The Journal of Engineering

The 7th International Conference on Renewable Power Generation (RPG 2018)

Experimental study of PV strings affected by cracks

eISSN 2051-3305
Received on 30th October 2018
Accepted on 11th December 2018
E-First on 21st June 2019
doi: 10.1049/joe.2018.9320
www.ietdl.org

Tian Cheng[1], Mohammad Al-Soeidat[1,2] ✉, Dylan Dah-Chuan Lu[1], Vassilios G. Agelidis[3]

[1]School of Electrical and Data Engineering, University of Technology Sydney, Sydney, Australia

[2]Department of Electrical Engineering, Al Hussein Bin Talal University, Ma'an, Jordan

[3]Department of Electrical Engineering, Technical University of Denmark, Lyngby, Denmark

✉ *E-mail: mohammad.r.al-soeidat@student.uts.edu.au*

Abstract: Crack is one critical factor that degrades the performance of photovoltaic (PV) panels. To gain a better understanding of the impacts of cracks appeared on PVs and also to mitigate it, its failure mechanism, detrimental effects, criticality, and potential risks on independent PV panels are firstly reviewed in this study. An experimental study which investigates the degree of series connected and parallel connected PV strings which are affected by cracked cells are presented. A comparison of impacts of the partially shaded PV panel string and cracked cells happened to the PV panel string is given to evaluate their criticality levels. The experimental results show that the series connected PV panel string is strongly affected once the cell is seriously cracked, as the current generation capability is clamped. Partial shading, however, shows better performance. In addition, though the overall power the parallel connected PV string is reduced, it is less affected by the cracked cells compared to the series connected one. Lastly, a bypass diode is added to a series connected PV panel string with cracked cells, and the experimental results show that it can be an effective way to minimise the negative impacts of cracks.

1 Introduction

With the increasing penetration of the photovoltaic (PV) in the energy market, its performance and reliability become critical issues. PV panels are considered as relatively reliable components with long service life compared to its interfaced power electronics circuits. Moreover, most of the manufacturers provide long-term power output warranty, which defined as, the output power of the solar panel would be no less than 80% of minimum 'Peak Power Standard Test Conditions' within the period [1, 2] (e.g. Sharp Mono: NURC300 (25-year [1]), all solar panels from Solar Technology International Ltd (20-year [2])). However, the most recent work claims that large power losses are induced by the micro-cracks in [3], which significantly reduce the power efficiency of the panel and shorten its lifespan. The conclusion is obtained from 10 PV panels (Panel Model: Romag SMT6 (60)P PV Modules with 25-year power output warranty) with 7-year operation age at the University of Huddersfield, United Kingdom. The measured efficiencies of the two degraded panels with defects are 80.73 and 85.43%, respectively, while the other normal panels are between 97–99%. The panel with an efficiency of 80.73% indicates it is approaching its end-of-lifetime, which is much shorter than the expected 25-year and do not meet the manufacturer's warranty.

Based on this concern, micro-cracks failure mechanisms are reviewed. The cracks most likely are generated during the manufacturing, transportation and installation stages, and the mechanical stress such as snow loads could increase its possibility to develop to a larger size [4]. It is also mentioned in [5] that, the direct impact of the micro-cracks on the solar panel is limited and no loss occurs when the separation area is under 8%. However, if the inactive area continuously grows with the cracks to around 12–50%, the power loss, increase almost linearly to the power of one double string. In [6], uniform load tests, followed by an artificial ageing process (humidity-freeze (HF) cycling) are implemented to evaluate the criticality of cracks. A high criticality is considered if a crack has high possibility to form an electrically isolated area of 16–24% potentially. The results verify the theory that cracks parallel to busbar are the most critical ones, which not only have a high probability to form an electrical disconnection, but also have a high degradation percentage after 200 HF cycles. Lamination experiments with varied loads are conducted in [7] aiming at predicting the loss caused by the cracks and its propagation. The results indicate that, cracks do not necessarily cause the electrical isolation. However, increasing the stress on the cracked cell will cause an increase of dark area which means a loose of electrical connection. However, the cracks occurred in parallel to the busbar are the most serious ones, which may permanently lose the connection with the remaining area which show a good agreement with the work in [6]. The corresponding *I–V* curves are measured to evaluate the cracks development and its loss performance. In [8], an investigation of the impact of the snail trail phenomenon and the micro-cracks on the solar panels is presented. The study concludes that the micro-cracks play a more significant role in the degradation of the solar panel performance. The decayed panel performs a lower maximum power point than the data sheet expected due to a reduced generated current.

The aforementioned researches reviewed the failure mechanism, detrimental effects, criticality, and potential risks of cracks on PV panels. As the supporting data in most work is collected from a large number of independent PV panels, the impact of cracked cells on the PV strings with different connections are still yet unknown. Though the general trends of the *I–V* or *P–V* curves may able to estimate theoretically, there is a lack of experimental work to support and verify it. In addition, to what extent are the cracked cells and the shaded cells acting on the degraded performance of the PV panels are also unclear. Hence, experiments focusing on evaluating the output power performances of PV strings which include both parallel and series connections are implemented. Experiments with and without a bypass diode in series connected PV strings are investigated. Besides, comparisons among a panel with two cells are shaded, a panel with two cells are cracked and a normal panel is given.

2 Review of impacts of different crack types on PV panel output performances

A series of experimental works are conducted to investigate the impacts of different crack types on their corresponding output performances. The measurements are implemented in the laboratory where the ambient temperature is set to 25°C. A 60 W solar panel which has 36 cells is used. The panel is reconfigured to

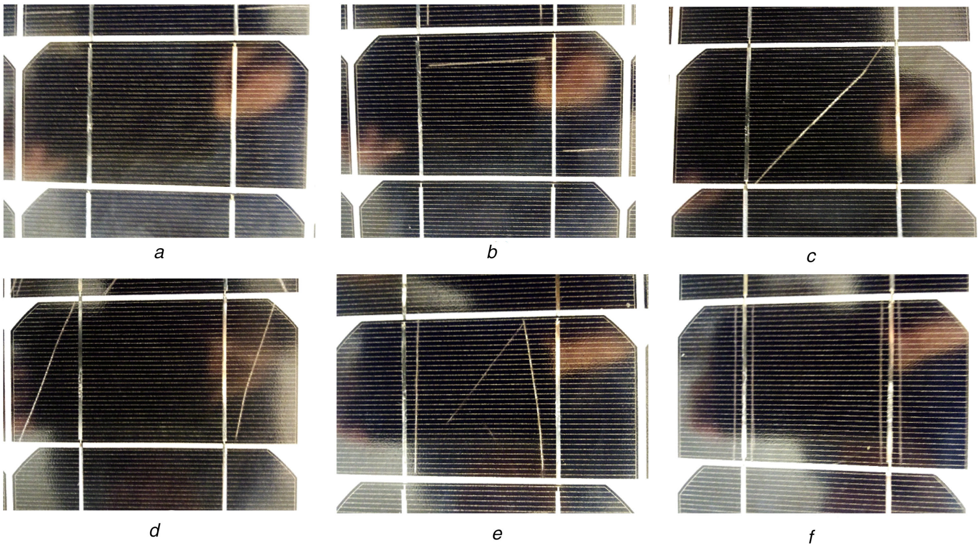

Fig. 1 *Enlarged look of a normal cell and five cracked cells in different PV strings*
(a) No cracks, ***(b)*** Horizontally cracked cell, ***(c)*** Diagonally cracked cell between busbar, ***(d)*** Diagonally cracked cell outside busbar, ***(e)*** Partially cracked cell between busbar, ***(f)*** Totally cracked cell

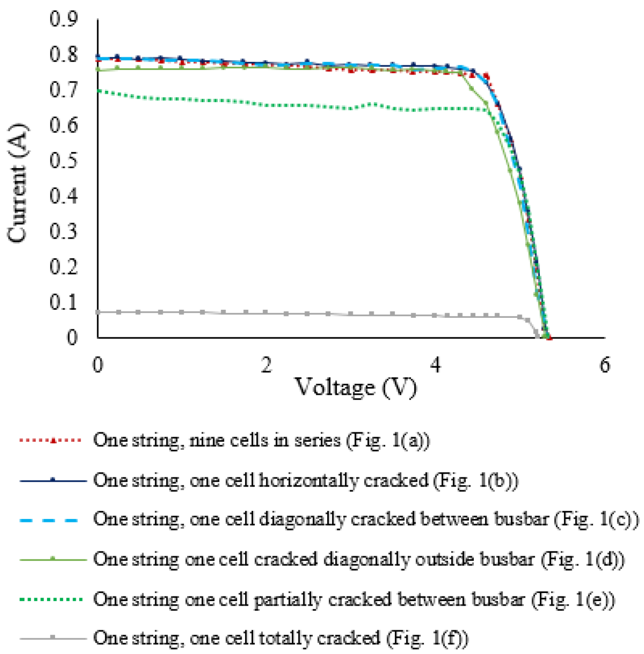

Fig. 2 *P–V curves of six different PV strings*

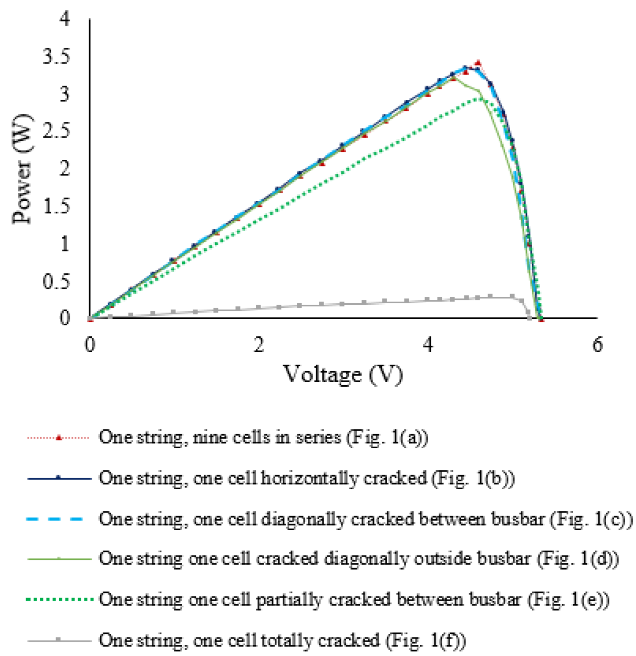

Fig. 3 *P–V curves of six different PV strings*

form four independent strings, with each string having nine cells in series. Owing to the fact that, cracks are formed and aggravated through a long operation period, and not all of crack types have significant impacts on the PV panel power generation capacity, artificial cracks are made in this experiment to mimic those serious decayed cracks. Two halogen lamps are used to simulate the solar radiation. Six cases are analysed to study the effects of different types of cracked cell on the output power of the strings. The enlarged photos of a normal cell and different cracked cells are shown in Fig. 1. The scenarios are listed as below:

i. *One string with no cracks (Fig. 1a)*: This string generates *I–V* and *P–V* curves under normal working condition, and it is used as a reference.
ii. *One string with one cell horizontally cracked (Fig. 1b)*: One cell in the second string is cut by utility knife, and this cut is perpendicular to the busbar.
iii. *One string with one cell diagonally cracked between busbar (Fig. 1c)*: One cell in the third string is cut between the busbar, and it has a 45° angle.
iv. *One string with one cell cracked diagonally outside busbar (Fig. 1d)*: This cut is similar to the previous cut, but outside the busbar (the cell effective area is reduced by 0.25%).
v. *One string with one cell partially cracked between busbar (Fig. 1e)*: In this case, two cuts, which parallel and close to the busbar are made. Although the cell is not fully isolated to the busbar, about half of the cell area is eliminated.
vi. *One string with one cell totally cracked (Fig. 1f)*: This cut is similar to the partial cracked between busbar. However, two more cuts are made to eliminate the whole cell from the string.

The measured *I–V* and *P–V* curves of these six cases are plotted in Figs. 2 and 3, respectively. As can be seen, the worst scenario happens when a cell is totally cracked, followed by when a cell is partially cracked. The totally cracked cell means the cell loses the electrical connection to the busbar while the partially cracked cell has a limited effective area to generate current. Both of these two cases show a reduced current of the entire PV string. That is because of the structure of the solar cell. The cell basically is a P-N junction, and the front layer is the negative layer while the back layer is the positive one. In order to link PV cells in series,

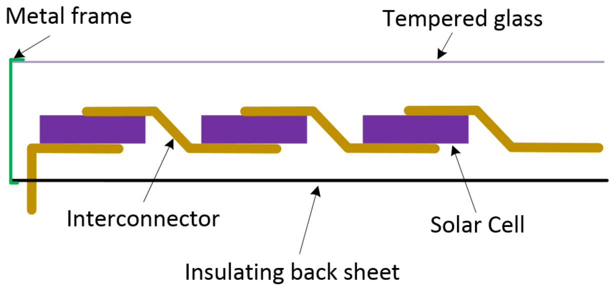

Fig. 4 *PV cell physical structure*

Table 1 Summarise of maximum power, virtual power, FF, efficiency and temperature of six different crack types

Case study (one panel with nine cells in series)	Maximum power	Vitual power (Ishort*Vopen)	Fill factor	Efficiency, %	Temperature, °C
normal panel, no cracks	3.410	4.216	0.8089	—	27
one cell horizontally cracked	3.343	4.221	0.7920	98.034	29
one cell diagonally cracked between busbars	3.338	4.195	0.7959	97.891	29
one cell cracked diagonally outside busbar	3.209	4.043	0.7937	94.093	30
one cell partially cracked between busbar	2.942	3.722	0.7904	86.272	31
one cell totally cracked	0.279	0.364	0.7677	8.194	34

connections are made by connecting the top layer of the first cell to the bottom layer of the second cell, as shown in Fig. 4. The current flows between the two layers, hence, any cells have serious cracks will affect the entire current path. Moreover, the temperature in each case is monitored, to study the potential risk of hot spot caused by cracks.

Table 1 summarised the maximum power, virtual power (the short circuit current multiply by the open circuit voltage), fill factor (FF) (the most important parameter that defines the quality of a PV panel, the value can be calculated by finding the ratio of maximum power over the virtual power which is used to define the quality of a PV panel, the higher FF means higher solar cell quality [4].), efficiency and temperature of these six cases are given. The results depict that, with the increasing of serious level of a cracked cell in a PV string, the string quality, maximum power generate capability, efficiency is reduced accordingly. The room temperature is set to 25°C, and the PV panel is cooled down before doing the next experiment. The temperature increases possibly due to the halogen lamps in the first case. With the increase of the serious level of cracks, the temperature rises accordingly. Case 6 shows the string increases to 34°C and the two neighbours increase to 31°C, which possibly can be developed to a hot spot.

3 Performance evaluation of PV panel strings with different connection methods

In addition, to study how cracked cells affect independent PV string output power, the following experimental work investigates and compares the performance of PV panel strings with different connections. It is worth noting that, the bypass diode, which is adopted to mitigate the crack impacts, is also studied and compared. Three groups of experiments are implemented:

i. Evaluation of output performances of a normal PV panel, a panel with two cracked cells and a panel with two shaded cells.
ii. Investigation and comparison of performances among three different PV panel strings, namely, two normal PV panels connected in series, two PV panels connected in series with one panel are seriously cracked, and two PV panels connected in series with one panel are seriously cracked and bypass diodes is used (Fig. 2).
iii. Investigation and comparison of output performances between two PV panels connected in parallel and two PV panels connected in parallel with one panel have serious cracked cells.

The experimental results of aforementioned three groups are shown in Figs. 5–7, respectively. As can be observed in Fig. 5, the detrimental impact of the cracks is more critical than the partial shading effect when the cells are seriously cracked. In Fig. 6, the results indicate that the serious cracked panel clamps the current of the PV string, and hence, significantly reducing the generated power. In addition, the extra bypass diode can effectively mitigate this phenomenon. The results shown in Fig. 7 that, the operation of the normal panel is not affected by the cracked one in the parallel connected PV string. Though the overall power is still lower.

4 Conclusion

In this paper, the failure mechanism, detrimental effects, criticality, and potential risks of cracks on PV panels are reviewed. A series of experiment works are implemented to review the impacts of different crack types on independent PV strings. The outcomes verify that loss of electrical connection between PV cell and busbar would cause a great reduction of the entire PV string power generation capability. Moreover, the performances of PV panel strings with cracked cells in one of the panels are also investigated. A comparison between the series and parallel connected PV panel strings are given. Bypass diodes are suggested to add to the PV panel string to mitigate the current reduction by the serious cracked cells.

5 Acknowledgment

Al-Soeidat gratefully acknowledges the Scholarship received towards his PhD from the Al-Hussein Bin Talal University (Ahu/4/2047). This research was funded (partially or fully) by the Australian Government through the Australian Research Council (Discovery Projects DP180100129).

6 References

[1] Sharp: 'Solar modules', NU-RC300 (300 W), datasheet. Available at https://www.sharp.co.uk/cps/rde/xchg/gb/hs.xsl/-/html/product-details-solar-modules-2189.htm?product=NURC300
[2] Solar Technology International Ltd: 'Mono & poly-crystalline (12 volt) silicone solar cell modules', 5WP-150WP. Available at http://www.solartechnology.co.uk/solar-panels/pv-logic-panels/standard-solar-panels
[3] Dhimish, M., Holmes, V., Dales, M., *et al.*: 'Effect of micro cracks on photovoltaic output power: case study based on real time long term data measurements', *IET Micro Nano Lett.*, 2017, **12**, (10), pp. 803–807
[4] Kontges, M., Kurtz, S., Jahn, U., *et al.*: 'Review of Failures of Photovoltaic Modules'. LEA PVPS Final Report, 2014
[5] Kontges, M., Kajari-Schroder, S., Kunze, I., *et al.*: 'The risk of power loss in crystalline silicon based photovoltaic modules due to micro-cracks', *Sol. Energy Mater. Sol. Cells*, 2011, **95**, pp. 1131–1137
[6] Kajari-Schroder, S., Kunze, I., Kontges, M.: 'Criticality of cracks in PV modules', *Energy Procedia*, 2012, **27**, pp. 658–663

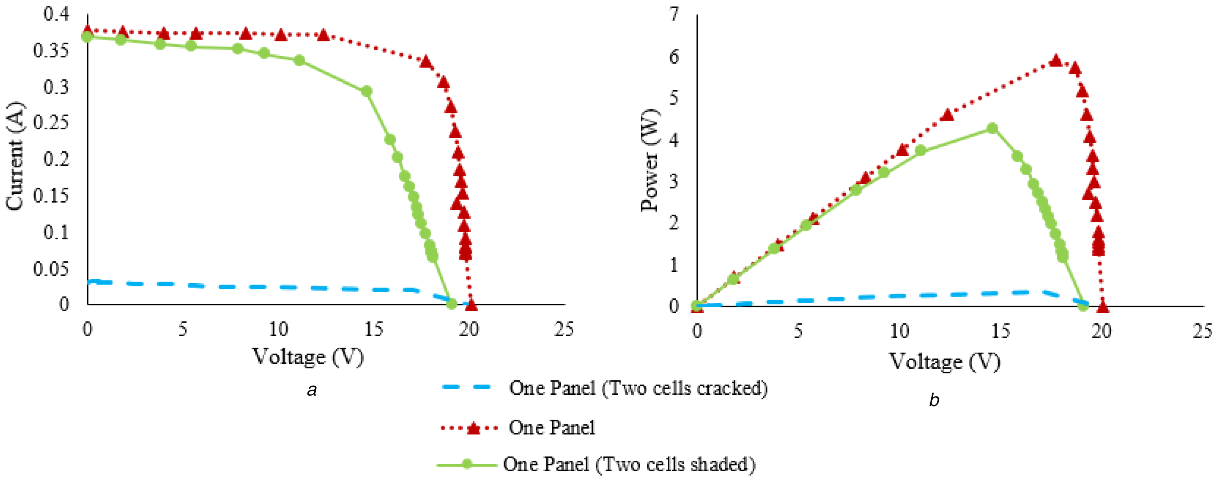

Fig. 5 *I–V and P–V curves for one normal panel, one panel with two shaded cells and one panel with two cracked cells*

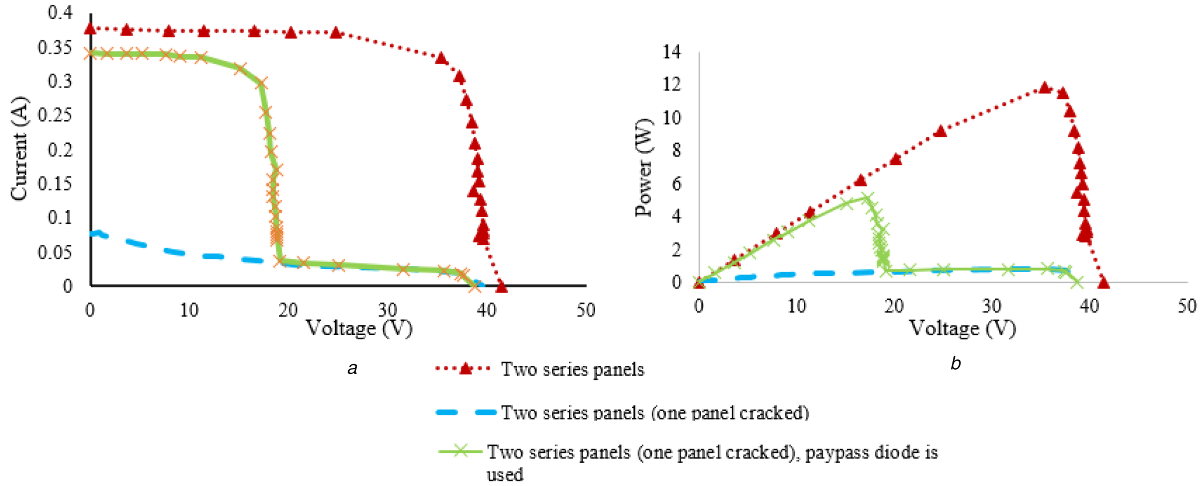

Fig. 6 *I–V and P–V curves for two panels connected in series, two panels connected in series with one cracked, and two panels connected in series with one cracked and a bypass diode is connected*

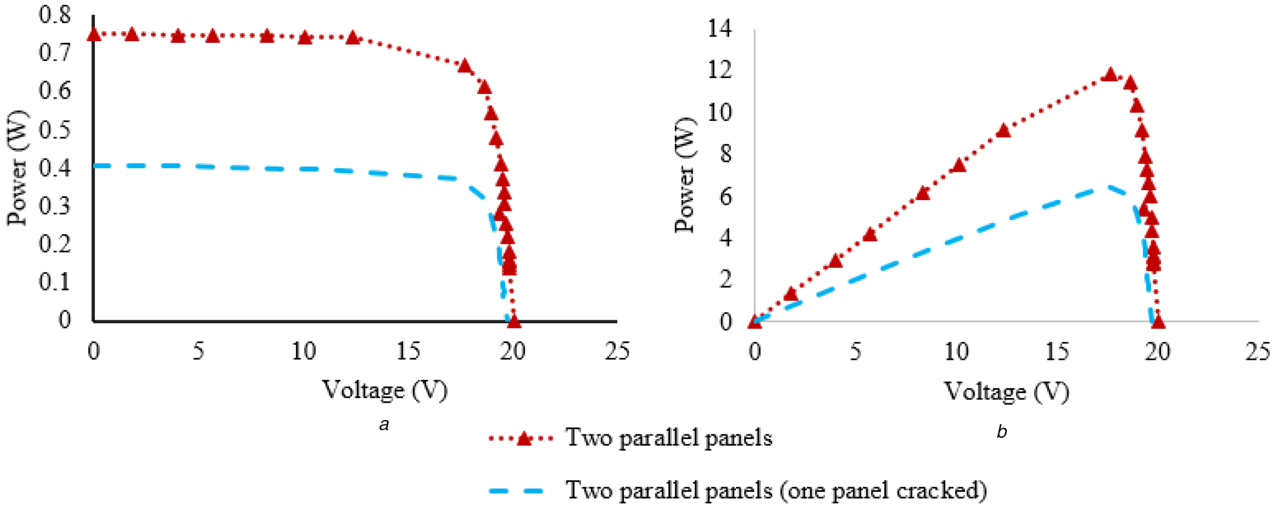

Fig. 7 *I–V and P–V curves for two panels connected in parallel and two panels connected in parallel with one cracked*

[7] Gade, V., Shiradkar, N., Paggi, M., *et al.*: 'Predicting the long term power loss from cell cracks in PV modules'. 2015 IEEE 42nd Photovoltaic Specialist Conf. (PVSC), New Orleans, LA, 2015, pp. 1–6

[8] Dolara, A., Leva, S., Manzolini, G., *et al.*: 'Investigation on performance decay on photovoltaic modules: snail trails and cell microcracks', *IEEE J. Photovoltaics*, 2014, **4**, (5), pp. 1204–1211