Fault Evolution in Photovoltaic Array During Night-to-Day Transition

Ye Zhao, Brad Lehman
Department of Electrical and Computer Engineering
Northeastern University
Boston, MA, US
zhao.ye@husky,neu.edu

Jean-Francois DePalma, Jerry Mosesian, Robert Lyons
MERSEN USA Newburyport-MA, LLC
Newburyport, MA, US

Abstract— **This paper focuses on fault evolution in a photovoltaic array during night-to-day transition. The effect of a maximum power point tracker on fault current is first discussed. When a PV fault occurs in daylight, overcurrent protection devices work properly. However, when the same fault occurs at night, our results demonstrate that the fault current is difficult to detect. As a result, the fault might be hidden in the PV array and become a potential hazard for system efficiency and reliability.**

Keywords - photovoltaic (PV); night-to-day transition; faults; overcurrent; maximum power point tracker (MPPT)

I. INTRODUCTION

Fault detection and protection in solar photovoltaic (PV) arrays are important tasks for improving PV system efficiency and reliability. Faults in PV arrays not only damage the PV modules and cables, but also lead to electrical shock hazards and fire risk. Furthermore, faults in PV arrays may cause large amount of energy loss. For example, in UK domestic PV systems, the annual energy loss due to faults in PV systems is estimated to be up to 18.9% [1]. To achieve proper fault detection and protection, conventional approaches usually add circuit breakers or fuses in series with PV components [2-4]. But these protection devices are able to trip faults and isolate faulty circuits only if they carry the large faulty current. In many cases, such as faults in PV arrays at low irradiance, the faults may not cause significant overcurrent. Additionally, the maximum power point tracker (MPPT) of the PV inverter may make fault detection and protection more complicated.

Previous literature studied instantaneous faults under high irradiance level [2, 4]. This paper, on the other hand, primarily discusses fault evolution in a grid-connected PV array during "night-to-day" transition. This is a unique type of fault to PV systems that has not been studied in the literature. As we show in this paper, however, these types of faults pose immense difficulties to either protect against or detect. Specifically, a "night-to-day" transition fault happens in the PV array at night when there is no solar irradiance. During sunrise, the irradiance on the PV array increases slowly, as does the PV array voltage. As long as the PV array voltage reaches the minimum start voltage of inverter, the PV inverter and its MPPT start to work (commonly by using Perturb and Observe (P&O) algorithm [5-6]). Then the PV system begins to feed energy to the utility grid. In both simulations and experiments, the MPPT responds quicker than the slow irradiance changes, which causes the system to operate at a lower power operation point. Consequently, instead of causing large overcurrent, the faulted PV array during night-to-day transition might lead to a smaller fault current, which is difficult to detect with conventional protection devices. On the other hand, if the same fault occurred in daytime, it would have been detected.

In summary, this research shows that previously unreported night-to-day transition fault brings challenges to PV systems as follows:

- System reliability: Conventional fault detection might not detect or trip a night-to-day transition fault, since there is not a large fault current. Because of this, the fault may remain undetected and cause DC arcs, which might lead to unexpected fire hazards and personnel safety issues on the fault path [7-9];
- System efficiency: Unlike normal operating conditions, the faulted PV array has a substantially different current vs. voltage (*I-V*) curve and reduced maximum power point (MPP). The PV system may still function after the night-to-day transition, but the output power will be greatly reduced.

II. LINE FAULT IN PV ARRAY IN DAYTIME

In order to understand the difficulties of PV system protection for night-to-day faults, it is helpful to understand and compare with faults that may occur during daytime/high irradiance conditions. Conventional fault protection devices can easily handle these types of faults.

A. Overview of A Typical PV System under Fault

1) PV array effects on fault current

Fig. 1 illustrates a typical grid-connected PV system containing 12 modules in a series-parallel configuration (for illustration purposes only). For instance, two modules are connected in series to create a string. Then 6 strings are all connected in parallel to build an array. For hot-spot prevention, one bypass diode is added in parallel with every module.

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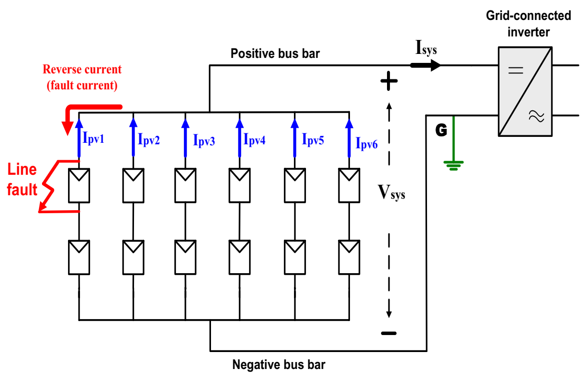

Figure 1. Schematic diagram for a typical grid-connected PV system

In the following fault analysis, it is considered that the PV array is the only source of fault current, since most small-scale grid connected inverters (10kW or less) cannot backfeed current into the faulted PV array from the utility grid [10]. Therefore, the electrical characteristic of the PV array plays a major role in the fault current.

The PV array can work normally around its present MPP at daytime, since the irradiance is usually high enough to start the inverter in the PV system. In the meantime, every parallel string is generating string current ($I_{pv1}\ldots I_{pv6}$) at the same operation voltage (V_{sys}). The string currents sum up at positive bus bar as system current (I_{sys}) and flow into the inverter. However, faults in the PV array may disturb the normal operation of the array and generate the fault current (I_{fault}) among them. Several types of faults that commonly occur in PV arrays are: ground faults, line faults, open-circuit faults and mismatch problems [11], among which the ground faults and the line faults could lead to large fault current. In this research, a line fault in the 1st string with zero fault impedance is mainly studied (see Fig. 1).

Generally, faults on PV arrays will cause voltage changes and unbalanced currents among strings. Sometimes, unbalanced currents may backfeed into the faulted string as fault current. The main reason for fault current is that the *I-V* curve of the faulted string changes to a lower open-circuit voltage (V_{oc}). However, the operating voltage of the array does not change immediately after the fault, since the MPPT in the inverter responds relatively slow compared to the fault. Therefore, the MPPT is keeping the system voltage relatively constant immediately after the fault. As a result, the faulted string must work in the 4th quadrant of its *I-V* curve as a load, instead of in the 1st quadrant as a source (see Fig. 3). If the fault happens on a clear day, it is likely that the fault current becomes sufficiently high and overcurrent protection fuses in series with the faulted PV string will be blown.

2) MPPT algorithm in PV array

A MPPT is an algorithm that is often integrated with the DC-DC converter (or DC-AC inverter) to harvest the maximum output power of PV arrays [12]. Since the MPPT keeps optimizing the array performance for given environmental conditions and array configuration (normal or faulted), the MPPT plays an important role in determining the normal current as well as the fault current.

The most commonly used MPPT algorithm is Perturb and Observe (P&O), which is developed and tested in this research. Fig. 2 shows the nonlinear power vs. voltage (*P-V*) curve of a PV array, which has a maximum MPP. The P&O perturbs the operating voltage of array in a certain direction and observes change of output power. From Fig. 2, it can be seen that if the change of power is in the same direction of voltage perturbation ($dp/dv>0$), then the operation point is on the left of the MPP, and the operating voltage should be increasing to reach the MPP. Otherwise, if the change of power is in the opposite direction of voltage perturbation ($dp/dv<0$), then the operation point is on the right of the MPP, and the operating voltage should be decreasing to approach the MPP. This P&O algorithm is processed iteratively until the MPP is reached ($dp/dv=0$) and then, the PV array will oscillate around its present MPP in steady-state operation.

B. Simulated I-V curve and P-V curve of PV Array under Fault

In simulation, a grid-connected PV array with the same configuration as Fig. 1 is built in MATLAB/Simulink. A typical PV module (manufactured by PowerFilm) is modeled using the one-diode model [13-14]. In order to study MPPT effects on fault current, the P&O algorithm of MPPT is developed and tested. The simulation parameters of PV system are given in Table I. The overcurrent protection is not used in simulation so that the fault current will evolve without interruption.

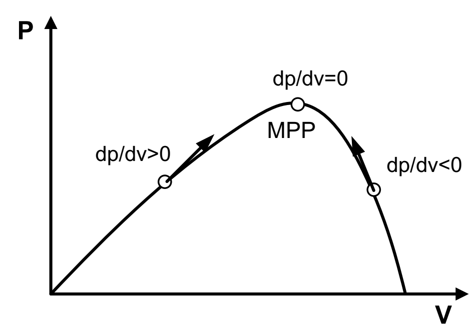

Figure 2. *P-V* curve for P&O MPPT algorithm

TABLE I. PARAMETERS OF COMPONENTS IN THE PV SYSTEM

Equipment	Parameters	
	Type	***Detailed parameters***
PV module	Power Film R7 (amorphous silicon)	At STC: V_{oc}=21.4V, I_{sc}=0.58A, V_{mpp}=15.8V, I_{mpp}=0.48A, P_{mpp}=7.5W
Grid-connected inverter	Enphase microinverter M190	Max. output power 190W, min. start voltage: 28V; MPPT voltage range: 22 ~ 40V

Fig.1 shows a line fault occurring instantaneously in the 1st string. Since the upper module of the 1st string is short-circuited, the 1st string has only one module left operating. Fig. 3 shows the corresponding *I-V* curve for the normal PV array, the faulted array and the faulted string at standard test condition (STC): solar irradiance of 1000W/m^2, temperature of 25°C, and air mass (AM) of 1.5. As discussed before, V_{oc} of the faulted string become much smaller due to the fault. Consequently, any working voltage above V_{oc} of the faulted string will cause backfed current into it.

The corresponding *P-V* curves of the normal and the faulted PV arrays are shown in Fig. 4. Before the fault in daytime, the normal array is working at MPP operation point *MPP1*. After the instantaneous line fault in the 1st string, the operation point of the array drops vertically to *F* immediately. It can be seen that the output power of array is therefore greatly reduced. At the same time, the reverse current (the fault current) into the 1st string reaches its maximum and could trip the overcurrent protection fuses. If the fault is not interrupted, the MPPT is going to change the operation of array from *F* to *MPP2*, which is the MPP for the faulted array.

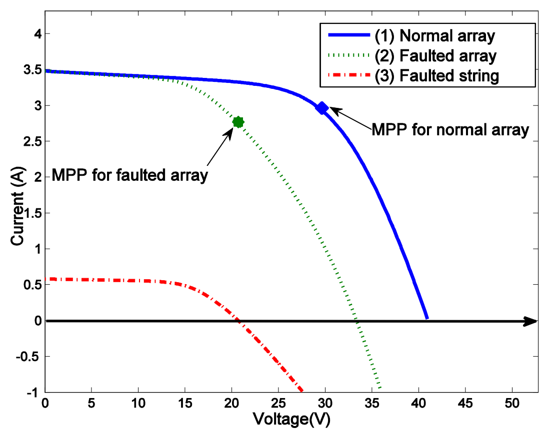

Figure 3. *I-V* curve of PV array under STC

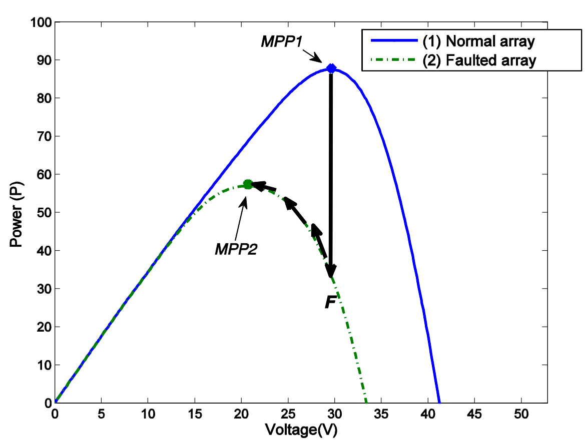

Figure 4. *P-V* curve of PV array under fault in daytime

C. Simulation Results of Faults in PV Array in Daytime

The simulation results of fault in daytime under STC are shown in Fig. 5, which plots the "normalized" faulted string current vs. time (I_{pv1}/I_{sc} vs. t, where I_{pv1} is the faulted string current and I_{sc} is the module short-circuit current under STC). In order to study the possible maximum fault current, the fault is not interrupted by overcurrent protection devices in simulation. Before $t=T_1$, the 1st string is working normally and generating positive current $0.86I_{sc}$ (0.5A) under STC. The simulated line fault occurs at $t=T_1$, and causes a negative reverse current (the fault current I_{fault}) with maximum magnitude $2.5I_{sc}$ (1.45A) into the faulted string (the 1st string), shown in Fig. 5. This fault current may be high enough to trip the fuses in series with the 1st string because the overcurrent protection devices (OCPD), such as fuses, are usually required to be sized at $1.56I_{sc}$ to protect the PV modules and conductors [10, 15]. At $t=T_1$, the MPPT of the inverter identifies the sudden drop of the array's output power and begins to look for a new MPP. During $T_1<t<T_2$, the MPPT reduces the array voltage as well as I_{fault}, in order to minimize the power consumed by the faulted string. As a result, I_{fault} oscillates and decreases over time rather than a constant value. After T_2, I_{fault} is decreased to a much smaller value, when the array oscillates around a new optimum working point.

III. Fault in PV Array during Night-to-Day Transition

If the same fault (in Fig. 1) occurs at night with no solar irradiance, the fault current evolves during night-to-day transition and behaves distinctively. The irradiance during a clear day is changing slowly with the peak level 1000W/m^2 (see Fig. 6).

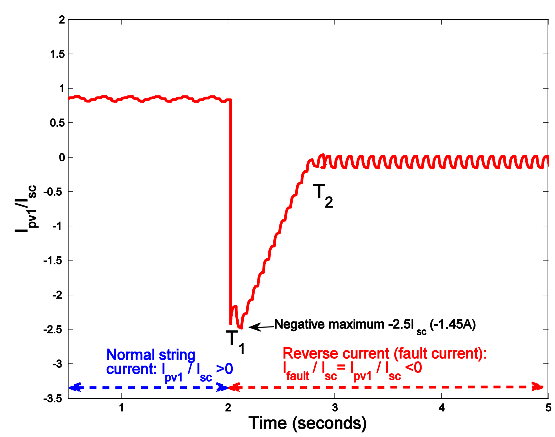

Figure 5. Simulation results: the "normalized" faulted string current (I_{pv1}/I_{sc})during the fault in daytime under STC.

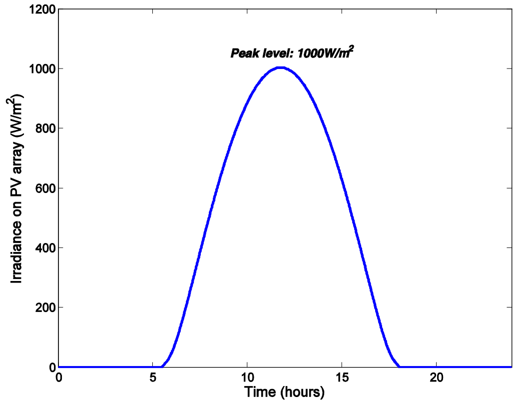

Figure 6. Simulated irradiance level during night-to-day transition

The simulated *P-V* curves during night-to-day transition fault are shown in Fig. 7. Under the irradiance level lower than 383W/m^2, the MPPT of the inverter has not started to work, because the array voltage is not as high as the minimum start voltage of the inverter. Therefore the array is at open-circuit conditions with zero output power. The operation point on the *P-V* curve is moved from *A* to *B* along with voltage axis. After the inverter starts at *B*, the MPPT of the inverter helps the operation point move from *B* to *C*, which is the MPP at irradiance of 383W/m^2. As time evolves and irradiance increases, the array transitions from MPP *C* to MPP *D*, where *D* is the MPP at STC.

The simulated PV array voltage and the fault current during night-to-day transition are shown in Fig. 8 and Fig. 9. Before $t=T_1$, the irradiance is zero and there is no voltage or current in PV array. During sunrise (after $t=T_1$) with irradiance increasing, the short circuit current and open circuit voltage of each string are increasing as well. During $T_1<t<T_2$, the inverter has not started to work yet, so that the PV array is still at open-circuit condition with zero total output current. But the PV strings are mismatched since the 1st string is already faulted with only one module operating. Hence, the currents of other strings have no path to flow but backfeed together into the 1st string. This negative reverse current is the fault current (I_{fault}), whose magnitude is also increasing with irradiance during $T_1<t<T_2$. When the PV array voltage reaches the minimum start voltage of inverter at $t=T_2$, I_{fault} reaches its negative peak -1.46I_{sc} (-0.846A). Meanwhile, the MPPT of the inverter starts to help the PV array work at its nominal MPP and minimizes I_{fault} to a much smaller value. Notice that I_{fault} never reaches a high enough value to blow a fuse, and therefore, the fault remains undetected.

The conclusions from these "night-to-day" simulations are as follows:

- Line faults in the PV array at night might be undetectable with conventional overcurrent protection devices;
- The faulted PV array might operate at a lower power output (forever) without ever triggering protection devices.

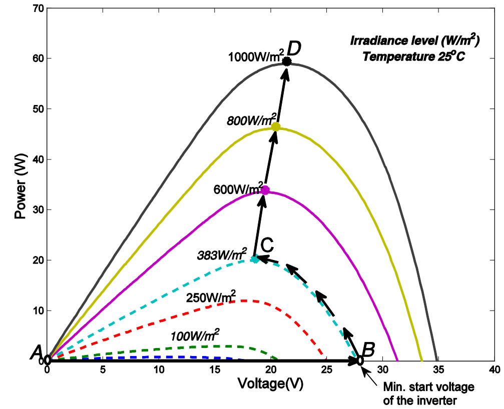

Figure 7. *P-V* curves of the faulted PV array with increasing irradiance during night-to-day transition.

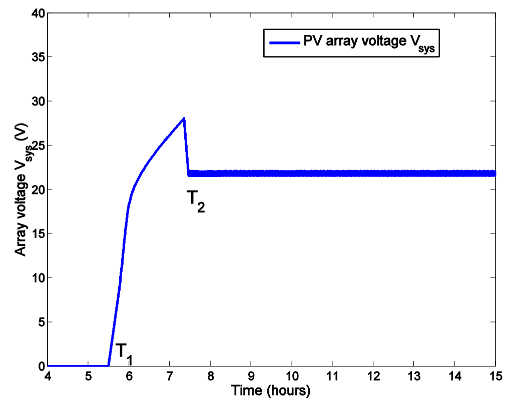

Figure 8. Simulation results: PV array voltage during night-to-day transition.

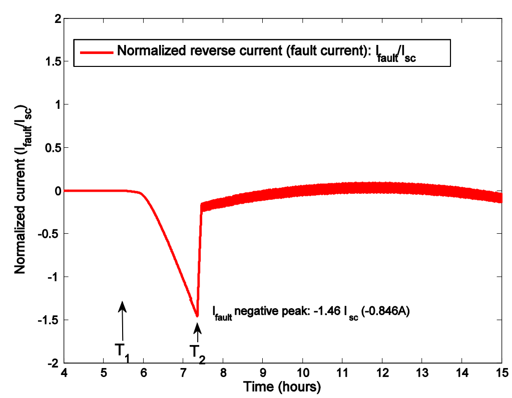

Figure 9. Simulation results: normalized fault current in PV array during night-to-day transition.

IV. EXPERIMENTAL VERIFICATIONS

A. Experimental Set-up

A small-scale lab test PV system has been established to verify our previous simulation results. Fig. 10 illustrates the PV system by 2×6 modules in series-parallel configuration, which has the same schematic diagram as the PV array in Fig. 1. The PV modules are made of amorphous silicon by PowerFilm Inc. The detailed parameters for PV modules and inverter in PV system have been given in Table I. As in simulations, the overcurrent protection is not used in experiments so that the fault current will evolve without interruption.

B. Experimental Results: Fault in PV Array in Daytime

Fig. 11 shows experimental results of a line fault occurring in daytime under real test conditions with high irradiance conditions (~900W/m^2). The experimental results are similar to expected results in previous simulation. Before $t=T_1$, each PV string is operating normally with string current $0.78I_{sc}$ (0.45A). At $t=T_1$, the fault occurs instantaneously. After some switching transients during $T_1<t<T_2$, the fault current (I_{fault}) reaches its negative peak $-2.43I_{sc}$ (-1.41A) immediately, and remains for $T_2<t<T_3$, which might be sufficient high to trip the fuse protection. From $T_3<t<T_4$, the MPPT responds and begins to optimize the operation points of array. After $t=T_4$, the PV system is working at reduced power output steady state. Finally, I_{fault} is reduced to $-0.6I_{sc}$ (-0.35A.) by the MPPT of the inverter.

C. Experimental Results: Fault in PV Array during Night-to-Day Transition

Fig. 12 and Fig. 13 illustrate the voltage and currents in PV array during night-to-day transition fault experiments. Similar to our simulation results, the magnitude of the reverse fault current (I_{fault}) is increasing with irradiance during $T_1<t<T_2$. At $t=T_2$, I_{fault} has negative peak $-1.3I_{sc}$ (-0.75A) when array voltage reaches the minimum start voltage of inverter (28V). After that, I_{fault} is clipped between $-0.34I_{sc}$~0 (-0.2A~0A) by the MPPT of the inverter. Therefore, I_{fault} during night-to-day transition is greatly reduced and will not be high enough to blow the fuse protection (rated at $1.56I_{sc}$).

Figure 10. Picture of PV system experimental set-up at Northeastern University, Boston.

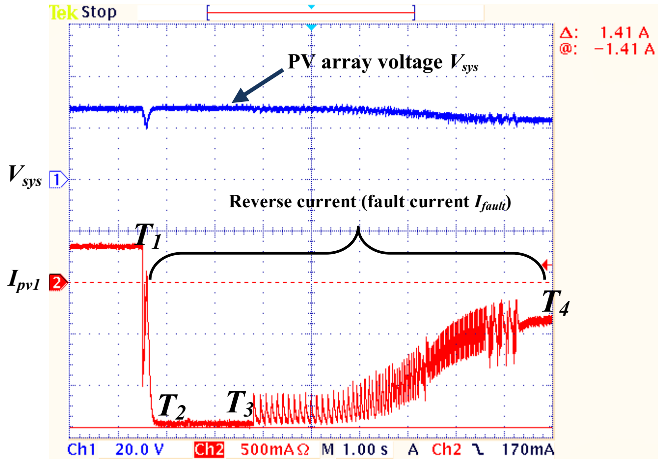

Figure 11. Experiment results: PV array voltage and faulted string current in daytime.

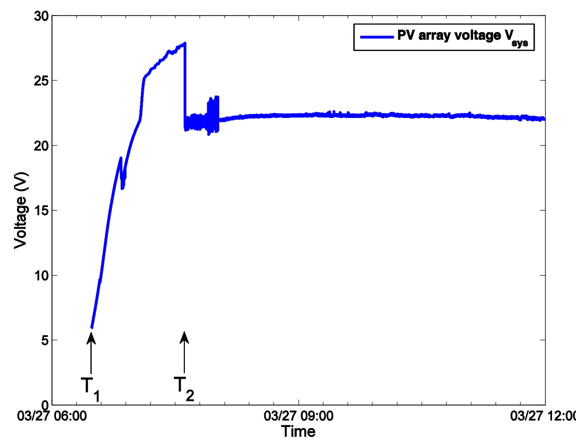

Figure 12. Experiments: PV array voltage during night-to-day transition.

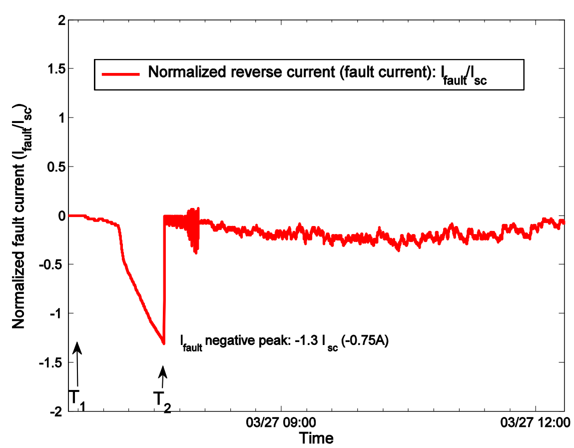

Figure 13. Experiments: normalized currents in PV array during night-to-day transition.

D. Discussion of Experiment Results

The summary of simulation and experimental results are given in Table II. According to National Electrical Code (NEC) [15], overcurrent protection devices (OCPD), such as fuses, are required to be sized no less than $1.56I_{sc}$ to protect the PV modules and conductors. In daytime fault experiments, the maximum magnitude of the fault current is $2.43I_{sc}$, which is large enough to trip a fuse properly designed for PV protection. But during night-to-day transition experiments, in fact, at the time of the inverter's startup, the magnitude of the fault current reaches its maximum magnitude (only$1.3I_{sc}$), which is not large enough to blow the fuse. After that, the magnitude of the fault current is reduced immediately and clipped between $0\sim0.34I_{sc}$ by the MPPT.

Additionally, the point of fault along the fault path may have large contact resistance that may lead to overheating and arcing problems. Therefore, the fault current of night-to-day transition can stay small enough so that it does not trip a fuse, but still large enough to cause arcing and fire hazards. Besides, due to the night-to-day transition fault, a large amount of power is lost at the faulted string. For example, in the simple test-setup in this paper, the experimental results show that power loss is approximate 28.3% of output power for PV array.

TABLE II. SUMMARY OF SIMULATION AND EXPERIMENTAL RESULTS

Line fault in the PV array	**Max. fault current**		***Working conditions***
	Daytime	***Night-to-day***	
Simulations	$-2.5I_{sc}$ (-1.45A)	$-1.46I_{sc}$ (-0.846A)	STC
Experiments	$-2.43I_{sc}$ (-1.41A)	$-1.3I_{sc}$ (-0.75A)	Real test conditions

V. CONCLUSIONS

This paper presents evolution and implication of faults in PV array during night-to-day transition. This paper also demonstrates the MPPT's effects on fault current. The simulation and experimental results (see Table II) both show that the fault current during night-to-day transition is reduced because the MPPT of the inverter forces the remaining PV modules to operate sub-optimally at lower power. Also, the same problem has been noticed in the simulation on a larger PV system (212V, 5.25kW). Furthermore, fault in "low irradiance" conditions during daytime, which is very common in real PV systems, might have the same issue as the "night-to-day" transition fault. Although the night-to-day transition fault in experiments does not involve large fault current, it may cause potential fire hazard at the fault path and significant output power losses. None of these results had previously been noticed in the literature before.

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