An on-Line Extraction Method for the Parasitic Capacitance of the Photovoltaic Panel

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Abstract—In the photovoltaic (PV) plant, the parasitic capacitance between the PV panel and the ground (C_{pv}) causes leakage current in the non-isolated systems. The case can be deteriorated in the rainy environment because the C_{pv} increases dramatically due to the rainwater. The existing off-line methods are either through simulation or measurement by impedance analyzer, which are not easy to conduct on-site especially in the PV plant when it rains. The existing on-line capacitance measurement method is to measure the amplitude of the main components of voltage and current on the capacitance, but the measurement results are inaccurate because the parasitic resistance and inductance of the PV panels are not considered. This paper presents a simple on-line extraction method for the C_{pv} , which is obtained through measurement of the oscillation period of the leakage current. In this way, the C_{pv} can be obtained even the equipment is running. The principle is analyzed in a full-bridge case and the simulation and experiment are carried out for the verification. Finally, the C_{pv} obtained in this method is compared with the 3D finite element simulation, the measurement by impedance analyzer and the existing on-line calculation method, which shows the accuracy of this proposed method.

Index Terms—Leakage current, parasitic capacitance, photovoltaic panel, oscillation.

I. INTRODUCTION

THE parasitic capacitances between the photovoltaic (PV) panel and the ground (C_{pv}) can be regarded as the sum of the three parts: cell-to-frame capacitance C_{cf} , cell-to-rack capacitance C_{cr} and cell-to-ground capacitance C_{cg} [1]–[4]. Other parasitic parameters of the PV panel, such as the equivalent inductance and resistance of the frame, rack and cable L_e and R_e [2]. As shown in Fig. 1(a). The C_{pv} depends on the installation method and the size of the panel [5]–[10]. Meanwhile, the rainwater as an electrode or dielectric can change the capacitances, sometimes dramatically [2]–[4]. In normal environment, the C_{pv} can vary from 7 nF/kW [11]–[12]

Fig. 1. (a) Distributed parasitic capacitance model of PV panel. (b) Simplified common mode leakage current in a PV transformerless inverter.

to 220 nF/kW [13]–[14]. However, it can even reach 1 μ F/kW in damp environment [2], [15]. In non-isolated systems, the parasitic capacitance C_{pv} causes common-mode (CM) current [5], [8], [16], as shown in Fig. 1(b). The CM current is sensitive to the C_{pv} , so it is crucial to extract the capacitance value accurately [2]–[5].

There are many researches on the extraction of this capacitance, the methods can be mainly characterized into four categories: analytical method [2], [11], [17]–[19]; numerical simulation [1]–[4], [20]; direct measurement method [4], [21] and indirect measurement method [7], [9], [22], [23].

The analytical method is to calculate the capacitance of the object based on the existing theoretical formulas. It is necessary to measure the shape and size of the PV panel, then calculate the capacitance according to the obtained data. But in the reality, the size of PV panels is complex and irregular that causes difficulty measuring [2]. In an ideal environment, the calculation process is relatively simple, but it will become very complicated when considering the actual factors such as edge effect.

By using the finite element (FE) analysis software such as Ansys Maxwell, the manual complicated operations can be avoided, so the numerical simulation method is proposed [2]–[4]. But the accurate results of this method still depend on accurate measurement and modeling. When the model contains too many factors such as the actual environment, it will lead to a time-consuming simulation.

Compared to the methods of analytical and numerical calculation, the direct measurement method will achieve accurate results with no consideration of factors such as size and environment. This method uses the test equipment such as impedance analyzer to get the measurement results directly. However, when many PV panels are connected in series, the high voltage of the ports will make the measurement process unsafe. Furthermore, this is an off-line measurement

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method, which is hard to operate on-site especially when the environmental factors change.

Thus, the indirect method can be applied to get the parasitic capacitance by measuring other electrical parameters on-line in the circuit. [7], [9] calculates the C_{PV} based on the amplitude of main components of voltage and current on the capacitance. According to Ohm's law, a series of capacitance values can be calculated under a series of voltage harmonics and current harmonic components. Then C_{PV} obtained by average of the series of capacitances. This is an on-line method to obtain the parasitic capacitance value, but it requires simultaneous measurement the amplitude of main components of voltage and current on the capacitance and does not consider the effects of parasitic resistance and inductance of the PV panels such as L_e and R_e . This will cause complex test operations and inaccurate results.

In order to solve the problems above, this paper proposes a simple on-line C_{PV} extraction method, which not only overcomes the shortcomings of off-line methods but also ensures the accuracy of the results. Firstly, by analyzing each switching process of single-phase full-bridge inverter circuit, a unified resonant circuit model is obtained. Secondly, according to the model, the relationship between the C_{PV} and the leakage current oscillation period T is derived. Then, simulations and experiments are presented below. Finally, the parasitic capacitance obtained in this proposed method is compared with the 3D FE simulation, the measurement by impedance analyzer and the existing on-line calculation method, which shows the accuracy of this method.

II. PHOTOVOLTAIC PANEL PARASITIC CAPACITANCE EXTRACTION METHOD

The single-phase full-bridge non-isolated inverter is chosen as an example for analysis in this paper, as shown in Fig. 2. The PV is a series of photovoltaic panels. C_{DC} is the DC side support capacitance that usually is a Millifarad level capacitance. $S_1 \sim S_4$ are the switches that form the full bridge. L_1 and L_2 are the filter inductance. C is the filter capacitance that is usually above 10 μF . R is a resistance load. R_g represents the resistance between load ground and chassis of the inverter. The V_{DC} is the voltage of the C_{DC} , which is considered as a stable voltage source. The $v_{C_{PV}}$ is the voltage of the C_{PV} , and its changes will lead to a leakage current i_{leak} [15]. The points 1 and 2 represent the outputs of bridges respectively, a and b are the two ends of the PV and the ground.

In Fig. 2, L_{bus1} , L_{bus2} , L_{bus3} and L_{bus4} are stray line inductances [5]. C_{p1} , C_{p2} , C_{p3} , and C_{p4} are the parasitic capacitances between the switch-to-heatsink/ground [24]. Due to the C_{PV} in a PV plant is much larger than the switch-to-heatsink/ground capacitances [24], [25], and the switch-to-heatsink/ground parasitic capacitances are connected in parallel with C_{PV} , so the capacitance of the switches can be ignored. The inductance of the filter inductor is much larger than the stray inductances of the line [5], and the stray inductances are connected in series with the filter inductances, so the stray inductance of the line

Fig. 2. Single-phase full-bridge non-isolated inverter with parasitics.

TABLE I
SWITCHING STATE OF UNIPOLAR & FREQUENCY MULTIPLICATION SPWM STRATEGY

State	Output	S_1	S_2	S_3	S_4
State1	P	ON	OFF	OFF	ON
State2	O1	ON	ON	OFF	OFF
State3	O2	OFF	OFF	ON	ON
State4	N	OFF	ON	ON	OFF

Fig. 3. The states of single-phase full-bridge circuit under the unipolar & frequency multiplication SPWM. (a) State 1. (b) State 2. (c) State 3. (d) State 4.

can be ignored.

When using the unipolar & frequency multiplication sinusoidal pulse width modulation (SPWM), the four switch states and output modes are shown in Table I. In the positive half cycle, the output of bridge switches between state 1 and state 2, or state 1 and state 3. And in the negative half cycle, the output is between state 2 and state 4, or state 3 and state 4. Next, the above switching processes will be analyzed respectively.

The circuit in these four states is shown in Fig. 3. The switch can be considered as short when it is active, the considered

Fig. 4. The simplified models of switching processes. (a) State 1 to state 2 (state 2 to state 1). (b) State 1 to state 3 (state 3 to state 1). (c) State 4 to state 2 (state 2 to state 4). (d) State 4 to state 3 (state 3 to state 4).

as open in other conditions. Based on these assumptions, the switching processes discussed above can be simplified as shown in Fig. 4.

The simplified models of switching processes are shown in Fig. 4, which the dotted line indicates the processes in the brackets. Then the models can be classified into the following four models. The model after switching from state 2 to state 1 (or state 3 to state 1) is shown in Fig. 5(a); the model after the switching from state 1 to state 2 (or state 4 to state 2) is shown in Fig. 5(b); the model after the switching from state 1 to state 3 (or state 4 to state 3) is shown in Fig. 5(c); the model after the switching from state 2 to state 4 (or state 3 to state 4) is shown in Fig. 5(d).

The oscillation period of the high-order circuit is only related to its structure, therefore the source can be ignored because it does not affect the resonant period in the circuit. Meanwhile, due to the support capacitor C_{DC} and the filter capacitance C are very large, they can be regarded as a short circuit in a high frequency environment. Then the classified models are normalized to a final model that is shown in Fig. 6.

From the final model, it is known that:

$$f_r = \frac{1}{2\pi\sqrt{L_{eq} \times C_{PV}}} \quad (1)$$

The f_r is the oscillation frequency of the equivalent resonant circuit model. The L_{eq} is the equivalent inductance of this equivalent resonant circuit model. The L_e inductance of the PV frame, rack and cable is much smaller than the filter inductor [2], and this inductance is connected in series with the filter inductances, so L_e can be ignored.

In Fig. 6(b), the L_{eq} is:

$$L_{eq} = \frac{L_1 \times L_2}{L_1 + L_2} \quad (2)$$

The R_{eq} is the equivalent resistance of this equivalent

Fig. 5. The classified models of the switching processes. (a) State 2 to state 1 (state 3 to state 1). (b) State 1 to state 2 (state 4 to state 2). (c) State 1 to state 3 (state 4 to state 3). (d) State 2 to state 4 (state 3 to state 4).

Fig. 6. (a) Equivalent resonant circuit model in each switching states. (b) Final equivalent resonant circuit model.

resonant circuit model, but R_{eq} has no effect on the resonant frequency and only affects the amplitude of the oscillation. Therefore, the C_{PV} extraction method proposed in this paper is more accurate than the existing online methods.

Since the impedance at the resonance frequency point is the smallest, there is a large current at the oscillation frequency of the equivalent resonance circuit, so the oscillation frequency of the leakage current is the oscillation frequency of the equivalent circuit.

The relationship between the parasitic capacitance C_{PV} and the oscillation period of the leakage current T is:

$$C_{PV} = \frac{L_1 + L_2}{4\pi^2 \times L_1 \times L_2} \times T^2 \quad (3)$$

Through (3), when the leakage current oscillation period T is obtained, the parasitic capacitance value of the PV panel C_{PV} can be calculated.

III. SIMULATION RESULTS

In order to verify the relationship between the T and the

TABLE II
KEY PARAMETERS

Parameter	Value
Input DC Voltage V_{DC}	18 V
Filter Inductance 1 L_1	1 mH
Filter Inductance 2 L_2	1 mH
Filter Capacitance C	25 μ F
Load Resistance R	5 Ω
Photovoltaic panel parasitic capacitance C_{PV}	5 μ F

Fig. 7. (a) The main simulation waveforms when C_{PV} is 5 nF. (b) Zoom in the main waveforms to get the oscillation period.

C_{PV} , a single-phase full-bridge simulation circuit is built. In the simulation, a certain value C_{PV} is given to measure the T . The key simulation parameters are listed in Table II.

When the value of C_{PV} is 5 nF, the main waveforms are shown in Fig. 7, in which, v_R is the voltage of the load resistance, $v_{C_{PV}}$ is the voltage of the C_{PV} and i_{leak} is the current of C_{PV} .

It can obtain the leakage current oscillation period value T of the simulation waveforms is 9.9 μ s when the C_{PV} is 5 nF. Then,

Fig. 8. (a) Simulation and calculation of the relationship between the parasitic capacitance value and the oscillation period. (b) Zoom in on the part of (a).

under the other parameters of simulation, T is brought into (3) and calculated the value of C_{PV} is about 5 nF.

In order to verify the relationship between the C_{PV} and T , the simulation is carried out under different C_{PV} . Fig. 8 shows the comparison between the simulated values and the calculated values by (3). It can get that the T obtained by circuit simulation and theoretical analysis is basically the same under the different C_{PV} values.

IV. EXPERIMENTAL RESULTS

In order to verify the correctness of the proposed method and accurately obtain the value of C_{PV} , the following experiments were carried out. First, an actual capacitor is connected to the DC source to simulate the PV panel to do the experiment. Then experiment with the actual PV panel, which type is SFPVM-50. Finally, the impedance analyzer is used to measure the C_{PV} of this actual PV panel under the same environment as the circuit experiment.

The single-phase full-bridge inverter experimental platform is shown in Fig. 9. The values of the DC voltage, filter inductance, filter capacitance, and the load are the same as those in Table II. The MOSFET used in the experiment inverter is IRF540NPbF. The inverter uses unipolar & frequency multiplication SPWM modulation with a switching frequency of 5 kHz. The leakage current is picked up by Tektronix TCP305 current probe and then analyzed by Tektronix MDO324 oscilloscope to get the time-domain waveform oscillation period and the Fast Fourier Transform (FFT) results.

Fig. 9. Single-phase full-bridge inverter experimental platform.

Fig. 10. (a) The main time-domain experimental waveforms for DC source circuit verification. (b) Zoom in on the main waveforms to get the oscillation period.

A. DC Source Experimental Verification of Oscillation Method

An actual 5 nF capacitance is connected to the 18 V DC source to simulate the PV panel to do the experiment. Fig. 10 shows the main time-domain experimental waveforms under the same parameters of the simulation above. Compared with the simulation, the parameters such as the actual device are not ideal, which results in the difference between the actual circuit waveforms and the simulation waveforms. The parasitic resistance in the loop consumes energy, causing the oscillation of the actual circuit is attenuation oscillation, but not affect the oscillation period of leakage current.

In order to observe the resonant frequency point more conveniently, the time-domain waveform of leakage current is analyzed by FFT, and the result is shown in Fig. 11. Due to the noise energy of the inverter is mainly concentrated near the switching frequency of integer multiples, the leakage current will have a series of peaks at the corresponding frequency point. However, At the resonant frequency point, the peak is more obvious because of the smallest impedance of the circuit

Fig. 11. Leakage current spectrum distribution map.

Fig. 12. Experimental and calculation of the relationship between the parasitic capacitance value and the oscillation period.

[26]. The amplitude of the leakage current harmonic at 100 kHz is the largest, and the system has a resonant peak near this frequency. The oscillation periods obtained in the time-domain and the frequency-domain are basically the same.

From the experimental time-domain waveforms and the spectral distribution, the leakage current oscillation period of the actual capacitance of 5 nF is about 9.6 us. Bring this oscillation period T into (3), and the calculated C_{PV} is 4.67 nF. The experimental result error is 6.6%, which is within the acceptable error range.

The reasons for the error may be:

- 1) The actual capacitance used and the filter inductances are not standard;
- 2) Errors caused by the experimental process;
- 3) Simplification in theoretical analysis.

In order to verify the method proposed in this paper, the experimental is carried out under different C_{PV} . Fig. 12 shows the comparison between the experimented values and the calculated values by (3). The results show that the T values obtained from the circuit experiment and theoretical analysis are very close at different C_{PV} values. When the C_{PV} is PicoFarad level, the experimental value is larger than the calculated value, because other parasitic parameters in the circuit, such as the parasitic capacitances between the switch-to- heatsink/ground, cannot be ignored directly. However in the actual PV plant, the C_{PV} vary from 7 nF/kW [11]–[12] to 220 nF/kW [13]–[14], the method proposed in this paper can accurately extract the C_{PV} of the actual PV plant.

Fig. 13. (a) 3D FE simulation method. (b) Impedance analyzer measurement platform.

B. Comparison of Photovoltaic Panel Parasitic Capacitance Extraction Methods

Because the C_{PV} will increase dramatically in a rainy environment [2]–[4], which has a great influence on the leakage current of the non-isolated system. It is important to extract the capacitance value accurately in a damp environment, so researchers pay more attention to C_{PV} in a rainy environment. This part compared with the on-line extraction method proposed in this paper with 3D FE simulation, the measurement by impedance analyzer and existing on-line calculation method, which are compared under the same rainy environment. The 3D FE simulation and the measurement through the impedance analyzer platform are shown in Fig. 13. The existing on-line calculation method platform is similar to the experimental platform of this paper, which is shown in Fig. 9.

According to the size of the actual PV panel, the PV model in the rainy environment is established in Ansys Maxwell, and the value of C_{PV} is obtained by simulation. The method of impedance analyzer measurement picks up the C_{PV} by Chroma 3302. Simulating the PV panel in the rainy environment by adding water to the PV panel. During the experiment, it was found that when the thickness of the water added to the PV was about 3 millimeters, the value of C_{PV} reached the maximum, so the PV in the experiment was carried out after adding water of 3 millimeters.

In the same rainy environment, an actual 18 V PV panel to do the experiment. the period in the on-line oscillation period method proposed in this paper can be obtained from the time-domain or frequency-domain of the leakage current. Fig. 14 shows the main time-domain experimental waveforms with the

Fig. 14. (a) The main time-domain experimental waveforms for the PV panel in the rainy environment. (b) Zoom in on the main waveforms to get the oscillation period.

Fig. 15. Leakage current spectrum distribution map in the rainy environment.

PV panel in the rainy environment. Fig. 15 shows the spectrum distribution of the leakage current in the rainy environment.

The parasitic resistance in the loop consumes energy, causing the oscillation of the actual circuit is attenuation oscillation. The amplitude of the leakage current harmonic at 115 kHz is the largest, and the system has a resonant peak near this frequency. From the time-domain experimental waveforms and the resonant peak of the spectrum distribution, the leakage current oscillation period T is 8.6 μ s, which is brought to the (3), and the calculated C_{PV} is 3.75 nF.

According to the existing on-line calculation method by reference [7], Table III shows the main components of voltage and current on the capacitance.

The C_{PV} value 3.21 nF was obtained by average of the series of calculated capacitance values in Table III. The results of the C_{PV} values of these four extracted are shown in Table IV.

The parasitic capacitance values extracted by these four

TABLE III
THE EXISTING ON-LINK CALCULATION METHOD

Harmonic frequency f (kHz)	Voltage on the capacitance V_{Cp} (V)	Current on the capacitance I_{Cp} (mA)	Capacitance (nF)
5	5.4	0.6	3.54
15	1.2	0.37	3.27
25	0.6	0.32	3.39
35	0.4	0.3	3.41
45	0.34	0.32	3.33
55	0.3	0.35	3.38
65	0.27	0.36	3.26
75	0.28	0.41	3.11
85	0.29	0.51	3.29
95	0.37	0.68	3.08
105	0.5	0.98	2.97
115	0.67	1.3	2.95
125	0.42	0.94	2.85

TABLE IV
PHOTOVOLTAIC PARASITIC CAPACITANCE VALUES OBTAINED UNDER DIFFERENT MEASUREMENT MODES

Measurement method	Parasitic capacitance C_{PV}
3D finite element simulation	3.50 nF
Impedance analyzer test	3.85 nF
Circuit test of oscillation period in this paper	3.75 nF
The existing on-line calculation method	3.21 nF

methods are close to each other. The method of the numerical simulation depends on the accurate establishment of the model. Although the direct method can be measured accurately, the off-line method is not suitable for the actual variable environment. The existing on-line calculation method does not take into account the effects of parasitic resistance of the PV panels, resulting in inaccurate results. From the above experiments, the on-line method proposed in this paper to extract the C_{PV} based on the leakage current oscillation period can accurately extract the value of C_{PV} .

V. CONCLUSIONS

This paper analyzes the switching processes of the single-phase full-bridge non-isolated inverter. Through these switching processes, a simplified resonant model is obtained. And the relationship between parasitic capacitance and leakage current oscillation period is derived. Through the analysis of the leakage current oscillation mechanism and the limitations of the existing PV panel parasitic capacitance extraction methods, this paper proposes an on-line method suitable for the actual running environment. After theoretical analysis

and simulations, then carries out experimental verification. The measurement is convenient and accurate. Finally, in the rainwater environment, this method is compared with the extraction method of 3D FE simulation, impedance analyzer test and the existing on-line calculation method, the accuracy of this method is verified.

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