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Topologies and modulation methods in leakage current suppression for PV grid-tied inverters

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Abstract. Photovoltaic (PV) inverters are widely discussed as solar energy became commonly used as a renewable energy source. Transformerless grid-tied inverters are often chose for their low cost and low energy loss. Since the existence of stray capacitance between PV cells and conducting surface causes a changing common-mode voltage (CMV) which would arise leakage current and thus pollute the output current quality to the grid and endanger human safety, novel topologies and modulation strategies are proposed to save the problem for transformerless inverters. In this paper, different methods to suppress the leakage current will be analysed. The theoretical analysis of CMV and leakage current generation by single-phase inverter is presented. Based on the basic principle of leakage current suppression topologies proposed to eliminate the leakage current are introduced. The effects of some well-known modulation methods on CMV controlling have been compared, and novel methods dealing with three-phase harmonic management are presented.

Keywords: grid-tied inverters, common mode voltage, leakage current.

1. Introduction

Nowadays, due to the increasing demand of energy and awareness to harmful environmental effects of fossil fuels, people make efforts on switching the fuel-based system to renewable-energy-based system. Photovoltaic, wind and water energies have become the fastest growing sources as an important piece of smart grid [1]. Among all these renewable energies, solar energy is most concerned because of its large amount, extensive distribution, short development cycles, stability and long service life [2]. In PV systems, grid-tied inverter is the core component which takes the function of converting the DC voltage produced by solar panel into AC output voltage to the grid. Therefore, reliability, efficiency, cost and safety are emphasized.

PV grid-tied inverters can be classified into two groups: isolated inverters and non-isolated inverters. Considering the type and position of transformer, isolated inverters can be further divided into PV inverter with a low frequency transformer on AC side or with a high frequency transformer in the middle stage. In PV grid-tied systems, isolated inverters with transformer are widely used to insure galvanic isolation between PV installations and the grid. However, the structure with a working frequency transformer suffers from high cost, large size and weight. For the structure with a high frequency transformer in the middle stage, the total efficiency of electricity generation is reduced. As a result, transformerless PV inverters have been widely concerned and discussed in recent years [3].

For transformerless inverters, there is no isolation that prevent solar panel harmonic from the grid thus a stray capacitor existed between PV cells and conducting surface needs to be take in consider. The capacitor would produce a leakage current which would pollute the grid current, cause reduction to the equipment work life and further endanger human safety. The efficiency reduction and increased total harmonic distortion (THD) caused by leakage current in the grid current need to be manipulated to fit the current THD requirements of the grid [4].

To minish the leakage current for transformerless grid-connected inverters, researches have been taken both in improving the main circuit topology and the modulation method. For topologies, many novel structures that could inject leakage current have been proposed such as H5 structure, H6 structure, highly efficient reliable inverter concept (HERIC), NPC structure, etc. These topologies will be discussed in section II. For modulation methods, bipolar method can efficiently alleviate the leakage current in single-phase inverters. Zero sequence voltage injection modulation (ZSVIM) is commonly used in PV systems because of its high utilization of DC voltage, thus derived third harmonic injection pulse width modulation (THIPWM) and other widely used methods in industrial conditions [5]. Based on these prominent modulation strategies, researches have been done on eliminating the common-mode current produced by leakage current and other resonant circuits. Recent years other solutions specifically against three-phase multilevel PV inverters have been proposed. Solutions focused on transformerless inverters with a filter to suppress CM current also created a lot of discussion. These solutions will be discussed in section III.

2. Analysis of leakage current in PV systems

The existence of stray capacitance to ground between PV cells and conducting surface, which is subjected to the DC source and environmental factors, forms a common-mode resonance circuit with the filter devices and power line impedance. The changing common-mode voltage (CMV) caused by the switch of the inverter treated the resonance circuit. Therefore, leakage current is produced and lead to a distortion to the grid current.

The leakage current is given by

$$I_{C_p} = C_p \frac{dV_{C_p}}{dt} \tag{1}$$

where C_p equals to the stray capacitance between PV panels and the ground, I_{C_p} is the leakage current. This equation expresses that leakage current is in proportion to the changing rate of CMV [6], which announced the principle of reducing leakage current.

For a single phase full-bridge structure, there are usually two modulation strategies. The two different conditions are discussed below.

2.1. Unipolar method

The inverter is comprised of three operation modes in the positive cycle.

Mode 1: S1 is ON while S4 is OFF, while the current goes through V3. The common -mode voltage is calculated as

$$u_{cm} = 0.5(u_{an} + u_{bn}) = 0.5(U_{PV} + U_{PV}) = U_{PV} \tag{2}$$

Mode 2: S1, S4 are ON, while the other switches are OFF. The voltage is calculated as

$$u_{cm} = 0.5(u_{an} + u_{bn}) = 0.5(U_{PV} + 0) = 0.5U_{PV} \tag{3}$$

Mode 3: S1 is ON while S4 is OFF, while the current goes through V2. The voltage is determined as

$$u_{cm} = 0.5(u_{an} + u_{bn}) = 0.5(0 + 0) = 0 \tag{4}$$

There are same conclusions for negative cycle. Common-mode voltage changes among 0, $0.5U_{PV}$ and U_{PV}, which would produce the leakage current.

2.2. Bipolar method
As for the bipolar method, there are two modes in the working process.

Mode 1: S1, S4 are ON, while other switches are OFF. The common-mode voltage is calculated as

$$u_{cm} = 0.5(u_{an} + u_{bn}) = 0.5(U_{PV} + 0) = 0.5U_{PV} \quad (5)$$

Mode 2: S2, S3 are ON, while other switches are OFF. The voltage is calculated as

$$u_{cm} = 0.5(u_{an} + u_{bn}) = 0.5(0 + U_{PV}) = 0.5U_{PV} \quad (6)$$

During the working time, the common-mode voltage constantly equals to $0.5U_{PV}$. According to equation (1), the numerical value of leakage current keeps a proportional relationship to the changing rate of CMV. Therefore, the bipolar modulation strategy performs effectively on restraining the leakage current in the circuit.

For half-bridge topology, CMV produced by stray capacitance has no relationship with switching frequency and numerically equals to the voltage on the grading capacitor. If the capacitors connecting to the grid have large and same capacities, the CMV would stay constantly about 0.5UPV, and no leakage current would be produced. In engineering conditions, due to the low power efficiency, half-bridge inverters are seldomly used.

The analysis of the production of leakage current for both full-bridge inverter and half-bridge inverter and how unipolar and bipolar methods have different effects on eliminating leakage current shows that topology and modulation strategy can both play a role on leakage current elimination. Continuously different topologies and modulation strategies are emerging to alleviate the leakage current.

3. Topologies for leakage current elimination
Nowadays, many topologies for non-transformer PV grid-tied inverters have been proposed. Among those structures, the most prominent and widely used structures for single-phase inverters are HERIC, H5, H6, NPC, etc.

3.1. H5 & H6 structure
H5 structure was raised by SMA Solar Technology AG in German in order to reduce the switching loss, as shown in Figure 1. A basic single-phase full-bridge topology forms the structure with an IGBT connected to its DC side. H5 structure has been used in the Sunny Mini Central inverter series for its few switches, simple management and high efficiency.

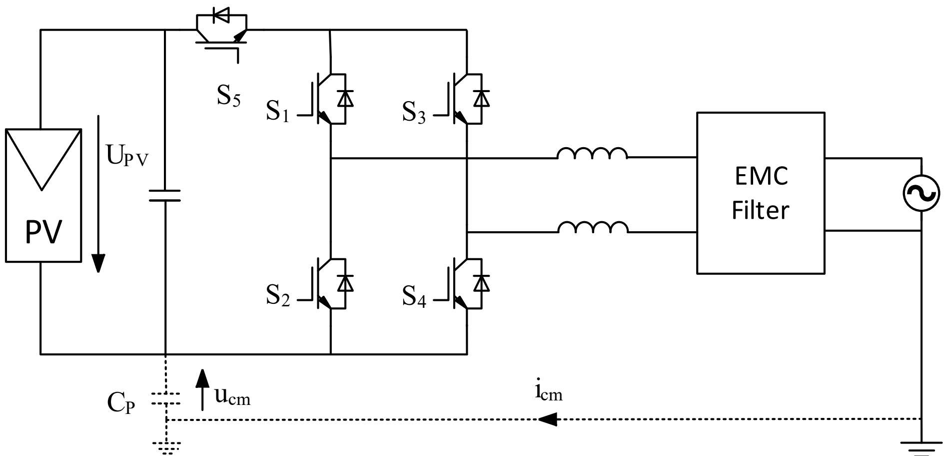

Figure 1. H5 topology.

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H5 structure keeps a common-mode voltage of $0.5U_{PV}$ in all the operation modes while using the unipolar modulation method, which reduce switching loss and improves efficiency.

Based on H5 topology, a H6 non-isolated FB inverter has been proposed by adding a controllable switch between the positive output side of PV cell and the midpoint of phase B. During the working process, the grid-tied current flows through 3 switches in half of working period, while passing 2 switches in another half of period [7]. Comparing with H5 topology, the conduction losses are reduced.

3.2. HERIC structure

Highly Efficient and Reliable Inverter Concept (HERIC) structure is the representation for AC blocking topology, as shown in Figure 2 [8]. Sunways AG proposed the topology. The prototype from Sunways contains a basic single-phase full-bridge inverter with a freewheel structure constituted by S5 and S6 added on its AC output side. Two diodes have been connected in series with the switches in order to prevent reverse current. HERIC structure also uses unipolar control method.

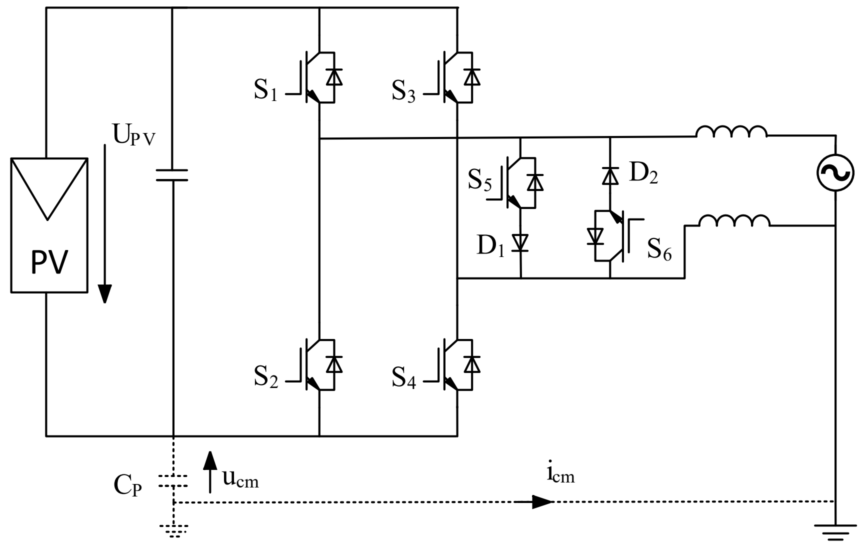

Figure 2. HERIC topology.

When working in mode 1 and mode 3, the reverse current pass through $L_1 \rightarrow grid \rightarrow L_2 \rightarrow S_6 \rightarrow D_2$, which makes the inversion circuit isolates from the PV array. Because of the voltage equalizing effect of the junction capacitor of switches, $u_{an} = u_{bn} = 0.5U_{PV}$, the common-mode voltage is calculated as

$$u_{cm} = 0.5(u_{an} + u_{bn}) = 0.5(0.5U_{PV} + 0.5U_{PV}) = 0.5U_{PV} \quad (7)$$

Therefore, the voltage remines unchanged, which leads to a limited leakage current according to equation (1).

3.3. Novel structures

When using H5 or HERIC topologies, additional switches have been added into the circuit to make CMV stays constantly thus PV array is theoretically isolated from the grid. However, the stray capacitance of the switches still leaves a flowing path for leakage current, which makes the isolation incomplete.

The topology of MOSFET neutral-point-clamped (M-NPC) inverter [9] is shown in Figure.3. This structure connects the midpoint of two capacitors on both input and output side, which allows CMV stay constant.

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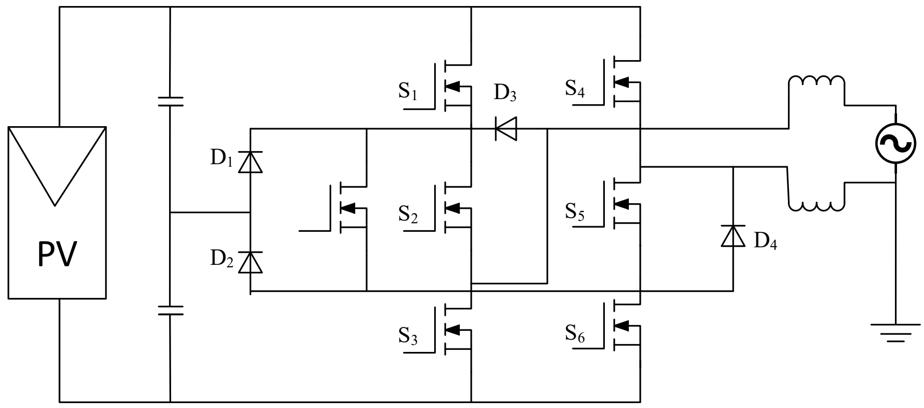

Figure 3. M-NPC topology.

A topology based on a switched-capacitor unit is proposed in [10]. The structure contains 2 power switches, a capacitor and a power diode. High efficiency and boosting ability can be achieved by switching the capacitors in a series-parallel way which allows capacitors charge or discharge alternately. Moreover, the harmonic is reduced by generating a multilevel waveform at the output side.

A switched-capacitor multilevel inverter (SCMLI) for PV system is presented in [11], which performs well on eliminating the leakage current. However, more capacitors have been used in this topology, which makes the structure less efficient comparing with other topologies. [12] proposed a cascaded 5-level H-bridge (CHB) structure, which can be generalized to higher levels.

Two structures that are capable for further dealing with leakage current are raised in [13], using a high-efficiency 5-level inverter. The structure has an output voltage of five-level leading to improve output current quality and reduce the harmonic distortion to the grid. Because of the connection between the outputs to the DC bus midpoint in the freewheeling bus, CMV oscillation and leakage current have been alleviated. This structure produces a high-quality current with lower THD compared with HERIC topology and M-NPC structure.

4. Modulation strategies for leakage current elimination

Widely-used space vector pulse width modulation (SVPWM) produces a high CMV amplitude and frequency which causes higher leakage current, and reduce the stability and safety of the PV grid-tied equipment system. In this section, analysis of modulation methods that proposed to control CMV and suppress the leakage current will be provided.

4.1. THIPWM method

SVPWM, SAPWM and THIPWM are the most commonly used method in electric industry. [14] analysed the CMV harmonic components of three methods by simulation. The zero-sequence voltage for three methods can be equivalent to:

$$V_{SV} = \frac{1}{2}\left[\frac{U_{dc}}{2} - \max\{V_x + k_x\} - \min\{V_x + k_x\}\right] \tag{8}$$

$$V_{SA} = -\frac{1}{2}[\max\{V_a, V_b, V_c\} - \min\{V_a, V_b, V_c\}] \tag{9}$$

$$V_{THI} = -\lambda V_m \cos(3\omega t + 3\theta_0) \tag{10}$$

λ is third-harmonic injection factor. Different waves of zero-sequence voltage indicate different influences to the common-mode loop.

The simulation result of the three methods shows that output current quality is improved with THIPWM method compared with SVPWM and SAPWM. A third-harmonic injection implementation method has been discussed in this paper, solved the problem of uncertain third-harmonic injection factor with a lower calculation burden of the controller by using current closed-loop control. This method has been used in Aotai Electric Co. non-isolated PV inverter series.

4.2. LMZVM method

LMZVM method has a clear effect on suppressing leakage current. The space-vector diagram contains 12 sectors and 13 vectors, constituted by 1 zero vector, 6 middle vectors and 6 large vectors. The CMV amplitude changes twice per cycle, while the maximum is $U_{dc}/6$. By using LMZVM method, CMV amplitude and frequency are reduced thus leakage current is limited [15].

However, due to the absence of regulation from small vectors, the system cannot run stably when neutral-point shift occurs. [16] proposed a mixed modulation of LMSVM and LMZVM. Comparing with LMZVM method, the proposed method has better performance on neutral-point regulation and a higher CMV frequency. When operating in practice, this method costs long regulation period, high fluctuation and complex management.

By improving LMZVM algorithm, [17] presents a large medium positive/negative small vector modulation (LMP/NSVM). The modulation is based on carrier wave, with better regulation and steady fluctuation.

4.3. Novel modulations

Guo et al. discussed the circumstances for transformerless three-phase flying capacitor PV inverters, and provide a modulation and logic function based on carrier wave to alleviate leakage current for the particular topology [18]. The method is able to maintain a constant CMV to eliminate the leakage current, but lose part of voltage vectors and thus lower the grid-tied current quality.

The methods presented below are not suitable for quansi-Z-source three-level T-type inverter (3LT2I). Qin et al. further introduced a space vector modulation (SVM) based on quasi-Z-Source 3LT2I which aims to solve the limitation of voltage buck operation for conventional three-level inverters [19]. This method inserts shooting-through states within zero vector by selecting shooting-through phase properly, thus the output voltage will not be affected. Therefore, CMV produced in 3LT2I can be limited to $U_{dc}/6$, with a voltage boosting simultaneously.

Solutions based on improved LCL (ILCL) filters have been also considered for its limited harmonic and lower magnetic core loss [14]. Comparing with single L and LC filter, LCL filter has a higher quality in restraining high frequency harmonic component of output current and preventing harmonic wave from injecting into the grid, therefore the high-frequency leakage current to ground is reduced by adding an ILCL filter in the circuit. However, resonance current generated in differential-mode (DM) circuit causes an additional common-mode resonance circulating current (CMRCC) which needs to be suppressed.

To solve the problem of leakage current increment and system instability for PV inverters with ILCL filter, several methods has been proposed. The authors adopted a damping resistor and active method to reduce the resonant current produced by CM and DM circuit, however, the method using a damping resistor will cause an increasing filter impedance that leads to increasing leakage current and power loss [20-22]. Different lossless active control methods were presented to reduce the DM resonance current with capacitor voltage-feedforward used in [22] and capacitor current-feedback used in [20], moreover, the time-delay problem is concerned by proper instant shifting.

Aiming to suppression of CMRCC, a mixed control strategy with PI and feed-forward control is mentioned in [23]. This method is achieved by adjusting zero-sequence duty cycle in each PWM cycles. The method efficiently suppresses the CMRCC therefore reduce the THD of inverter-side current.

5. Conclusion

Transformerless grid-tied inverters are now widely used for its advantages on cost and efficiency compared to isolated inverters. To deal with the leakage current arouse by CMV produced by stray capacitance between PV array and circuit, which would lower the output current quality and endanger human safety, topologies and modulation strategies are proposed.

This paper has presented a theoretical analysis of the formation of CMV and leakage current caused by stray capacitance in PV systems, with basic principles of reducing leakage current from both topology and modulation method. Commonly used topologies such as H5, H6, HERIC, NPC, CHB structures have been introduced both in theoretical way and practical engineering, while based on these structures some proposed topologies raised in recent years are also presented. For prominent modulation methods, THIPWM has better performance on common-mode resonant current control comparing with SVPWM and SAPWM. LMZVM and LMSVM are evaluated in their functions of suppressing leakage current, and recent improvements of these methods are mentioned. On the other hand, solutions based on LCL filters are presented. In engineering conditions, instead of experimentally excellent, stability, low cost and less burden of manipulation should be considered cautiously. The detailed analysis of these methods has its significance for reference in actual applications.

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