Integrated Common-Mode and Differential Mode Filter Circuit for Leakage Current Suppression in Transformerless Photovoltaic Inverter Systems

Xinjun Li*, Zuhaina Zakaria, Muhamad Nabil Hidayat

Abstract - **The transformerless photovoltaic inverter system will lead to a large leakage current between the photovoltaic inverter system and the ground, and the current reduction is mainly based on the optimization of circuit topology and control mode. This paper first analyzes the causes of ground leakage current, as well as several strategies and mechanisms to control the ground leakage current. On this basis, a novel integrated common-mode and differential mode filter circuit is proposed to reduce the leakage current of transformerless photovoltaic inverter system. Through theoretical analysis and circuit simulation, it is proved that the suppression technology can effectively reduce the leakage current of transformerless photovoltaic inverters.**

Index Terms - **Common mode, Differential mode, filter, ground leakage current, photovoltaic inverter**

I. INTRODUCTION

With the continuous progress of new energy power generation technology, photovoltaic power generation has been widely promoted and applied in many countries around the world. According to the data of China Photovoltaic Industry Association, the global photovoltaic newly installed capacity in 2022 will reach 230GW, an increase of 35.3% over 2021, and the newly installed capacity will hit a new record high [1]. Photovoltaic power generation has become one of the fastest growing new energy power generation methods in the world.

The current photovoltaic inverter grid-connected system is mainly divided into isolated type and transformerless type, because the transformerless photovoltaic inverter grid-connected system saves the power frequency isolation transformer, so it has higher system conversion efficiency and lower cost, and has been widely used in small and medium power and string photovoltaic inverter system. However, in a photovoltaic system without transformer isolation, because the negative electrode of the photovoltaic panel cannot be directly grounded, and there is a certain parasitic capacitance between the positive and negative electrodes of the photovoltaic panel to the outside, it will lead to a loop between the photovoltaic panel and the ground and cause a certain leakage current, which will bring safety risks to the operator, and also cause harmonic hazards in the power grid.

At the same time, it is also the main source of Electromagnetic Interference (EMI) common mode noise [2], so the photovoltaic inverter grid-connected must meet the corresponding leakage current and safety standards such as DIN VDE 0126-1-1[3] and IEC 60755:2017[4], and the Chinese national standard GB/T30427-2013[5].

Aiming at the problem of common mode leakage current of transformerless photovoltaic inverter system, literature [6-9] proposed many leakages current reduction measures based on circuit topology and control mode, which have also been widely used in the industry. However, the basic idea of these improvement countermeasures based on circuit topology is to cut off the panel and the high-frequency AC side during the continuous flow or construct a new continuous flow loop, which requires increasing the number of semiconductors.

For the change of the control mode, it is necessary to make all the switching tubes work at high frequency, which will lead to a large increase in the loss of the switching tubes and magnetic devices and reduce the efficiency of the system. Based on the mechanism of inverter leakage current generation, an integrated differential mode and common mode filter circuit is proposed in this paper, which can effectively inhibit the generation and transmission of leakage current without adding additional power devices or changing unipolar control algorithm. Through theoretical analysis and circuit simulation, the feasibility of the principle and technology application is confirmed.

II. MECHANISM OF FORMATION OF GROUND LEAKAGE CURRENT BY PHOTOVOLTAIC INVERTERS

As depicted in (1), the leakage current in transformerless photovoltaic inverter systems is influenced by the distribution of capacitors within the photovoltaic panels. Literatures [10-11] have analyzed and introduced the concept of capacitor distribution in photovoltaic panels. This distribution depends on factors like the panel's encapsulation structure, the dielectric constant of its packaging material, material thickness, and various weather conditions such as temperature and humidity.

Based on practical engineering experience, it has been observed that the distribution of capacitors in photovoltaic panels typically falls within the range of about 50 to 150 nF/KW . It's important to note that these distributed capacitances are connected in parallel. Consequently, in larger photovoltaic systems, the equivalent distributed capacitance

This manuscript is submitted on 2 October 2023, revised on 23 April 2024, accepted on 22 July 2024 and published on 31 October 2024. Xinjun Li was born in Hunan, China, in 1980. He is now pursuing Ph.D. degree in School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA. Zuhaina Zakaria and Muhammad Nabil Hidayat are with the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor.

*Corresponding author
Email: 649442386@qq.com

becomes greater, leading to an increase in common mode leakage current to the ground.

$$i_{CM} = C_{PV}(dV_{CM})/(dt) \quad (1)$$

It can also be seen from (1) that in addition to the distributed capacitance of photovoltaic panels, another main factor affecting the common mode leakage current is the high-frequency common mode voltage V_{CM}. Fig.1 is a typical circuit model of a single-phase H4 bridge photovoltaic inverter grid-connected system. To improve the conversion efficiency, the unipolar SPWM control mode is generally adopted. The generation mechanism of leakage current is simply analyzed based on this circuit [12].

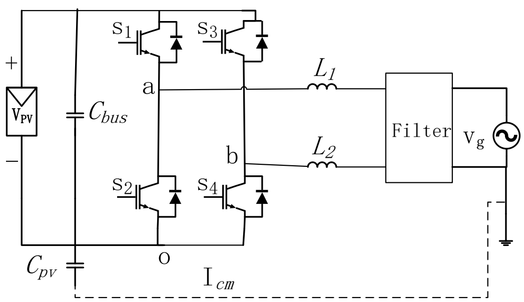
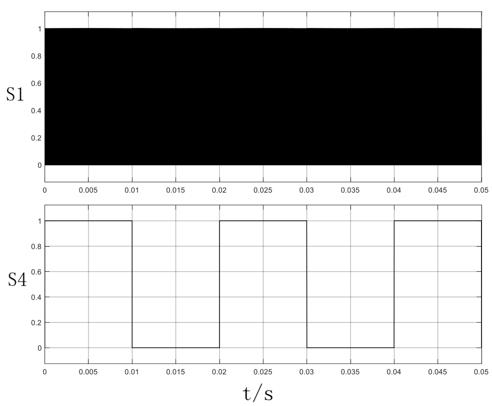
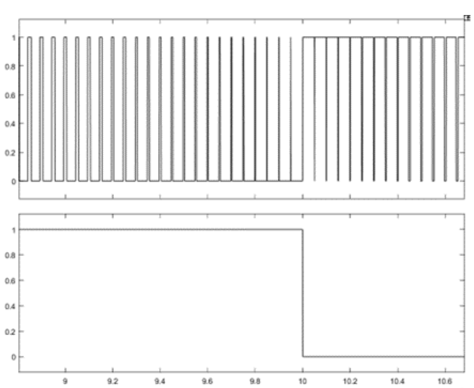


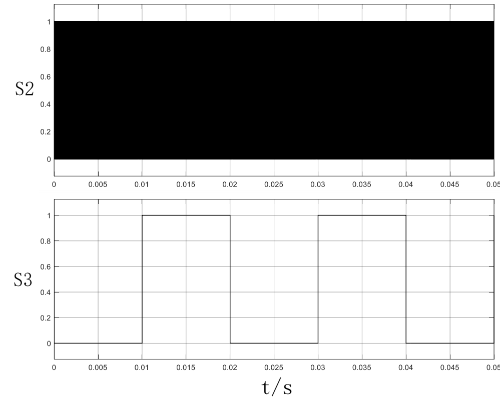
Fig .1. Leakage current model for PV system



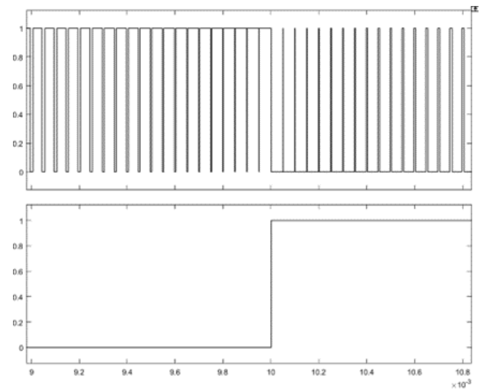
(a) Driver signal for S1, S4



(b) Amplified driver signal for S1, S4



(c) Driver signal for S2, S3



(d) Amplified driver signal for S2, S3

Fig. 2. Driver signal for H4 Bridge

In the unipolar H4 bridge control mode, two high frequency tubes and two low frequency tubes (power frequency) are generally combined. The specific switch timing is shown in Fig.2. In positive half wave, S1 and S 4 are a group, S1 is high frequency switch, S4 is on, S2 is high frequency switch, S3 is off; in negative half wave, S2 and S3 are off, S2 is high frequency switch, S3 is on, S1 is high frequency switch, and S4 is off. Since the control signals of S1 and S2 are complementary high frequency pulse modulated by unipolar, and the control signals of S3 and S4 are complementary pulses of power frequency, therefore, the two bridge arms S1 and S2, S3 and S4 will not be directly connected.

Due to the alternating switch of the switch tube, a high-frequency alternating voltage U_{a0} is formed between the o-point of the A-point to the DC bus, as shown in Fig.3.

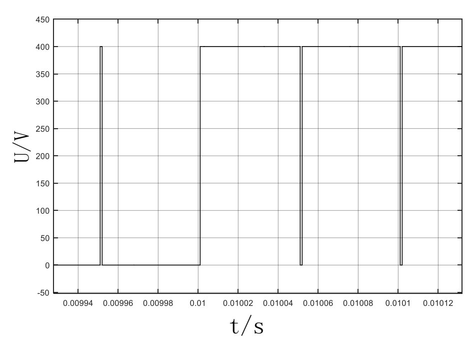


Fig. 3. U_{a0} voltage wave

Due to the existence of alternating voltages V_{a0} and V_{bo}, a circuit is formed through filtering inductors L_1, L_2, EMC filters, power grids V_g, and photovoltaic panel to ground capacitor C_{PV}. The current flowing C_{PV} through current I_{CM} is the ground leakage current, also known as the ground common mode current. The V_{a0} and V_{bo} appear alternately in unipolarity control, so from the perspective of the time domain model, it can be analyzed in Fig. 4 and Fig. 5. In order to facilitate the analysis, it can be simplified to the model of Fig. 6, and the high frequency voltage source is reflected simultaneously [13].

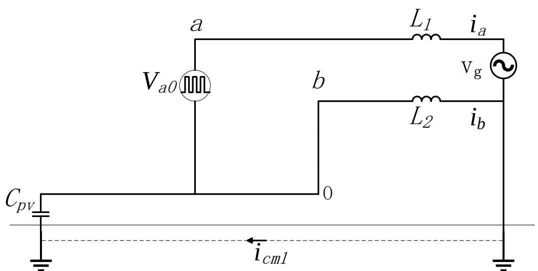


Fig. 4. Equivalent circuit model 1

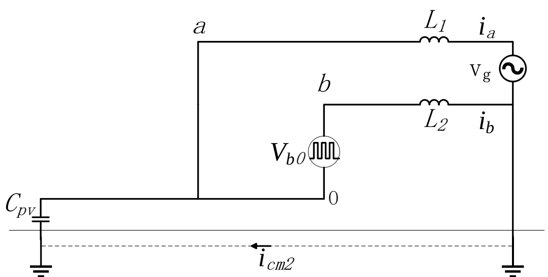


Fig.5. Equivalent circuit model 2

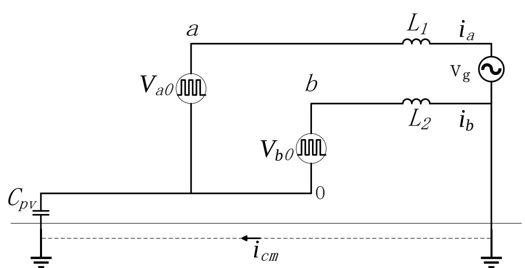


Fig. 6. Equivalent circuit model 3

According to Kirchhoff's voltage law, (2) and (3) are derived:

$$V_{ao} = V_{L_1} + V_g + V_{CM} \quad (2)$$

$$V_{bo} = -V_{L_2} + V_{CM} \quad (3)$$

It can be derived from (2) and (3):

$$V_{CM} = V_{ao} - V_{L_1} - V_g \quad (4)$$

$$V_{CM} = V_{bo} + V_{L_2} \quad (5)$$

According to the law of electromagnetic induction, the inductance voltage drop can be derived as follows. Since the two inductances have the same amount and current, it can be considered that the absolute values of the inductance voltage drop are the same and the direction is opposite:

$$V_L = L(di)/(dt) \quad (6)$$

As can be known from the SPWM modulation mode that the high-frequency ripple is the largest at 45° and 135°, and the high-frequency ripple is the smallest at 0° and 90°, so the entire common-mode voltage presents a spindle type during the operation of V_{bo}, and there will be an offset due to the superposition of grid voltage during the operation of V_{a0}. Because it is a low-frequency power grid voltage V_g, the leakage current caused by the ground capacitance is very small and can be approximately ignored, so the influence of the power grid voltage V_g is basically not reflected on the common-mode current I_{CM}. The specific simulation waveform of the common-mode voltage V_{CM} and I_{CM} is shown in Fig.7.

The simulation tool adopts MATLAB 2022a, circuit simulation parameters are as follows: bus voltage 400V, $L_1=L_2=1mH$, unipolar control, switching frequency 20KHz, ground capacitance 300nF, load 20Ω, the effective value of output AC voltage is about 220V.

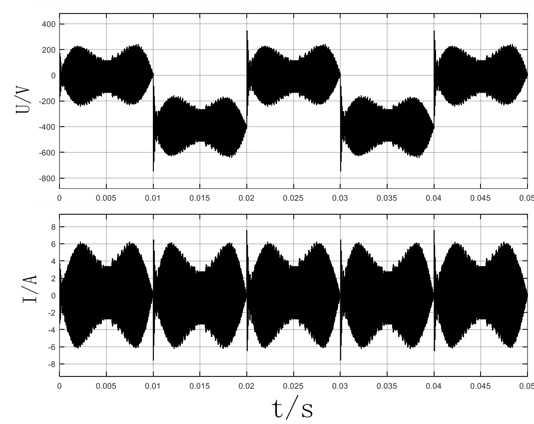


Fig. 7. Simulation wave for CM voltage and CM current

It can be derived from (4) and (5):

$$V_{CM} = (V_{ao} + V_{bo} - V_g)/2 \quad (7)$$

Due to the low-frequency power grid voltage V_g, the leakage current caused by the ground capacitor is very small and can be approximately ignored, so it can be approximately equal to:

$$V_{CM} \approx (V_{ao} + V_{bo})/2 \quad (8)$$

The FFT transformation of the common mode voltage and the common mode current respectively shows the frequency and amplitude distributions of the main harmonic components. Specifically, are shown in Fig. 8 and Fig. 9.

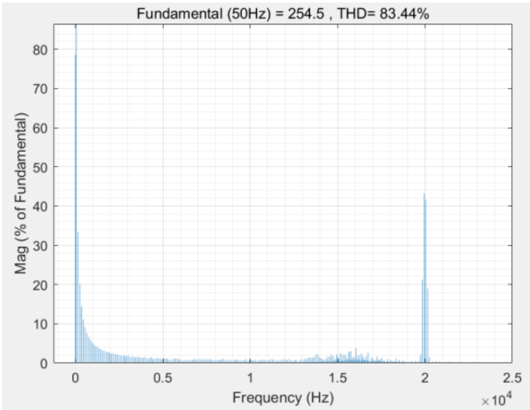


Fig. 8. FFT for CM voltage

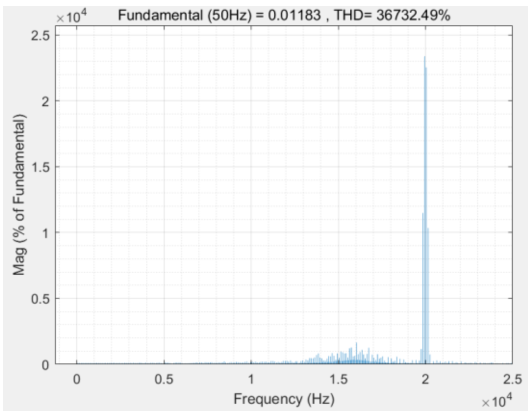


Fig. 9. FFT for CM current

According to the FFT transformation results, the main harmonic component frequency of the common mode voltage and the current on the unipolar H4 topological to-ground capacitor C_{PV}, is the switching frequency of 20 kHz and its doubling frequency, and the harmonic voltage and current amplitude at 20 kHz reach 80 V and 6 A, respectively.

III. Introduction of the Existing Leakage Current Suppression Technology

Since the inverter must meet the corresponding EMI and harmonic requirements when connected to the grid, the leakage current of the traditional unipolar control H4 bridge must be suppressed accordingly. For the formation mechanism of the leakage current, some countermeasures are adopted to reduce the leakage current mainly from the following perspectives.

A. Leakage Current Suppression Technology Based On The Control Mode

From (8), if V_{CM} can be controlled as a constant value, no common-mode voltage will occur, and naturally there will be no leakage current. In the case that the simulation parameters are the same, only the control mode will be changed from unipolar control to bipolar control, because under the bipolar SPWM control mode, the four switching tubes are in a high frequency switching state. In addition, the two bridge arms are sympotically switched on alternately, so that the sum of V_{a0} and V_{bo} is a constant bus voltage value.

Theoretical analysis and experiments show that the common mode voltage and common mode current are much smaller than unipolar SPWM control. However, because the bipolar control mode requires four switching tubes to work at high frequency, the loss of switching tubes will increase greatly. At the same time, the voltage difference of each switching cycle on the inductor will also increase, which will lead to the increase of the magnetic flux change value ΔB of the inductor. According to the Steinmetz equation, the loss of the inductor core will also increase significantly. Therefore, from the perspective of system loss, the bipolar control mode will increase the loss of the inverter switching tube and inductor, which is not conducive to improving the system efficiency, so not much is actually used [14].

B. Leakage Current Suppression Technology Based on Circuit Topology

In addressing leakage current concerns from a circuit topology perspective, two main approaches have emerged. The first approach involves the separation of the AC side and the DC side to ensure continuous flow, primarily achieved by emphasizing continuous flow on the AC side. A notable example of this approach is the H5 topology by Germany's SMA and the H6 (Heric) topology by Sunways.

The second approach focuses on establishing a relatively static point directly or indirectly linked to the negative or positive terminal of the photovoltaic panel through a series of capacitors. This configuration creates a fixed voltage value between the panel and the grid, effectively reducing the common-mode voltage between the panel and the ground. Topologies following this approach include the midpoint clamp topology, three-level topology, half-bridge topology, among others [15].

The H5 topology is to add a switching tube based on the H4 topology, which is opened during the main current conduction and closed during the continuous flow, so that the AC side and the DC side are separated. By closing the S_5, and the AC side is controlled by the switching tube to form a continuous flow loop, which is equivalent to short circuit point a and point b. Thus, there is basically no leakage current flowing through the C_{PV} during the continuous flow, but the disadvantage of this topology is due to the addition of a high frequency switch pipe, which leads to the total switch pipe loss and the cost increase [16]. The H5 circuit is shown in Fig. 10.

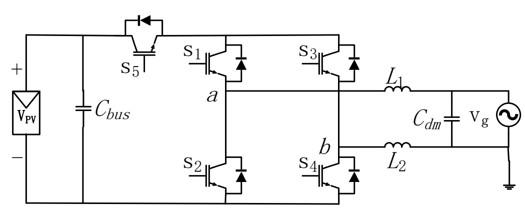


Fig. 10. H5 topology

The H6 topology is based on the H4 topology by adding two switching tubes S_5 and S_6 between point a and point b. And through the reverse series constitute a function of bidirectional switch, during the main current turn-on, S_5 and S_6 off, in the continuous flow, S_5 and S_6 open, so that during the continuous flow is equivalent to a short circuit between point a and point b, forming a circuit that only continues on the AC side, thus it can also be realized during the continuous flow basically does not produce leakage current flowing through C_{PV}. However, the disadvantages of this topology are similar to those of H5 in that the total switching tube loss increases significantly due to the addition of two high frequency switching tubes [17]. The H6 circuit is shown in Fig. 11.

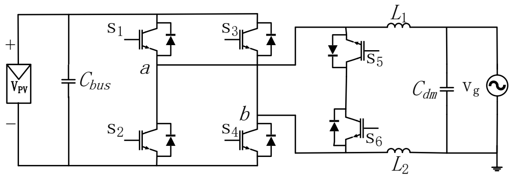


Fig. 11. H 6 topology

The midpoint clamping topology is to use two small capacitors on the network side to form a relative midpoint and connect it to the negative or positive electrode of the photovoltaic panel. Because the grid voltage is the low frequency voltage can be seen as a static point, which is equivalent to connecting the negative electrode (or positive electrode) of the photovoltaic panel to a static point. As shown in Fig. 12 specifically, the ground common mode voltage V_{CM} is basically equal to V_{Cm2}. Since the voltage fluctuation on C_{cm2} is relatively small, the common mode current I_{CM} will correspondingly decrease a lot. However, because C_{cm1} and C_{cm2} are connected behind the filter, they cannot be too large, otherwise they will affect the filtering effect of the inverter [18]. The midpoint clamp is shown in Fig.12.

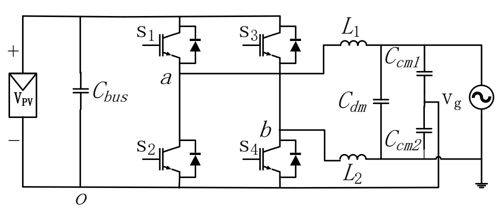


Fig. 12. Neutral point clamp topology

In addition, the topology structure that can suppress leakage current also has the form of three-level topology, half-bridge topology and so on. The three-level topology is mainly to achieve soft switching technology through complex control methods to improve the conversion efficiency of the system, and its disadvantage is that it needs to increase the additional large partial voltage bus capacitance, which has a certain impact on the cost and life (electrolytic capacitance will gradually weaken, and the higher the temperature, the faster the weaken).The half-bridge topology is essentially Buck inverter, due to the capacitive voltage division, resulting in the actual working voltage is only $0.5V_{PV}$, low voltage utilization, so it is not suitable for high-power occasions.

IV. Leakage Current Suppression Technology Of Photovoltaic Inverter Integrating Common Mode And Difference Mode Filter Circuit

Considering the limitations observed in existing leakage current suppression technologies discussed earlier, this paper introduces an innovative solution that combines both common-mode and differential-mode filter circuits. This circuit effectively mitigates both common-mode and differential-mode signals, offering comprehensive suppression as depicted in Fig. 13.

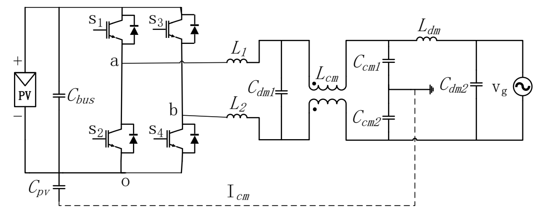


Fig. 13. Circuit topology based on integrated CM and DM

This circuit, L_{cm} is a common mode choke, also known as a common mode inductor, C_{cm1} and C_{cm2} are common mode capacitors, whose role is to filter out the common mode noise interference in the power line. When there is a current through the common mode inductor L_{cm}, because the magnetic flux direction generated by each group of coils is the same, the magnetic induction of the two groups of coils will strengthen each other, and the total amount of inductance will increase sharply.

According to the high-frequency characteristics of the inductor, the high-frequency harmonics in the current will be difficult to flow, playing the role of filtering out high-frequency harmonics. C_{cm1} and C_{cm2} can be connected to the output end, can also be connected to the input end, where the point is connected to the ground, can play a role in suppressing common mode noise interference. C_{dm1} and C_{dm2} as a differential mode filter capacitor straddled between two power lines, the differential mode inductor L_{dm}, the role of the differential mode capacitor and inductor is to filter out the differential mode noise interference in the line [19].

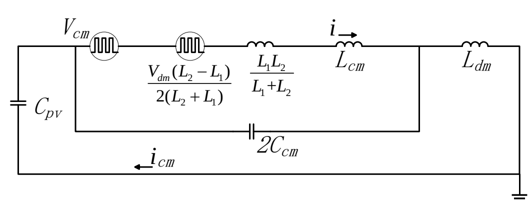


Fig. 14. Equivalent circuit

In addition, because the power grid voltage is low frequency signal basically does not constitute high frequency leakage current, so the V_g can also be ignored, the model is further simplified to the model without model of V_g. The equivalent circuit is shown in Fig.14.

The simulation tool adopts MATLAB 2022a, the circuit simulation parameters are as follows: bus voltage 400 V,$L_1 = L_2 = 1\text{mH}, C_{cm1} = C_{cm2} = 4700\text{pF}, C_{dm1} = C_{dm2} = 0.02\text{uF}, L_{dm} = 3.3\text{mH}$, the common mode inductor L_{cm} in each group of coil is 10mH, unipolar control, switching frequency 20 kHz, ground capacitor 300nF, load 20Ω, and the effective value of output AC voltage is about 220 V. The simulation results are shown in Figs. 15 - 17.

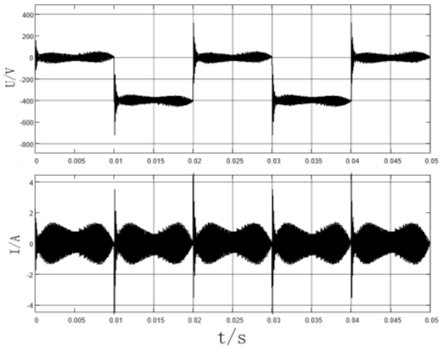


Fig. 15. Simulation wave for CM voltage and CM current

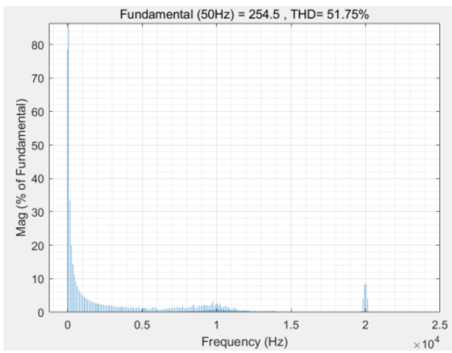


Fig.16. FFT for CM voltage

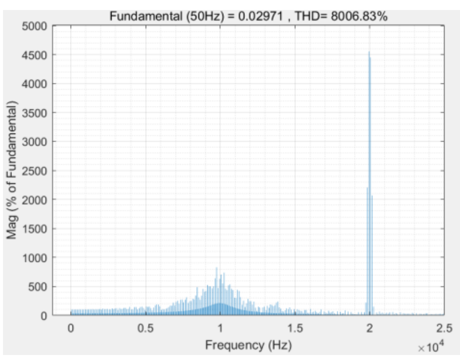


Fig. 17. FFT for CM current

According to the FFT transformation results, the main harmonic component frequency of the common mode voltage and current on the circuit topological ground capacitor C_{PV}, and the harmonic voltage and current amplitude at 20 kHz are 20 V and 0.9 A respectively. From the above results, it is easy to see that the leakage current of the circuit has significantly decreased, therefore, this suppression strategy is feasible.

V. CONCLUSION

This paper has introduced a robust solution for the suppression of leakage currents in photovoltaic systems, employing an integrated common-mode and differential mode filter circuit. Through rigorous theoretical analysis, model development, and circuit simulations, the practical feasibility and effectiveness of this approach have been demonstrated. The proposed technique not only addresses the pressing issues of ground leakage current and EMI noise in transformerless photovoltaic inverter systems but also presents a cost-efficient alternative by reducing the overall EMI filtering expenditure. Moreover, its user-friendly implementation process makes it an attractive choice for practical application. In summary, this technology offers significant advantages, particularly for single-phase unipolar control of transformerless bridge photovoltaic inverters. It contributes to the reduction of ground leakage current, enhancement of EMI characteristics, and substantial cost savings in EMI filter implementation, marking a substantial step forward in the field of photovoltaic systems.

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