as shown in Fig. 4.

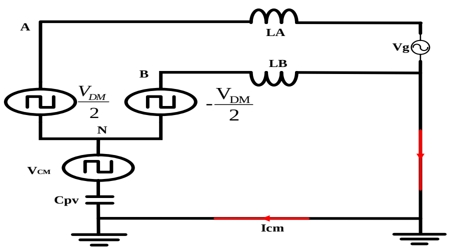


Fig .4. Resonant circuit of H-Bridge GCTLPVI in the form of CM and DM voltages

Now there are three voltage sources, as shown in Fig.4 Common mode voltage V_{CM}, differential mode voltage V_{DM} and grid voltage V_G. They all have different values and different frequencies. It needs to simplify this circuit for a clear understanding of leakage current behavior in the transformerless grid-connected H-bridge PV inverter. Hence, further step by step simplification has been done for getting the expression of leakage current in terms of inverters parameters.

A. Step-1(Conversion of voltage sources into current sources)

The voltage source $V_{DM/2}$ in series reactance of $X_{LA,}$ as shown in Fig. 4 can be converted into equivalent current source $\frac{V_{DM}}{2X_{LA}}$ in parallel with the reactance of $X_{LA,}$ as shown in Fig 5.
In the same way voltage source $-V_{DM/2}$in series with reactance X_{LB} can be converted into equivalent current source of $-\frac{V_{DM}}{2X_{LB}}$ in parallel with reactance X_{LB}. Now both current sources are operating at very high switching frequency f_{SW}(10-20kHz) compare to grid voltage frequency f_G(50 Hz). Therefore, for the analysis of the circuit at high frequency, the grid voltage can be neglected because it shows very less effect

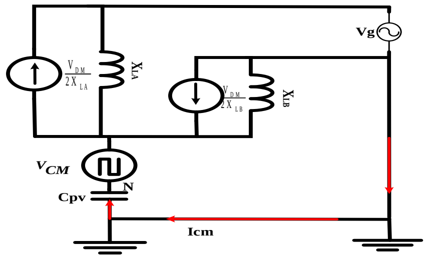


Fig .5. Equivalent circuit in the form of current sources

on leakage current, and thus, the circuit will be simplified, as shown in Fig.6[7][2].Both current sources can be combined into a single current source with parallel to the filter equivalent reactance values, as shown in Fig. 7.

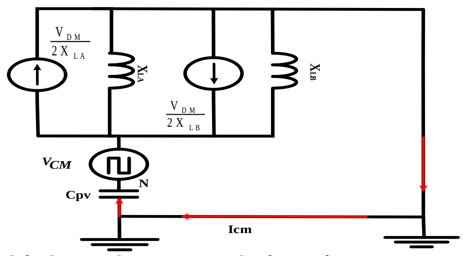


Fig .6. Simplified equivalent circuit in the form of two current sources and a single voltage source

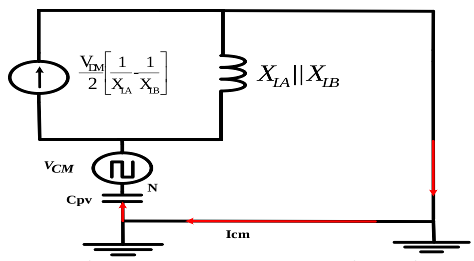


Fig .7. Simplified equivalent circuit in the form of single current sources and a single voltage source

B. Step 2(Conversion of the current source into a voltage source)

The single current source, as shown in the Fig.7 in parallel with the equivalent reactance, can be converted into a voltage source in series with the equivalent reactance, as shown in the next Fig.8.

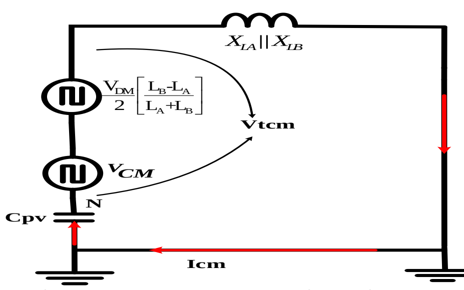


Fig .8. Simplified equivalent circuit in the form of single voltage source

C. Step 3(Addition of two voltage sources)

The two voltage sources can be combined into one single voltage source that will be called V_{tCM} total common-mode voltage. The expression of V_{tCM} can be expressed as

$$V_{tCM} = V_{CM} + \frac{V_{DM}}{2}\left[\frac{L_B - L_A}{L_A + L_B}\right] \qquad (4)$$

From (4), it is clear that if we put equal value of filter inductor in phase and *neutral* wire, i.e., $L_A=L_B$, then V_{tCM} will be equal to V_{CM}, i.e., as expressed in (1). If both inductor values are not equal or anyone inductor is absent, then Vtcm will behave the cumulative effect of CM voltage and DM voltages.

D. Leakage current

Now the V_{tCM} voltage is responsible for leakage current flow into parasitic capacitance, as shown in Fig. 8.

The expression of leakage current can be given as

$$i_{CM} = \frac{V_{tCM}}{\left(X_{LA} \parallel X_{LB}\right) + \left(X_{CPV}\right)} \qquad (5)$$

For the case of filter inductor symmetricity, i.e., for $L_A=L_B$ the following expression of leakage current will be valid

$$i_{CM} = \frac{V_{CM}}{\left(X_{LA} \parallel X_{LB}\right) + \left(X_{CPV}\right)} \qquad (6)$$

Further, it can be concluded that leakage current will depend on the value of CM voltage and filter inductive reactance value with parasitic capacitive reactance value along at the frequency of CM voltage.

E. Resonant frequency

A resonant circuit is formed because of the existence of inductance and capacitance of two energy storage elements, as shown in Fig.8.The circuit starts resonate at a frequency called resonance frequency can be expressed by the following expression

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{L_{eq.}C_{eq.}}} \qquad (7)$$

Where

$$L_{eq.} = \frac{L_A \times L_B}{L_A + L_B} \text{ ; and } \qquad C_{eq.} = C_{CPV} \qquad (8)$$

III. LEAKAGE CURRENT IN H-BRIDGE GCTLPVI WITH BIPOLAR PWM MODULATION STRATEGY

There are two modes of operation in bipolar PWM modulation strategy for H bridge inverter shown in Table II. In Mode 1, switches S_1 and S_4 are triggered synchronously at the same time to give positive output voltage to the grid. In mode 2, switches S_2 and S_3 both conduct simultaneously and provides negative voltage to the output. Pole voltages with DM voltages and CM voltages are tabulated in Table II for both half cycles. The operating frequencies of all switches are summarized in Table III. The gate pulse pattern generated by the bipolar PWM scheme has been shown in Fig. 9, along with its constituent signals.

It is clear from Table II, that V_{CM} remains constant in each mode of operation in both half-cycles, so leakage current expression for (6) becomes

$$i_{cm} = \frac{V_{CM}}{\left(X_{LA} \parallel X_{LB}\right) + \left(X_{CPV}\right)} = \frac{V_{CM}}{\left(\frac{X_{LA} \times X_{LB}}{X_{LA} + X_{LB}}\right) + \left(X_{CPV}\right)} \qquad (9)$$

From (9), it is clear that leakage current will be zero at steady state because whole denominator terms become infinity at ω=0.

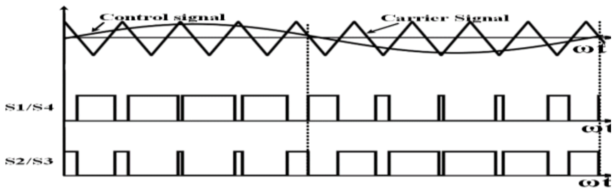


Fig .9. Bipolar PWM pulses for H-Bridge Inverter along with control and carrier signals

It can be observed that in H-Bridge GCTLPVI with bipolar modulation strategy, leakage current is zero, even when CM voltage has a constant value. Therefore, the bipolar PWM techniques show better CM characteristics and have the attribute to be used in transformerless solution. But the problem is poor DM characteristics because of two voltage levels in output, which increases the ripple in current and causes increased inductor core losses, which shows poor power conversion efficiency. It restricts its usefulness in grid-connected applications.

TABLE II
OPERATIONAL MODES OF H-BRIDGE GCTLPVI WITH BIPOLAR MODULATION STRATEGY

Positive Half Cycle ($V_{control} > 0$)				**Negative Half Cycle ($-V_{control} > 0$)**			
S1,S4				S1,S4			
V_{AN}	**V_{BN}**	**V_{DM}**	**V_{CM}**	**V_{AN}**	**V_{BN}**	**V_{DM}**	**V_{CM}**
$+V_{dc}$	0	$+V_{dc}$	$+V_{dc}/2$	$+V_{dc}$	0	$+V_{dc}$	$+V_{dc}/2$
S2,S3				S2,S3			
V_{AN}	**V_{BN}**	**V_{DM}**	**V_{CM}**	**V_{AN}**	**V_{BN}**	**V_{DM}**	**V_{CM}**
0	$+V_{dc}$	$-V_{dc}$	$+V_{dc}/2$	0	$+V_{dc}$	$-V_{dc}$	$+V_{dc}/2$

TABLE III
OPERATING FREQUENCIES OF ALL SWITCHES IN H-BRIDGE GCTLPVI WITH BIPOLAR MODULATION STRATEGY

Switch	S_1	S_2	S_3	S_4
Frequency	*fs*	*fs*	*fs*	*fs*

IV. LEAKAGE CURRENT IN H-BRIDGE GCTLPVI WITH UNIPOLAR PWM MODULATION STRATEGIES

In unipolar PWM adopted H bridge grid-connected inverter has four modes of operation for a complete grid cycle, and this scheme provides three voltage levels in the output. Therefore, they exhibit better DM characteristics compared to bipolar PWM technique. The different voltages of the inverter in each operating modes are summarized in Table IV.

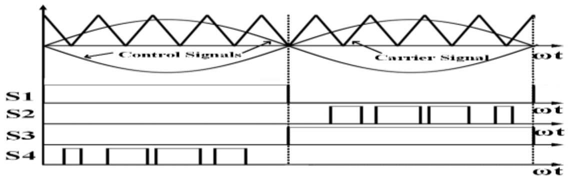


Fig .10. Unipolar PWM pulses for all four switches

In contrast, unipolar modulation shows variable common-mode voltage, which varies from $+V_{dc}$ to $+V_{dc}/2$ in each switching instant. Consequently, large leakage current flow, as per expression (9), it may exceed the limit as prescribed by the VDE-0126 standard. So it can be summarized that unipolar PWM exhibits better DM characteristics but shows poor CM characteristics as compared with bipolar PWM. The operating frequencies of all switches are summarized in the Table V, and the gate pulse pattern generated for driving the switches has been shown in Fig. 10.

TABLE IV
OPERATIONAL MODES OF H-BRIDGE GCTLPVI WITH UNIPOLAR MODULATION STRATEGY

Positive Half Cycle ($V_{control} > 0$)							
Active mode [$V_{control} > V_{carrier}$]				**FW mode [$V_{control} < V_{carrier}$]**			
S1,S4				S1,D3			
V_{AN}	V_{BN}	V_{DM}	V_{CM}	V_{AN}	V_{BN}	V_{DM}	V_{CM}
$+V_{dc}$	0	$+V_{dc}$	$+V_{dc}/2$	$+V_{dc}$	$+V_{dc}$	0	$+V_{dc}$
Negative Half Cycle ($-V_{control} > 0$)							
Active mode [$-V_{control} > V_{carrier}$]				**FW mode [$-V_{control} < V_{carrier}$]**			
S2,S3				S3,D1			
V_{AN}	V_{BN}	V_{DM}	V_{CM}	V_{AN}	V_{BN}	V_{DM}	V_{CM}
0	$+V_{dc}$	$-V_{dc}$	$+V_{dc}/2$	$+V_{dc}$	$+V_{dc}$	0	$+V_{dc}$

TABLE V
OPERATING FREQUENCIES OF ALL SWITCHES IN H-BRIDGE GCTLPVI WITH UNIPOLAR MODULATION STRATEGY

Switch	S_1(+)	S_2	S_3(-)	S_4
Frequency	*f1*	*fs*	*f1*	*fs*

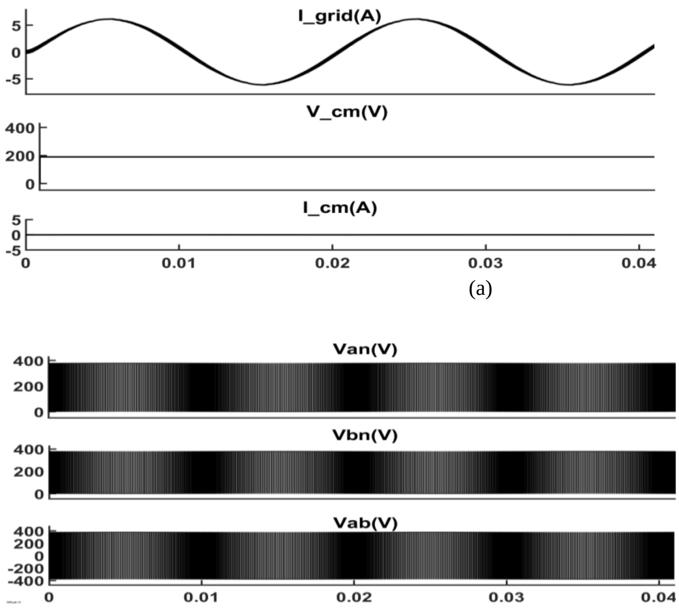
V. SIMULATION RESULTS

The complete circuit diagram, as shown in Fig.2, has been simulated in the Matlab Simulink platform for transformerless grid-connected H-bridge PV inverter with both modulation techniques, i.e. bipolar PWM and unipolar PWM. The sampling time has been chosen 1μs which is less than the carrier signal time period (100μs for 10 kHz).

TABLE VI
SYSTEM PARAMETERS USED FOR VERIFICATION IN SIMULATION

Parameter	**Value**
Power Ratings	1kW
Dc Input Voltage, Vdc	380 V
Switching frequency, f_{sw}	10 kHz
Filter Inductor L_A=L_B	11mH
Filter Capacitor C_f	110 *nf*
Load Resistance R_o	52.91 Ω
Grid Voltage V_{grid}	230 V
Parasitic Capacitance, C_{pv}	100 *nf*

Input PV voltage has been taken constant in all conditions, which is equal to 380 V. Grid voltage has been considered to be in phase with grid current, and hence unity power factor condition is achieved. Grid utility is operating at 230V and 50 Hz. The switching frequency has been chosen as 10 kHz. LC filter has been applied to reduce ripple in current as well as in voltage produced by the inverter. Since Parasitic capacitance for a PV panel has been approximated to be about 50-150 nF/kW in a normal weather condition[7]. Hence 100 nF has been chosen for the 1kW PV system as parasitic capacitance, Cpv. All circuit parameters are tabulated in Table VI, which is being used for simulation study. The ground resistance of 11Ω has been chosen from reference[8][9] to damp the peak of leakage current.

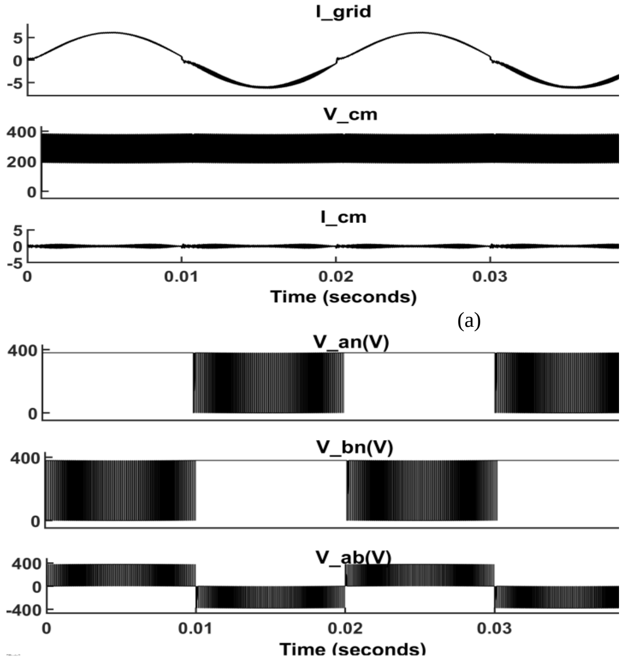


(b)

Fig .11. Simulation results of H-bridge GCTLPVI with bipolar modulation strategy: (a) Grid current I_grid, Common-mode voltage

V_cm, and leakage current I_cm (b) Pole voltages Van, Vbn and DM voltage Vab

For bipolar modulation, the strategy adopted for full-bridge grid-connected PV inverter simulation results is shown in Fig. 11. The RMS value of leakage current is 29 mA, and the THD in the grid current is equal to 3.47%. It can be observed that from Fig.11(a) CM voltage is constant, which is half of the PV voltage, i.e., 190 V, and the leakage current is almost negligible. Hence it is verified that bipolar PWM shows better CM characteristics compared to unipolar. The RMS value of the grid current is 4.32 A, and efficiency is 99.84%. The DM characteristics achieved in bipolar PWM are shown in Fig. 11(b). However, when unipolar modulation strategy is used in full-bridge grid-connected inverter, then simulation results are shown in Fig.12. The RMS value of leakage current is 351mA at switching frequency, and the THD of the grid current is equal to 4.8%, which is too high. RMS value of the grid current is 4.32 A, and efficiency is 99.57%, which is achieved slightly smaller compared to the bipolar scheme. Fig.12(a) shows the CM voltage and leakage current produced in unipolar PWM operated inverter. The DM characteristics achieved in unipolar PWM are shown in Fig. 12(b).



(b)

Fig .12. Simulation results of H-Bridge GCTLPVI with unipolar modulation strategy : (a) Grid current I_grid, Common-mode voltage V_cm, and leakage current I_cm (b) Pole voltages Van, Vbn and DM voltage Vab

VI. CONCLUSIONS

In this paper, leakage current issues with transformerless grid-connected PV full-bridge inverter has been investigated in detail for both modulation techniques unipolar and bipolar PWM. Common mode modeling of resonant circuit forms in grid-connected transformerless PV full-bridge inverter has been derived, which includes the derivation of leakage current and resonant frequency expressions. For verification of modeling of H-Bridge GCTLPVI with both PWM strategy, simulation has been carried out for the 1kW grid connected PV system, and it is observed that full-bridge inverter driven with bipolar modulation technique produces constant common-mode voltage(+Vpv/2) hence, very less leakage current because of the resonant circuit excitation. However, unipolar PWM causes fluctuation in the common-mode voltage from +Vpv to +Vpv/2 at switching frequency and causes large flow of leakage current in the system. THD in grid current and efficiency along with leakage current gets poorer in unipolar compare to bipolar modulation for the same system because of the fluctuations in CM voltage.

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