Complete Parasitic Capacitance Model of Photovoltaic Panel Considering the Rain Water

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Abstract: Common mode current suppression is important to grid-connected photovoltaic (PV) systems and depends strongly on the value of the parasitic capacitance between the PV panel and the ground. Some parasitic capacitance models have been proposed to evaluate the magnitude of the effective parasitic capacitance. However, the proposed model is only for the PV panels under dry and clean environmental conditions. The dependence of rain water on the capacitance is simply described rather than analyzing in detail. Furthermore, the effects of water are addressed quite differently in papers. Thus, this paper gives complete parasitic capacitance model of the PV panel considering the rain water. The effect of the water on the capacitance is systematically investigated through 3D finite element (FE) electromagnetic (EM) simulations and experiments. Accordingly, it is clarified how the water affects the parasitic capacitance and methods of minimization of the capacitance are proposed.

Keywords: Parasitic capacitance, photovoltaic panel, water, 3D FE EM analysis, electromagnetic field.

1 Introduction

It is known that common mode current is generated in non-isolated photovoltaic inverters due to grounded loop caused by parasitic capacitances[1-4].

Because of the parasitic capacitance, the leakage current can flow through the panels and the earth, leading to serious problems such as: grid current distortion, radiated electromagnetic interferences(EMI) and additional losses in the PV system[5-6]. The seriousness of these effects has been an area of concern and controversial discussion over past years. The techniques to suppress the leakage current can be divided into the main three groups: modulations solutions[7-8], topology solutions[9-10], power filter solutions[11-13].

Among the common mode loop impedance, the parasitic capacitance is also a key factor that greatly influences the leakage current[1-2]. Although, there have been many papers established to study this parasitic parameter, little attention is paid on how to suppress the leakage current by reducing the parasitic capacitance. The previous research of parasitic capacitance can be characterized simply into two groups: single-capacitor model[14-16]and multi-conductor array model[17-19].These models of the parasitic capacitance are mostly used to analyses the parasitic capacitance as leakage current path. It is not enough to provide the direct guidance for minimization of the capacitance based on these models.

The value of this parasitic capacitance depends on several factors, e.g., the size of the module, the height above the ground, the weather conditions and relative humidity[20-21], the way to obtain the value is mainly estimation based on experience. It varies from 7nF/kW to 220nF/kW[22-23]. Some papers address the parasitic capacitance of PV panel becomes larger in the humid environment. However, they do not give more explanation on how the weather condition influences the parasitic capacitance and why heavy humidity or rain might result in a significant boost of parasitic capacitance. In [24], it is proposed that if the panel surface is wet, the relative permittivity of the water turns out to be 80 in calculation and the parasitic capacitance will increase dramatically compared with dry surface condition. Nevertheless, in [25], the explanation as to why the parasitic capacitance becomes larger in the rain condition is that the surface of PV panel is covered by a conducting layer that increases the effective area between silicon cells and frame. It remains unclear whether the water should be considered as a dielectric or an electrode and how it affects the panel capacitance.

This paper gives systematic research on the parasitic capacitance of the PV panel. The research starts with establishing models of parasitic capacitance of a PV panel. Then, the effect of the water on the parasitic capacitance is analyzed by considering it as a dielectric or an electrode respectively through numerous 3D FE EM simulations. Further, the EM mechanism behind is carefully examined for better understanding. Finally, experiments are conducted to validate the simulation and clarify the property of the water. Based on the analysis, the complete parasitic capacitance model of the PV panel considering the rain water is established and some methods are proposed to minimize the parasitic capacitance.

2 The capacitance model of the PV panel in the dry environmental conditions

The PV cell is an energy converter with a crystal diode that uses these miconductor P-N junctions to convert light energy into electrical energy. In order to extract the voltage and current generated by the photovoltaic effect, the upper surface of the silicon cell will be made by the metal grid line where the whole

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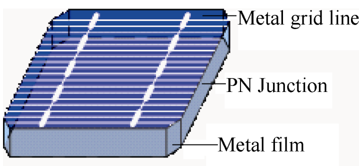
back surface is attached by a layer of metal film, as shown in Fig.1(a). The electrode area on the cell module of a PV panel depends on the power of the PV panel, shown in Fig.1(b), the larger the power, the greater the electrode area of the cell module.

Given the structure of the PV panel, the other electrodes of the PV panel are the aluminum frame, the rack and the generalized earth. The simplified diagrams of these electrodes are shown in Fig.2.

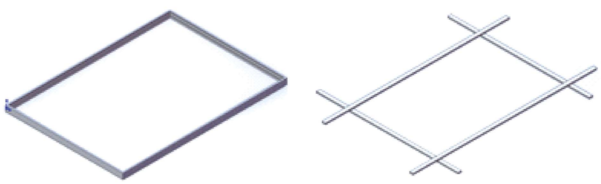
Generally, the aluminum frame of the PV panel, the metal rack, the generalized earth and the silicon cell will form a multi conductor capacitance matrix: cell-to-frame capacitance C_{cf}, cell-to-rack capacitance C_{cr}, cell-to-ground capacitance C_{cg}, frame-to-rack capacitance C_{fr}, frame-to-ground capacitance C_{fg}, rack-to-ground capacitance C_{rg}. In fact, the aluminum frame and the rack are always grounded. So C_{fr}, C_{fg}, C_{rg} will not exit in the real PV system. In [24], the detailed pi-shape model is proposed, the parasitic capacitance are split into three parts, the C_{cg}, the C_{cf} and the C_{cr}, as illustrated in Fig.3(a). The capacitance model in dry and clean conditions can be extracted in Fig.3(b). Since the aluminum frame and the mounting rack are all grounded in the real PV system, for the sake of simplicity, it is assumed that they have the same potential level. Therefore, these three capacitances are paralleled, and the total parasitic capacitance of a single piece PV panel should be the sum of the three parts.



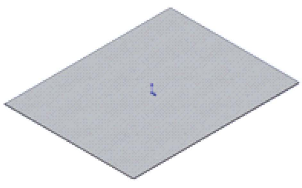
(a) A silicon cell

(b) The cell module

Fig.1 The electrode of the silicon cell

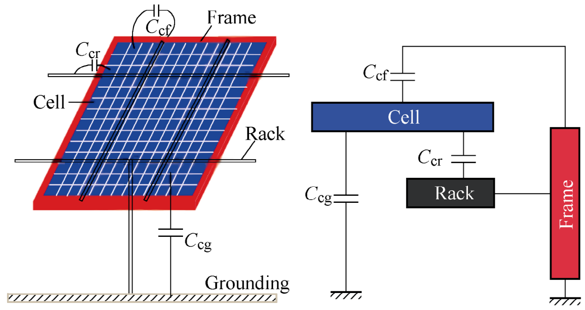


(a) The aluminum frame (b) The rack



(c) The earth

Fig.2 The other three electrodes



(a) The traditional capacitance model of a PV panel (b) Three types of panel capacitances

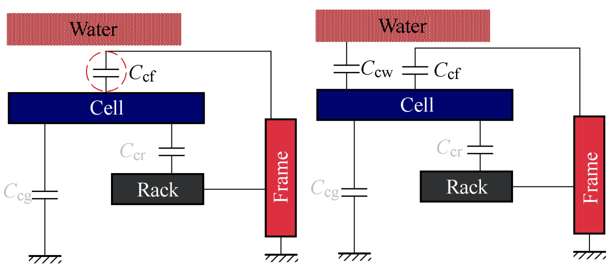
Fig.3 Parasitic capacitance model for a PV panel

The C_{cf} has a certain relationship to the frame size of the PV panel. The C_{cr} is related to the structure, size and shape of racks, where its value is very small when compared with C_{cf}. The C_{cg} depends on the height of ground. If the height between the panel and the ground is more than 500mm, C_{cg} is less than 20pF per square meter and can be omitted. In addition to the factors of the PV panel itself, weather related factor can play a main role which influences the parasitic capacitance. The capacitance C_{cr} and C_{cg} are not easily affected by the weather condition. Thus, both the parasitic capacitances C_{cr} and C_{cg} can be neglected in the following analysis. The capacitance C_{cf} is the dominant parasitic capacitance in PV panel. In this paper, how the water affects the capacitance C_{cf} will be investigated in detail. The principle can also be applied to the C_{cr} and C_{cg}.

According to previous research related to the capacitance in rain conditions, the property of water can be summarized as one of two categories: a dielectric with high permittivity or an electrode equivalent to a conducting layer. If the water is only considered as the dielectric, it may have some effects on the C_{cf}, where the corresponding model is shown in Fig.4(a). If it is considered as the electrode, a new capacitance coupling between cell and water may be formed. Cell-to-water capacitance C_{cw} will be added to the model, as proposed in Fig.4(b). The next analysis will investigate the real reason for the effect of water on the capacitance.

3 The effect of water on the PV panel capacitance

The C_{cg} is coupled by the two electrodes silicon cell and the frame. It is the intrinsic capacitance of a PV panel, and the value comparatively is fixed when

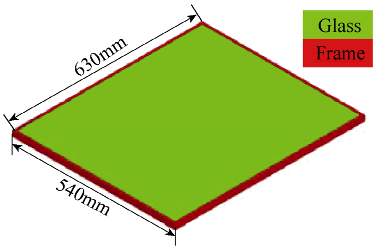


(a) The model of water as dielectric (b) The model of water as electrode

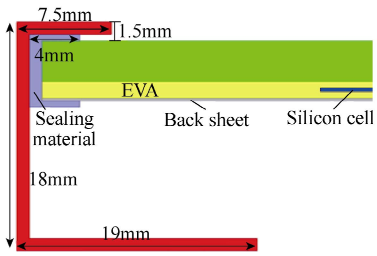
Fig.4 Capacitance models extracted from the previous paper the panel has been manufactured. The region between silicon cell and frame is not a standard parallel plate capacitor structure. In [26], this structure of capacitive coupling between silicon cell and frame is called the parasitic edge capacitance and some analytical formulas are derived to calculate the value of C_{cf}. The method by formulas is not inadvisable here due to its complexity. 3D FE EM simulations are employed for a comprehensive analysis.

3.1 The 3D simulation model

According to the actual construction of the PV panel, the simulation model can be built in Ansys Maxwell 3D. The effects of permittivity and size of the inner materials (glass, EVA, back sheet, etc.) are taken into account the capacitance simulation. Fig.5(a) shows the simulation model referring to the real PV panel with rated power 50W. The thickness and permittivity of each layer are listed in Table 1. The overall dimensions can be measured and the thickness of the glass and is provided by the manufacturer. The other thicknesses of the inner layers are not provided and hard to measure. Also, the permittivity of the materials is not provided either. However, this data can be obtained from paper[24]. The permittivity of the material is similar from case to case, but the thickness of the inner layers can vary a little bit for different PV panels. However, because the inner layers, such as EVA and edge seal, are much thinner than the glass, their effect on the parasitic capacitance just take a minor part. Further, the error of their thickness only affects the absolute capacitance rather than the effect of the water on the parasitic capacitance.



(a) Simulation model



(b) The physical structure and dimensions

Fig.5 Simulation models in Ansys Maxwell

Table 1 Simulation parameters

Layer	Thickness/mm	Relative permittivity ε_r
Frame	1.0	—
Glass	3.2	5.7
EVA	0.5	2.6
Si	0.3	—
Edge seal	0.5	4.4
Back sheet	0.2	10

3.2 Simulation analysis of effect of the water as a dielectric or an electrode

In simulation, software can only treat water as an electrode or a dielectric in one process. Thus, in the following research, the property of water is assigned as a dielectric and an electrode respectively for comparative analysis. The research covers the dependence of positions and physical dimensions of the water on the parasitic capacitance.

3.2.1 Effect of the position of water

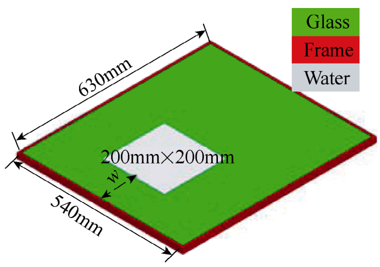
Modeling of the position variation of the rain in the panel surface using the water block model is shown in Fig.6(a). The water touches the frame at beginning, then the distance w keeps increasing along the direction until the water block touches another side frame.

The simulated result is shown in Fig.6(b). The C_{cf_water} represents the simulation value of cell-to-frame capacitance C_{cf} with the water in the panel surface. It can be observed that when the water block has a certain distance with the frame, in both situations, the C_{cf_water} is about 61pF, which is the same value as the simulated results of the PV panel surface without water. When the water touches the frame, the value of C_{cf_water} will increase, especially for the water as an electrode. Its value is much greater than water as a dielectric.

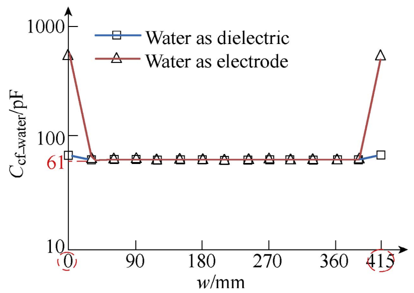
3.2.2 Effect of the water size

- No electrical contacts with the frame

The water block is placed in the middle of the panel surface in Fig.7(a). Its width w keeps increasing from 200mm to 500mm. The simulated results of C_{cf_water} versus width w are shown in Fig.7(b). As the water area gradually become larger, both the C_{cf} under these two situations basically keep a steady value about 61pF, which is the same value as the simulated results of the PV panel surface without water. Thus, no matter what the properties of the water, there is no influence on the C_{cf} if the water keeps a distance with the frame.

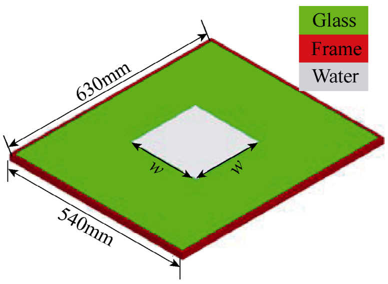


(a) 3D simulation model of a panel with a water block in the surface

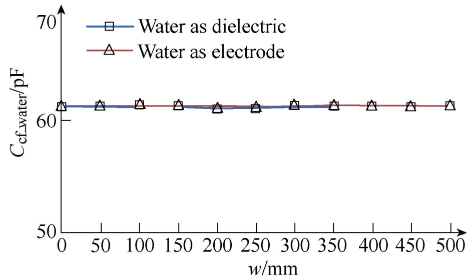


(b) Simulated C_{cf_water} at different positions

Fig.6 The effect of water on C_{cf} in different position



(a) 3D model of a panel with a water block in the center



(b) Simulated C_{cf_water}

Fig.7 The effect of water area on the capacitance C_{cf} when the water has no electrical contacts with the frame

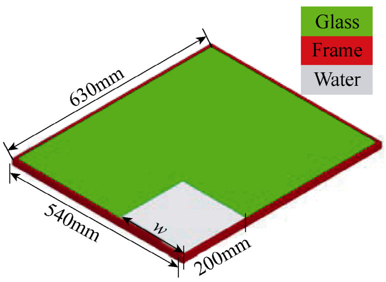
- Electrical contacts with adjacent sides of the frame

One side of the water block electrically contacts with the frame with the width of 200mm, while the other side be elongated along the frame, as shown in Fig.8(a).

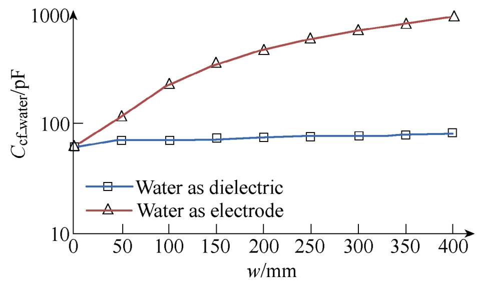
As shown in Fig.8(b), although the simulation results of water as an electrode is much larger than water as a dielectric, in both the two cases, capacitance is getting larger as w is gaining its length. Thus, no matter if water works as a dielectric or an electrode, the larger the exposure to the frame, the greater the capacitance is.

- Electrical contacts with all sides of the frame

The marginal area of the panel is gathered by the water, its width w keeps increasing until the water covers all the panel surface, as shown in Fig.9(a).

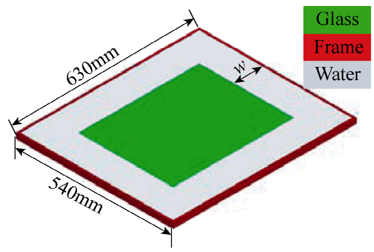


(a) 3D model of a panel with a water block touching two edges

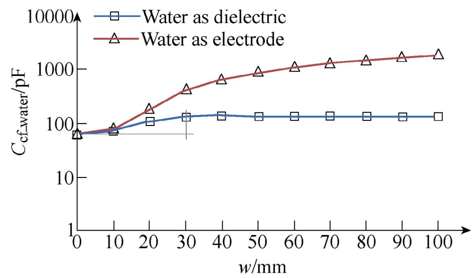


(b) Simulated C_{cf_water}

Fig.8 The effect of water area on the capacitance C_{cf} when the water electrically contacts with adjacent sides of the frame



(a) 3D model of a panel with water touching all edges



(b) Simulated C_{cf_water}

Fig.9 The effect of water area on the capacitance C_{cf} when the water electrically contacts with all sides of the frame

The simulation results are shown in Fig.9(b). It can be seen that if water is assigned as a dielectric, the capacitance increases as width w increases in the initial stage. Then, the value remains steady as the width w reached about 30mm and beyond. By contrast, if water works as an electrode, the capacitance increases as the width w increases and becomes the maximum when water covers all the surface panel. It can be seen that the capacitance caused by the water as an electrode is 30 times larger than that caused by the water as a dielectric.

According to the simulation results, some guidelines can be concluded. Fig.10 shows the effective area of water that influences the capacitance C_{cf}. The panel can be divided into two areas that are A and B. Area B is the close region near the edges of the panel and A is the middle region not adjacent to the edges.

- If the water is considered as a dielectric, it is able to affect the C_{cf} only when it gathers in area B. The water in region A has no effect on the capacitance.
- If the water is considered as an electrode, it has influence on the capacitance only when it electrically contacts the edge. The capacitance C_{cf} increases proportionally with the area of the water.
- When the water fully covers the panel, the capacitance C_{cf} simulated if the water is considered as electrode is about 30 times larger than that if the water is considered as a dielectric. It shows that the increase of the capacitance C_{cf} affected by the water as electrode is much larger than that if the water is a dielectric.

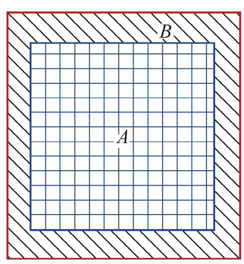


Fig.10 The effective area of water that influences on the capacitance C_{cf} of a PV panel

3.3 The EM field mechanization behind the parasitic capacitance

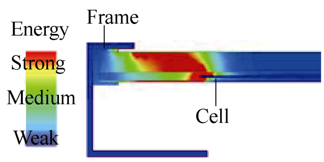
In an effort to obtain an insight into these issues, electric field energy (EFE) simulation is employed here to investigate the electric field energy distribution responsible for the capacitance value. The stronger the energy the greater the capacitance value is.

The following Fig.11 shows the distribution of the 2D electric field energy of PV panel in different situations. Fig.11(a) shows the simulation results of panel model without water on surface, the EFE mainly concentrates on the edge area of the silicon cell. It indicates that the capacitive coupling space is between the frame and the cell in dry conditions. When a layer of water covers the surface panel and keeps a certain distance from the frame, the distribution of EFE is similar with the PV panel in a dry condition, as shown in Fig.11(b). That is why the value of C_{cf} in these two situations is approximately equal.

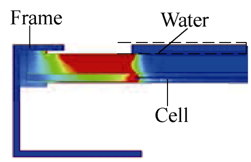
Once the water electrically contacts with the frame, the distribution of EFE will be different. In Fig.11(c), the water collects around the frame and its property is set as the dielectric. Although the water is involved in the capacitance coupling due to its dielectric characteristics, the EFE still mainly concentrates on the edge region. That means the capacitance is still coupled between the cell and frame. The C_{cf} becomes larger owing to the high permittivity of water in this situation. When the water is considered as an electrode, the EFE distribution is shown in Fig.11(d). The most important feature demonstrated by the simulation is that the capacitive coupling not only through the edge region but also through the space between the cell and the water. The new capacitance cell-to-water capacitance C_{cw} will be formed in this situation. A large amount of EFE stored between the cell and water leads a quite large parasitic capacitance.

4 Experimental validation

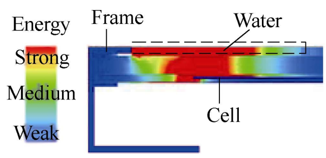
Measurements were firstly performed to validate the accuracy of the simulation. The PV panels with three sizes in dry environmental condition, whose rated power varies from 10W to 250Ware selected. Fig.12 shows the experimental setup. It is measured by



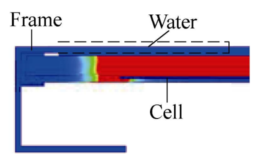
(a) A PV panel without water on the surface



(b) The water is not close to the frame



(c) The water electrically contacts the frame as dielectric



(d) The water electrically contacts the frame as electrode

Fig.11 The distribution of the 2D electric field energy through Ansys Maxwell 2D

Fig.12 Experimental setup

Chroma 3302, which has the same principle with RLC instrument. The positive pole and the frame are respectively clamped to test the capacitance C_{cf}. The experimental and simulation results of C_{cf} are presented in Table 2. It can be seen that the results are close to each other, but with some error. The main reasons of the error are listed as follows:

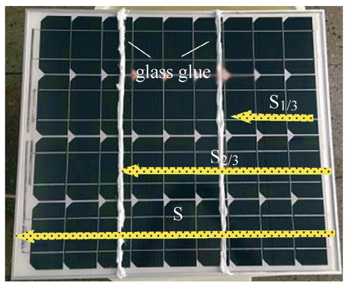
- These parameters in Table 1 are a reference in other literature and may not be completely consistent with the real experiment model we used.
- The overall dimensions of the simulation model may be a little different from the real PV panels due to measurement errors.
- The numerical calculation has 5% error itself.

Considering the above circumstances, these errors are in an acceptable range. The experiments can verify the accuracy of the simulation methods.

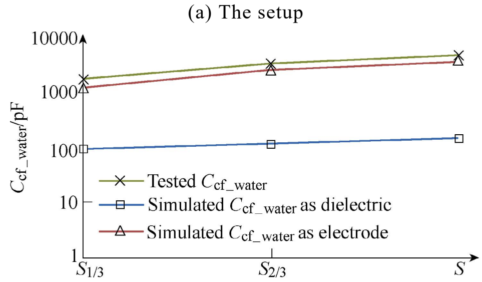
The following experiments were carried out to validate the simulation analysis. The glass glue was used to divide the panel surface into three areas, as shown in Fig.13(a). The symbol $S_{1/3}$ represents the water covering the one third of the panel surface. $S_{2/3}$ is two-thirds of the surface, and S means the water covers the whole panel surface.

Table 2 Comparison of experimental and simulation results

Power/W	Simulated /pF	Tested/pF	Error(%)
10	23	31	26
50	61	85	28
250	240	300	20



(a) The setup



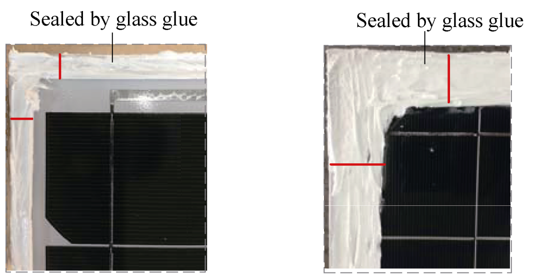
(b) The tested and simulated results

Fig.13 Experiment of the effect of water on the capacitance when the frame is exposed

It is found in Fig.13(b) that the C_{cf_water} increases as the area of water increases. Compared to the simulation results considering the water as a dielectric, the simulation data considering water as an electrode is very close to the tested value. By impression, it seems that water should be considered as electrode according to the measurements. However, it can be seen that the measurement results are always a little bit larger than the simulation. The difference can be from the error between measurements and simulation as described above. However, by looking carefully, it seems that the water can be regarded as a combination of electrode and dielectric in terms of the effect on capacitance.

To further validate whether the water has effect as a dielectric, another measurement is conducted. Unlike the exposed frame in Fig.13(a), the metal frame surface in Fig.14(a) was attached by a thin layer of glue to isolate the water from the metal frame. Another form of sealing is not only sealing the surface of the frame, but also the region between the cell and the frame, as shown in Fig.14(b). Then, the experiment is carried out in accordance with the above procedures.

The tested results are shown in Fig.15, it is clear that the value of C_{cf} decreases dramatically with the frame sealed by glue. This is because once the water is isolated from the frame, the cell-to-water capacitance C_{cw} no longer leads into the grounded loop. As a result, the tested capacitance is still the coupling capacitance between cell and frame. Another observation is that the capacitance value in form 1 is a little larger than form 2. It is because the water gathered around the edge of the panel in Fig.14(a) enhances the ability of binding capacity of the charge due to its property of dielectric. It validates that the water also has some effects on the capacitance due to its dielectric characteristics in practice. The water can be regarded as a combination of an electrode and a dielectric.



(a) The frame sealed in form1 (b) The frame sealed in form2

Fig.14 Experimental of the effect of water on the capacitance when the frame is sealed by glue

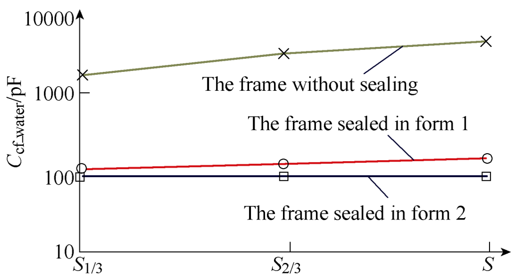


Fig.15 The tested results in different condition

5 The complete capacitance model of PV panel considering the rain environment

Regarding the effect on the parasitic capacitance, the water can be regarded as a combination of an electrode and a dielectric. Thus, the complete model of the parasitic capacitance of the PV panel can be derived as shown in Fig.16. When the water gathers in the panel surface, the cell-to-water capacitance C_{cw} will be formed. If the water electrically contacts the frame, for example when the rain water covers the panel, the switch in Fig.16 should be closed and the C_{cw} is led into the grounded loop. Its value depends on the effective overlap area between the water and the cell. If the water does not electrically contact the frame, for example when the panel is in humid environment and the water drops discretely on the surface, the switch will be opened and the C_{cw} is separate from the grounded loop. The water can only increase the capacitance C_{cf} a little bit due to its property as a dielectric.

6 Methods of minimization of the parasitic capacitance

Some methods for minimization the capacitance are listed based on above analysis.

As shown in Fig.11(a), the electric-field energy mainly concentrates on the field of tempered glass. It is the dominant factor which has a great influence on the value of the capacitance. According to the simulated calculation, if the permittivity of tempered glass is reduced by half, the parasitic capacitance of the PV panel would have a 40% or so decline. So, from the respect of materials, we can reduce the parasitic capacitance by lowering the permittivity of the tempered glass.

The above conclusions also reveal that if the water electrically contacts with the frame, the capacitance increases dramatically as the area of water increases. Therefore, a layer of polymers can be attached around the mental frame to avoid the water electrically contacting with the frame, as shown in Fig.14. The feasibility of this optimal consideration has been proven in the above experiment.

By optimizing the layout of PV panels, it can also minimize the capacitance in a rain environment. Ideally, the panel is mounted with a certain tilt θ to the ground, as proposed in Fig.17. The area of water accumulated

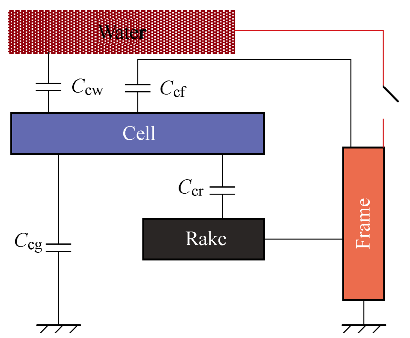


Fig.16 The complete capacitance model of the PV panel considering rain environment

(a) PV panel on the roof (b) PV panel on the ground

Fig.17 PV panels in two typical applications

on the panel surface is usually very large for those building applied photovoltaic which is almost mounted in parallel with the building roof, as shown in Fig.17(a). When the water covers the panel surface and electrically contacts the frame, the capacitance will depend on the area of water. So, the tile to the ground of the PV panel should be considered to avoid a large amount of water accumulating on the panel surface. For those surface power station in Fig.17(b), the C_{cf} could not be heavily affected by water due to its larger tilt θ to the ground.

7 Conclusion

This paper presents comprehensive analysis about the effect of water on the parasitic capacitance of the PV based on numerous 3D FE simulations. The EM mechanization behind the parasitic capacitance in different situations is explained. The experimental results validate the simulation analysis and clarify the property of the water. The water can be regarded as a combination of an electrode and a dielectric in terms of the effect on the capacitance of the PV panel. However, the role as an electrode is dominant on the effective parasitic capacitance of the PV panel. If the water covers fully the panel surface and electrically contacts the grounding edge, the effective parasitic capacitance can increase 30 times in our case. Thus, to minimize the panel capacitance, the core method is to isolate the electrical contact between the water and the grounding system or to decrease the area of the water. Of course, if a panel without metal frame is used, that will eliminate the dominant effect of water on the parasitic capacitance.

References

[1] R. Selvamuthukumaran, A. Garg, and R. Gupta, "Hybrid multicarrier modulation to reduce leakage current in a transformerless cascaded multilevel inverter for photovoltaic systems," *IEEE Transactions on Power Electronics*, vol. 30, no. 4, pp. 1779-1783, April 2015.

[2] W. J. Cha, K. T. Kim, Y. W. Cho, S. H. Lee, and B. H. Kwon, "Evaluation and analysis of transformerless photovoltaic inverter topology for efficiency improvement and reduction of leakage current," *IET Power Electronics*, vol. 8, no. 2, pp. 255-267, Feb. 2015.

[3] H. Xiao, and S. Xie, "Leakage current analytical model and application in single-phase transformerless photovoltaic grid-connected inverter," *IEEE Transactions on Electromagnetic Compatibility*, vol. 52, no. 4, pp. 902-913, Nov. 2010.

[4] B. Yang, W. Li, Y. Gu, W. Cui, and X. He, "Improved transformerless inverter with common-mode leakage current elimination for a photovoltaic grid-connected power system," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 752-762, Feb. 2012.

[5] J. M. A. Myrzik, and M. Calais, "String and module integrated inverters for single-phase grid connected photovoltaic systems - a review, " *IEEE Bologna Power Tech Conference Proceedings*, pp. 8pages, vol.2, doi: 10.1109/PTC. 2003. 1304589, 2003.

[6] Fritz Schimpf, and Lars E. Norum, "Grid connected converters for photovoltaic, state of the art, ideas for improvement of transformerless inverters, " *NORPIE/2008, Nordic Workshop on Power and Industrial Electronics*, June 9-11, 2008.

[7] M. C. Cavalcanti, K. C. de Oliveira, A. M. de Farias, F. A. S. Neves, G. M. S. Azevedo, and F. C. Camboim, "Modulation techniques to eliminate leakage currents in transformerless three-phase photovoltaic systems," *IEEE Trans. Ind. Electron*., vol. 57, no.4, pp. 1360-1368, Apr.2010.

[8] E. Un, and A. H. Have, "A near-state PWM method with reduced switching losses and reduced common-mode voltage for three-phase voltage source inverters, " *IEEE Trans. Ind. Appl*., vol. 45, no.2, pp.782-793, Mar./Apr.2013.

[9] S. M. Araujo, P. Zacharias, and R. Mallwitz, "Highly efficient single-phase transformerless inverters for grid-connected photovoltaic systems, " *IEEE Trans. Ind. Electron*., vol.57, no. 9, pp. 3118-328, Sep. 2010.

[10] T. Kerekes, R. Teodorescu, P. Rodriguez, G. Vazquez, and E. Aldabas, "A new high-efficiency single-phase transformerless PV inverter topology, " *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 184-191, Jan. 2011.

[11] L. Palma, M. H. Todorovic, and P. N. Enjeti, "Analysis of common-mode voltage in utility-interactive fuel cell power conditioners, " *IEEE Transactions on Industrial Electronics*, vol. 56, no. 1, pp. 20-27, Jan. 2009.

[12] A. von Jouanne, Haoran Zhang, and A. K. Wallace, "An evaluation of mitigation techniques for bearing currents, EMI and overvoltages in ASD applications," *IEEE Transactions on Industry Applications*, vol. 34, no. 5, pp. 1113-1122, Sep/Oct 1998.

[13] D. Dong, F. Luo, X. Zhang, D. Boroyevich, and P. Mattavelli, "Gridinterface bidirectional converter for residential DC distribution systems—part 2: AC and DC interface design with passive components minimization," *IEEE Trans. Power Electron*., vol. 28, no. 4, pp. 1667-1679, Apr. 2013.

[14] A. Zarein, M. S. Ghazizadeh, and A. Mosallanejad, "An improved transformerless grid connected photovoltaic inverter with reduced leakage current and soft-switching technique," *2017 8th Power Electronics, Drive Systems & Technologies Conference (PEDSTC)*, Mashhad, pp. 466-471, 2017.

[15] Y. Zhou, and H. Li, "Analysis and suppression of leakage current in cascaded-multilevel-inverter-based PV systems," *IEEE Transactions on Power Electronics*, vol. 29, no. 10, pp. 5265-5277, Oct. 2014.

[16] J. S. Lee,and K. B. Lee, "New modulation techniques for a leakage current reduction and a neutral-point voltage balance in transformerless photovoltaic systems using a three-level inverter," *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 1720-1732, April 2014.

[17] T. Zhang, G. He, M. Chen, and D. Xu, "A novel control strategy to suppress DC current injection to the grid for three-phase PV inverter," *2014 International Power Electronics Conference (IPEC-Hiroshima 2014-ECCE ASIA)*, Hiroshima, pp. 485-492, 2014.

[18] F. Spertino, J. Sumaili, H. Andrei, and G. Chicco, "PV module parameter characterization from the transient charge of an external capacitor," *IEEE Journal of Photovoltaics*, vol. 3, no. 4, pp. 1325-1333, Oct. 2013.

[19] V. Nasirian, A. Yadav, F. L. Lewis, and A. Davoudi, "Distributed assistive control of power buffers in DC microgrids," *IEEE Transactions on Energy Conversion*, vol. PP, no.99, pp.1-1,2017.

[20] R. Araneo, S. Lammens, M. Grossi, and S. Bertone, "EMC issues in high-power grid-connected photovoltaic plants," *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, no. 3, pp. 639-648, Aug. 2009.

[21] J. M. Shen, H. L. Jou, and J. C. Wu, "Novel transformerless grid-connected power converter with negative grounding for photovoltaic generation system," *IEEE Transactions on Power Electronics*, vol. 27, no. 4, pp. 1818-1829, April 2012.

[22] T. K. S. Freddy, N. A. Rahim, W. P. Hew, and H. S. Che, "Modulation techniques to reduce leakage current in three-phase transformerless H7 photovoltaic inverter, " *IEEE Transactions on Industrial Electronics*, vol. 62, no. 1, pp. 322-331, Jan. 2015.

[23] J. Zhang, W. Chen, B. Zhang, X. Song, and H. Huang, "Optimal design of EMI filters for PV system based on parasitic parameter and stability analysis, " *9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, Seoul, pp. 2744-2751, 2015.

[24] W. Chen, X. Yang, W. Zhang, and X. Song, "Leakage current calculation for PV inverter system based on a parasitic capacitor model," *IEEE Transactions on Power Electronics*, vol. 31, no. 12, pp. 8205-8217, Dec. 2016.

[25] O. Lopez, R. Teodorescu, and J. Doval-Gandoy, “Multilevel transformerless topologies for single-phase grid-connected converters,” *32nd Annual Conference on IEEE Industrial Electronics*, pp. 5191-5196, Nov. 2006.

[26] Wenjie Chen, Xiaomei Song, Hao Huang, and Xu Yang, "Numerical and experimental investigation of parasitic edge capacitance for photovoltaic panel," *2014 International Power Electronics Conference (IPEC-Hiroshima 2014-ECCE ASIA)*, Hiroshima, pp. 2967-2971, 2014.

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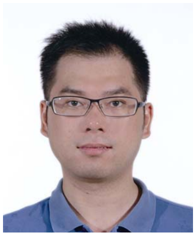

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