Challenges to Overcurrent Protection Devices under Line-line Faults in Solar Photovoltaic Arrays

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***Abstract*—Solar photovoltaic (PV) arrays behave distinctively from conventional power sources so that they need special consideration in fault analysis and protection. The faults inside PV arrays usually cause overcurrent that may damage PV components. This paper focuses on the challenges to overcurrent protection devices (OCPDs) in a PV array under two types of unique fault scenarios. One is a line-line fault that occurs under low irradiance conditions. In this circumstance, the fault current may not be large enough to trip the OCPDs in the PV array, even when high irradiance occurs later in the day. The other fault scenario is that when PV blocking diodes are used in the PV array, the reverse current may be greatly limited. However, OCPDs might not detect the reverse current properly. In both fault scenarios, the fault may not be cleared successfully by conventional OCPDs. Therefore, faults may remain undetected, which could lead to reduced system efficiency, reduced system reliability, and even unexpected safety hazards.**

I. INTRODUCTION

Fault analysis in solar photovoltaic (PV) arrays is a fundamental task to increase reliability, efficiency and safety in PV systems. PV arrays need special protection consideration since their fault scenarios are different from conventional power sources. Faults inside PV arrays (e.g. line-line faults, or ground faults) usually cause overcurrent backfeeding into the faulted modules. Among these faults, line-line faults in a large PV array need special consideration, since they are more difficult to detect by conventional protection devices than ground faults [1]. Although line-line faults are not common in PV systems, they still must be protected against for safety reasons. The line-line fault could be interpreted as a short-circuit fault in the grounded system (e.g. in US), or a double ground-fault in the ungrounded system (e.g. in Europe or Japan).

To prevent PV modules and connection wirings from line-line faults, overcurrent protection devices (OCPDs), such as fuses, are required in series with PV components by *NEC* [2]. But OCPDs are only able to clear faults and isolate faulty circuits if they carry a large fault current. However, this research shows that faults in PV arrays may not be cleared by OCPDs under some fault scenarios, due to the current-limiting nature of PV arrays, maximum power point tracker (MPPT) of PV inverters, or uses of blocking diodes.

This paper examines two types of unique faults found in a grid-connected PV array that have not been studied in the literature. The first one is a line-line fault that occurs in a PV array under low irradiance condition. Previous literature mainly studied faults in PV arrays under high irradiance level in [3] and [4]. In these cases, fault current is usually large enough to be cleared by protection devices easily. However, unlike "high irradiance" conditions, faults in the PV array under low irradiance tend to have a small fault current [5]. Furthermore, the operation of MPPT of the inverter may keep the fault current small [6]. Thus, the fault current never reaches the minimum trip level of OCPDs. As a result, the potentially dangerous fault is never cleared.

Similarly, there are dangerous implications to conventional OCPDs under faults in PV arrays when blocking diodes are also installed. Blocking diodes are often used in standalone PV systems to prevent the reverse current from battery storages at nighttime [7]. Occasionally, blocking diodes are also used in grid-connected PV arrays, but they seem to be a first point of failure [8]. During the fault, the reverse current may be totally cut off by blocking diodes at the expense of losing the proper fault interruption of OCPDs. Specifically, under line-line faults: (1) If there is no blocking diode, the OCPD on the faulted string has a good chance to clear the large reverse current properly. (2) But if blocking diodes and OCPDs are both installed in the PV array, the OCPD on the faulted string may not detect or clear the fault. Therefore, blocking diodes may bring the risks that conventional OCPDs may not function properly under line-line faults. These potential risks may lead to DC arcs, overheats, and even fire hazard.

In summary, this research shows

- System reliability and efficiency: Some "blind spots" of fault protection methods exist in PV arrays. OCPDs might not immediately clear all types of line-line faults. The undetected fault may cause DC

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arcs and even unexpected fire hazards. Also, the faulted PV array may still operate but will have a substantially different output characteristics and reduced maximum power point (MPP);

- Challenges brought by blocking diodes: Blocking diodes in series with PV modules will stop OCPDs from working properly. The reverse current under line-line faults will be cut off by blocking diodes. Therefore, without being noticed, the fault may be hidden in the array until the system fails entirely.

This paper proceeds as follow: Section II briefly introduces the fundamental background of a grid-connected PV system and its protection devices; Section III demonstrates the research results of a line-line fault occurring under low irradiance conditions; Section IV discusses the challenges to OCPDs from blocking diodes in PV arrays; Section V shows experimental validation of our theory and simulation results; Section VI concludes the paper and gives future research plans.

II. A TYPICAL GRID-CONNECTED PV SYSTEM

A. *Overview of a grid-conencted PV System*

A typical grid-connected PV system shown in Fig. 1 is the research target of this paper. It consists of several major components, including the PV array, centralized inverter with MPPT algorithm, electrical connection wirings, and protection devices, such as overcurrent protection devices (OCPDs) and ground fault protection devices (GFPDs). Note that the PV system in the research is a grounded system, which has a system grounding point G_{sys} inside the GFPD.

The PV array typically contains $m \times n$ PV modules connected electrically in series and parallel configuration. This array configuration is, nowadays, most common in PV technologies [9]. There are *n* PV strings in parallel. Each PV string consists of *m* modules in series. To build a large PV plant, a number of parallel typical arrays can scale up to meet the higher power demand [10].

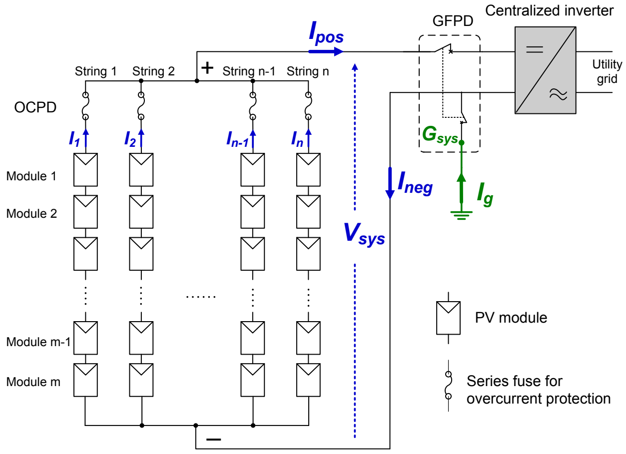

Figure 1. Schematic diagram of a typical PV system

Using the developed PV numerical model [1], this paper first builds a large simulation PV system in Matlab/SIMULINK that consists of 10×10 PV modules (m=10, n=10). The main parameters of PV modules under standard test condition (STC) are as follows: the maximum power P_{mp}=175W, the number of series solar cells per module N_s=72, the open-circuit voltage V_{oc}=44.4V, the maximum power voltage V_{mp}= 35.4V, the short-circuit current I_{sc}=5.4A, the maximum power current I_{mp}=4.95A and 3 bypass diodes per module.

When PV modules are electrically connected, non-uniform shading or fault conditions on only small portion of the modules could affect their overall performance [11]. To better study the fault scenarios in the PV array, the simulated PV system is capable of studying ground faults, line-line faults and mismatches among modules. More importantly, the MPPT (e.g. Perturb & Observe, P&O) of the inverter is included for fault analysis in PV arrays. The research results show that the MPPT might keep optimizing output power of a PV array (system) for given environmental conditions and array configurations (normal or faulted). Therefore, instead of a fixed value, fault current may be reduced by the response of the MPPT during fault. This is further validated experimentally in this paper with a small-scale PV test system.

B. *Conventional Protection Devices in PV arrays*

A typical grounded PV system (in the US) usually has two types of protection devices on PV arrays: Overcurrent protection devices (OCPD, i.e. fuses) to clear line-line faults; ground-fault protection devices (GFPD) to clear ground faults [2, 12]. Our paper only focuses on the protection challenges to OCPDs under line-line fault conditions.

In grounded PV systems, one OCPD shall be permitted on the top of each string to protect PV components from the damage due to large reverse current [2]. In the simulation, the PV series fuse is rated at I_n=10A, which is consistent with the US *NEC* requirement: The fuse current rating (I_n) is no less than $1.56 I_{sc}$ [2]. Furthermore, the *UL standard 2579* requires the minimum interrupting current of fuses as $1.35 I_n$ [13]. In other words, in order to trip the fuse, the magnitude of the reverse current should be no less than $=2.1 I_{sc}$ and must last for a specific period of time, given specific fuse's current vs. melting time characteristics.

C. *Blocking diodes in PV arrays*

Although blocking diodes are mentioned in standards [2, 14], they are not required in PV arrays. Since diodes only permit the current flow in one direction, occasionally people use blocking diodes for reverse current protections. For example, to avoid the power loss from the battery storage at nighttime, blocking diodes may be added on top of each PV strings. However, this research demonstrates (by simulations, theory and experiments) that the blocking diodes may bring challenges to existing PV OCPDs that have never previously been reported in the literature. In the existence of blocking diodes, the reverse current may not be large enough to trip the OCPDs. As a result, the line-line fault may not be interrupted properly. However, the fault current may still flow on the fault path, which could cause DC arcs, overheats, and even fire hazards.

III. FAULTS UNDER LOW IRRADIANCE CONDITIONS

In this research, a line-line fault with zero impedance between String #1 and String #2 has been created in this simulation system (see Fig. 2). A line-line fault is an accidental short-circuiting between two points in the array with different potentials. Line-line faults may be caused by insulation failure of current carrying conductors, short-circuit faults within the PV junction box due to mechanical damage, water ingress and corrosion, or double ground faults at the same time in the PV array [15].

The line-line fault will cause electrical unbalance between faulted PV strings and normal strings, resulting in reverse current (I_{rev}) into the most faulted string (i.e. String #1 in Fig. 2) and fault current (I_{fault}) along the fault path between the fault points *F1* and *F2*. In the following fault analysis, it is considered that PV array is the only source of fault current, since most PV inverters are transform-based that could provide good galvanic isolation between PV arrays and utility grids. It is commonly known that the output power of PV arrays is closely related to environmental factors, especially solar irradiance level. For the sake of simplicity, it is also assumed that the operating temperature of the PV modules is always at 25°C in the simulation. Therefore, for given specific line-line fault, the maximum possible magnitudes of I_{rev} and I_{fault} only depend on irradiance level.

A. Irradiance levels on a cloudy day

In the simulated PV system, real irradiance data (see Fig. 3) with one-minute resolution is used as input. The irradiance data during a cloudy day is sampled in Eugene, Oregon [16]. It is noticed that the irradiance data is varying greatly during a daytime with the maximum irradiance 1000W/m^2 and the minimum irradiance 200W/m^2. The irradiance with such a large variation is good to test the fault characteristics of the PV array and the MPPT responses to fault conditions.

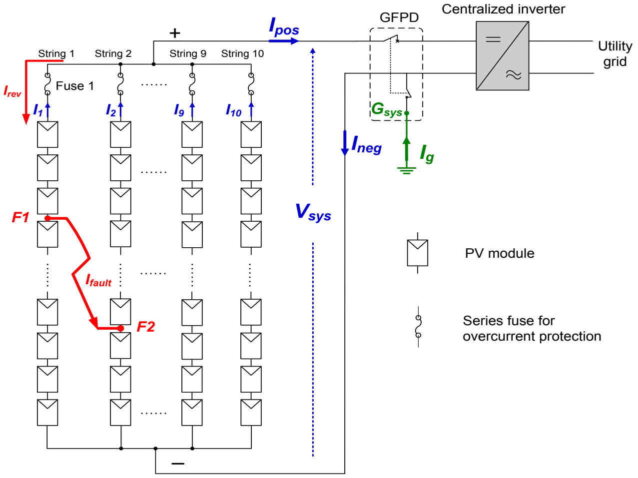

Figure 2. A line-line fault in a PV array of 10×10 modules

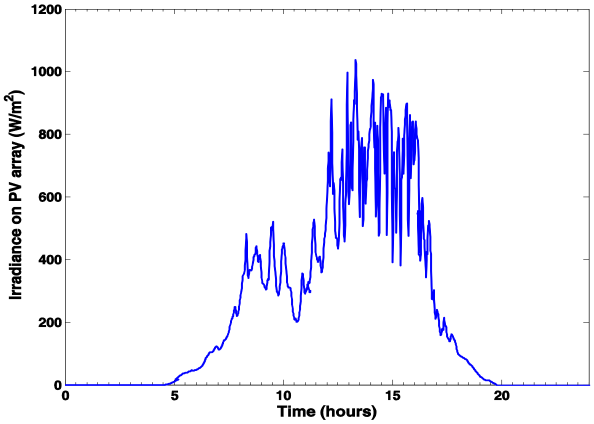

Figure 3. Irradiance level during a cloudy day

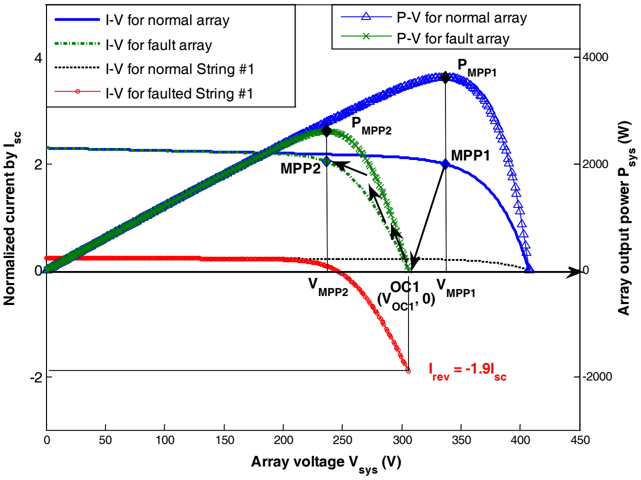

Figure 4. I-V curves of a line-line fault under low irradiance

B. Fault analysis under low irradiance conditions

The line-line fault occurs in the PV array under low irradiance (230W/m^2, at 8AM of the day). The *I-V* and *P-V* curves plotted in Fig. 4 can predict the peak of reverse current (I_{rev}) and the fault evolution. The current axis of the *I-V* and *P-V* curves is normalized by I_{sc} for clarity of explanation. In brief, I_{rev} is not large enough to trip the series OCPD at the fault under low irradiance, no matter how irradiance changes afterwards. Therefore, the fault may remain undetected in the PV array.

1) Fault scenario of the PV array

Before the fault occurs, the PV array is normally operating at its maximum power point *MPP1* on its *I-V* curve. At the moment of the fault, the *I-V* curve of the array is changed suddenly with reduced open-circuit voltage and new maximum power point *MPP2*. At the same time, the system operating point drops to point *OC1* (V_{oc1}, I_{oc1}) from *MPP1*. Since V_{oc1} is the maximum voltage that the array can maintain, the array becomes open-circuit condition with zero output current or power (I_{oc1}=0). Since V_{oc1} is large enough to sustain the inverter's operation, the MPPT of the inverter will still work.

After the fault, the MPPT will detect the sudden power drop of the PV array and begin to optimize the array's output power (P_{sys}). As a result, in order to increase P_{sys}, the operating voltage of the array (V_{sys}) will be reduced. Following the arrows drawn in Fig. 4, the optimal working point will move to *MPP2* on the *I-V* curve eventually. Notice the PV array has a much reduced P_{sys} at *MPP2* compared with the normal condition at *MPP1*.

2) *Reverse current into faulted PV String #1*

With the help of the *I-V* curve for String #1, I_{rev} into String #1 can be easily predicted. At the moment of the fault, the array becomes open-circuit condition at point *OC1* with zero output current. But other strings (i.e. String #2 – String #10) may still generate current. These currents have no path to flow but to backfeed into String #1. Therefore, I_{rev} reaches its magnitude maximum, flowing reversely into String #1 ($|I_{rev}| = 1.9I_{sc}$). However, this I_{rev} cannot trip series OCPD successfully, since the reverse current magnitude should be at least $2.1I_{sc}$ to melt the fuse. Therefore, the fault will evolve in the PV array without interruption.

Instead of a power source, faulted String #1 consumes power as a load. Until V_{sys} is reduced to V_{MPP2}, I_{rev} is almost reduced to zero. Then the current of String #1 is oscillating around zero since the MPPT keeps perturbing V_{sys} and optimizing P_{sys}.

C. *Fault evolution after the fault*

The irradiance keeps changing after the PV array reaches *MPP2*. Different *I-V* curves are plotted under irradiance 230W/m^2, 400W/m^2, 600W/m^2, 800W/m^2, and 1000W/m^2 in Fig. 5. *MPP2*, *MPP3*, *MPP4*, *MPP5* and *MPP6* are their maximum power points respectively. Assume the MPPT responds quickly enough to varying irradiance. Therefore, the MPPT always makes the PV array work around the MPPs of different *I-V* curves (see Fig. 5). During the irradiance changing, the current of String #1 is restricted to a small value by the MPPT all the time that is never large enough to melt OCPDs.

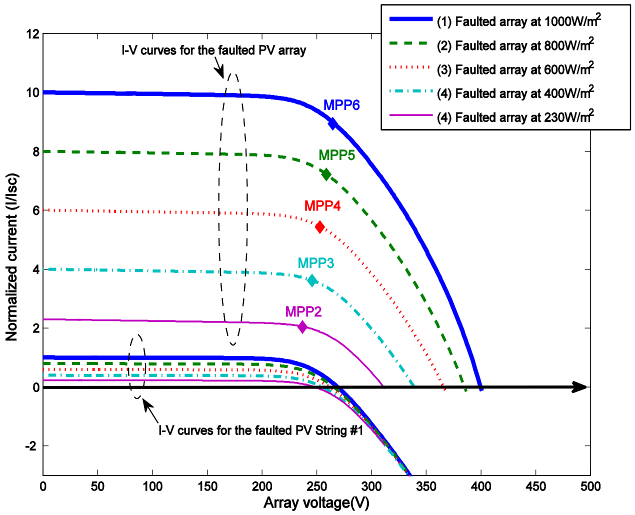

Figure 5. *I-V* curves under different irradiances

D. *Time domain analysis*

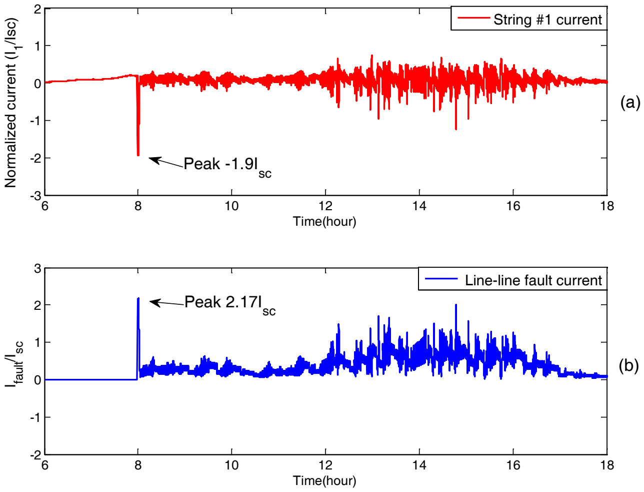

Figure 6. Fault evolution during a cloudy day: (a) String #1 current, (b) the line-line fault current

The evolution of String #1 current (I_1) and line-line fault current (I_{faul}) have been simulated in Fig. 6. Notice that the peaks of $|I_{rev}|$ and $|I_{fault}|$ occur at the moment of the fault. After the fault, as we previously discussed, $|I_{rev}|$ is clipped within a small value by the MPPT of the inverter (see Fig. 6 (a)). Even high irradiance occurs in the late of the day, the MPPT of the inverter responds fast enough to make the faulted PV array work at its nominal optimal operating point. Therefore, in this specific example, $|I_{rev}|$ is not high enough to be cleared by OCPDs during the day. Similarly, I_{fault} is also reduced smaller than its peak value at the fault. Furthermore, it is likely that $|I_{rev}|$ may not be detected by OCPDs as well during night-to-day transition [17]. As a result, the fault might remain unnoticed in the PV arrays until the PV system fails entirely.

E. *Discussion*

The same line-line fault has been simulated under high irradiance as well. Under 1000W/m^2, the peak of $|I_{rev}|$ can reach as high as $4.2I_{sc}$, which is much larger than minimum interrupting current of fuses ($2.1I_{sc}$). Therefore, given current vs. melting time characteristics of fuses, the same line-line fault has a much larger chance to be cleared under high irradiance than low irradiance.

IV. BLOCKING DIODES IN PV ARRAYS

This section focuses on the challenges to OCPDs brought by the use of blocking diodes in the PV arrays. By blocking the reverse current into the faulted PV string, blocking diode may stop OCPDs from working properly. This is another unique fault scenario in PV arrays that has not been discussed in the literature.

As shown in Fig. 7, blocking diodes are added at each PV string for the purpose of blocking the reverse flow of current into PV strings [7]. Blocking diodes only permit the current flowing in one direction and block the current in the other direction. When a fault occurs in the PV array (e.g. ground faults or line-line faults), the faulted string usually has a reduced open-circuit voltage, which could result in a large reverse current into the faulted string from other strings. Therefore, the faulted PV string will become a load instead of a power source. To avoid the reverse current under line-line faults, the blocking diode may be put on top of the faulted string to cut off the reverse current. However, the blocking diodes might conflict with the OCPDs, since OCPDs cannot detect any overcurrent. Therefore, although the reverse current is zero, the fault remains undetected and the fault is still hidden in the PV array.

A line-line fault with zero fault impedance has been studied to examine the protection challenges from blocking diodes. In the simulation, the PV array is assumed to work under STC with high irradiance 1000W/m^2.

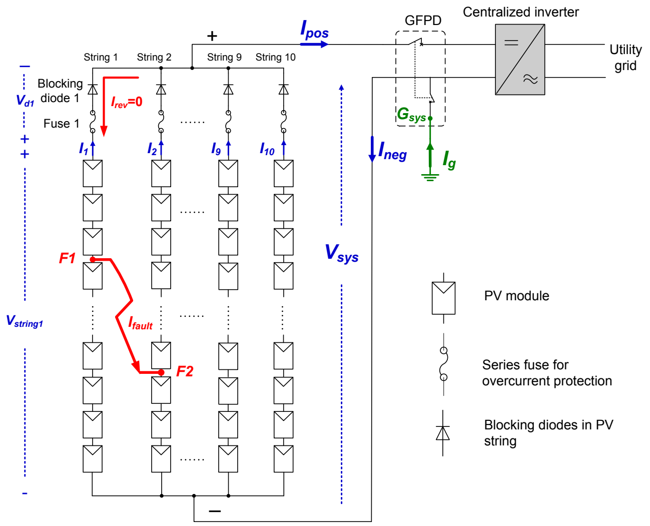

Figure 7. A line-line fault in the PV array with blocking diodes

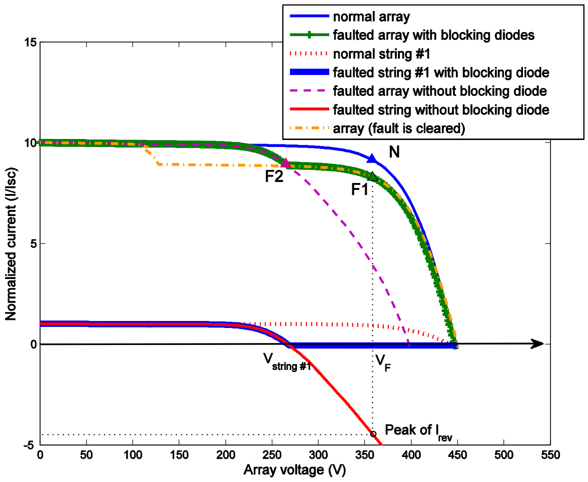

Figure 8. *I-V* curves of the line-line fault with blocking diodes

A. Line-line fault in the PV array with and without blocking diodes

1) I-V curve anlysis under STC

I-V curve analysis with normalized current-axis can be used to predict the faults scenarios in the PV array with or without blocking diodes (see Fig. 8).

a) With blocking diodes

Before the fault, the PV array is working at point *N*. At the moment of the fault, the system operating point drops to point *F1*, which has an operating voltage V_F. Notice that *F1* happens to be the MPP of the faulted array with blocking diode. The *I-V* curves show that point *F1* has similar operating voltage as point *N*, but point *F1* has reduced output current and output power: P_{sys} at *N* is 17.6kW; P_{sys} at *F1* is 16kW.

Meanwhile, the voltage of String #1 is reduced to $V_{string1}$ and the current of String #1 becomes zero. In other words, the reverse current into String #1 is blocked by Blocking diode #1. According to Kirchhoff's voltage law (KVL), the voltage loop along with String #1, Blocking diode #1 and other normal strings can be derived as: $V_{string1} - V_{d1} - V_F = 0$. The voltage stress on Blocking diode #1 will simply be the difference between V_{sys} and $V_{string1}$. Since $V_{string1} < V_F$, the blocking diode will be reverse biased. By using the *I-V* curve, V_{d1} can be found around –90V.

b) Without blocking diodes

In addition, the *I-V* curves of faulted PV arrays without blocking diodes are plotted in Fig. 8 for comparison. There are two *I-V* curves drawn for this case: The fault is cleared (dotted line in orange), or the fault remains in the PV array (dotted line in magenta).

When the fault is cleared, the corresponding MPP is the same as *F1* (P_{sys}=16kW). When the fault remains in the PV array, the MPP of array is *F2* (P_{sys} is only 12.8kW).

Also, the peak of $|I_{rev}|$ can be predicted in Fig. 8. At the fault, the PV array without diode will work at voltage V_F. The current of String #1 is reverse with peak $4.2I_{sc}$. After that, if the fault is cleared by the OCPD successfully, the operating point of the array will move up to *F1*. On the other hand, if the fault cannot be cleared by the OCPD properly, with the help of MPPT, the operating point of the faulted array may move to *F2* instead.

2) Simulated reverse current under STC

In order to understand the use of blocking diodes, it is helpful to compare String #1 current (I_1) with and without blocking diodes. To better observe the fault evolution, OCPDs are not used in the simulation so that the fault can evolve without interruption. The “normalized” String #1 current vs. time (I_1/I_{sc} vs. time) at STC has been plotted in Fig. 9.

In Fig. 9 (a), when the line-line fault occurs at $t=t_1$, if there is no blocking diode, the reverse current into String #1 will have peak ($-4.2I_{sc}$) as we predicted by using *I-V* curves. During $t_1<t<t_2$, I_{rev} remains at its peak value. According to

the OCPD's current vs. melting time characteristics, if this peak value lasts long enough, the reverse current is likely to melt the OCPD. After $t=t_2$, if the fault is not cleared and still remains in the PV array, the MPPT of the PV inverter may optimize the output of the fault PV array. As a result, $|I_{rev}|$ will be reduced gradually until a new MPP is found.

On the other hand, in Fig. 9 (b), if blocking diodes are used to block the reverse current, the OCPD will not clear the fault. When the fault occurs $t=t_1$, instead of a large reverse current, the current of String #1 remains at zero as we expected. In other words, the reverse current is totally cut off by the blocking diode. Therefore, OCPDs do not have any chance to detect the overcurrent, so that the fault may be hidden in the PV array (forever).

3) *Simulated voltage stress on blocking diodes under the fault*

The voltage stress on the blocking diodes has been simulated in Fig. 10. Before the fault occurs ($t<t_1$), the blocking diode is forward biased and its voltage drop is the forward voltage, usually 0.5 ~ 1V. When the fault at $t=t_1$, the voltage stress V_{d1} drops to –90V for this specific example. Since the MPPT of the PV inverter is still working, V_{sys} is always perturbed by the MPPT (e.g. P&O method) so that V_{d1} is oscillating as well.

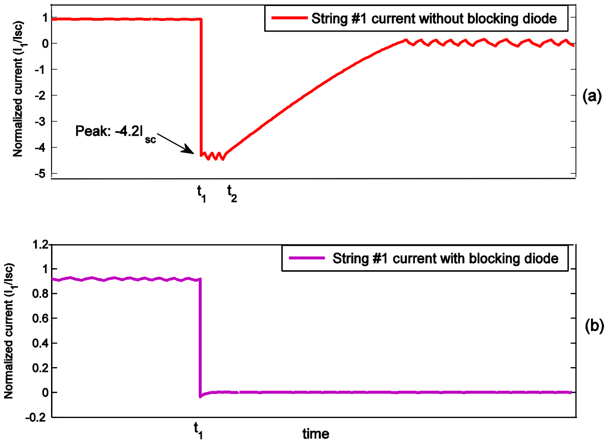

Figure 9. Simulated String #1 current: (a) without blocking diode; (b) with blocking diode

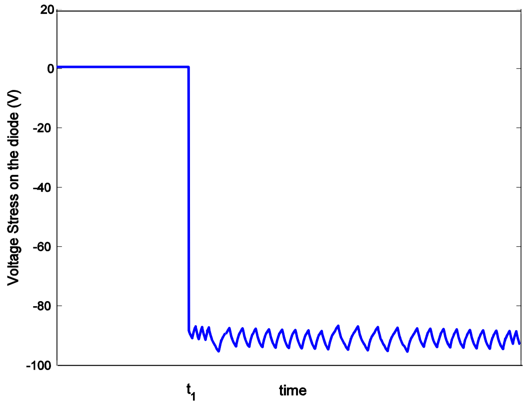

Figure 10. Simulated voltage stress on Blocking diode #1 during the fault

B. *Discussion*

The results of *I-V* curve analysis in this particular case have been summarized in Table I and discussed as follows.

- Blocking diodes will block I_{rev} and optimize P_{sys} under the fault, at the expense of losing the chance to clear the fault by OCPDs;
- OCPDs will not clear the fault successfully when blocking diodes are used, since the current through OCPDs is zero during the fault;
- Instead of blocking diodes, if the PV array only has OCPDs, there is a good chance that the fault will be cleared by OCPDs when $|I_{rev}|$ is large enough;
- "The faulted PV array with blocking diodes" vs. "the fault is cleared by OCPDs in the PV array without blocking diodes": at post-fault steady state, these two cases have the same MPP but different *I-V* curves.

TABLE I. SUMMARY OF *I-V* CURVE ANALYSIS

Case		**Operating Point**	
Status of PV array	***Fault cleared by OCPDs?***	***MPP***	***Peak of I_{rev}***
Normal PV array (no fault)	N/A	*N (17.6kW)*	N/A
Faulted PV array with blocking diode	No	*F1 (16kW)*	0
Faulted PV array without blocking diode	No	*F2 (12.8kW)*	$-4.2I_{sc}$
Faulted PV array without blocking diode (fault has been cleared by OCPDs)	Yes	*F1 (16kW)*	$-4.2I_{sc}$

V. EXPERIMENTAL VERIFICATION

A small-scale grid-connect PV system has been established to verify our simulation results. Fig. 11 illustrates the PV system by 2×6 modules in series-parallel configuration, which has the same schematic diagram as the PV array in Fig. 12. The detailed parameters for PV modules and PV inverter are given in Table II.

Figure 11. Picture of PV system experimental set-up

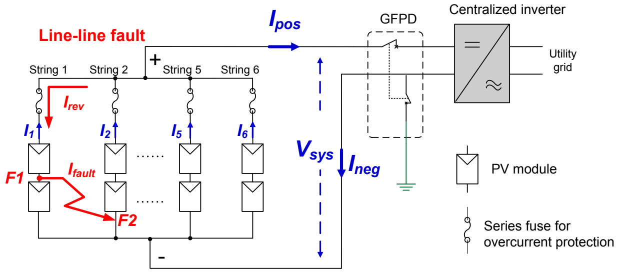

Figure 12. Schematic diagram of the experimental PV system

TABLE II. PARAMETERS OF PV COMPONENTS

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

A. Low Irradiance Conditions

As shown in Fig. 12, a line-line fault occurs at String #1 under low irradiance. Fig. 13 gives the experimental results of V_{sys} and I_1 during the fault. Fig. 14 shows the experimental results of V_{sys}, I_{sys} and P_{sys}. The time base is all 1s/div. It is shown that when the fault occurs at t=t_1, the fault will cause the peak of the reverse current into String #1. However, the maximum magnitude of I_{rev} is only 0.86I_{sc} (0.5A) under low irradiance, which will not be high enough to melt the series fuse protection (min. interrupting current >2.1I_{sc}). P_{sys} is reduced to 18W at the moment of the fault.

After the fault (t>t_1), the MPPT of the PV inverter will detect the sudden drop of P_{sys} and will begin to look for new MPP. As a result, V_{sys} will oscillate at first and then settle down at new MPP (P_{sys}=24W) with reduced V_{sys}. After the fault, the MPPT may respond fast enough to irradiance changes during the day, so that $|I_{rev}|$ will be always clipped within a small value that will never trip the fuse.

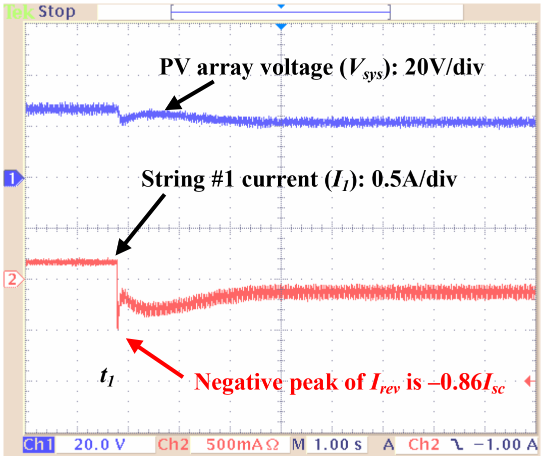

Figure 13. Experiments: V_{sys} and I_1 at line-line fault under low irradiance

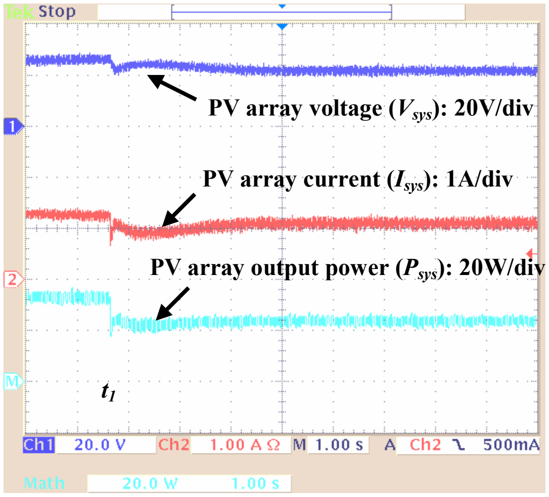

Figure 14. Experiments: V_{sys}, I_{sys} and I_1 at line-line fault under low irradiance

B. Uses of Blocking Diodes

The same line-line fault is implemented in the experimental PV system with blocking diodes. As shown in Fig. 15, when the fault occurs at t=t_1, the reverse current into faulted String #1 is totally blocked by the blocking diode in series with String #1. As a result, the fuse on String #1 will never detect the reverse current. Therefore, the fault will remain undetected in the PV array and become a safety hazard.

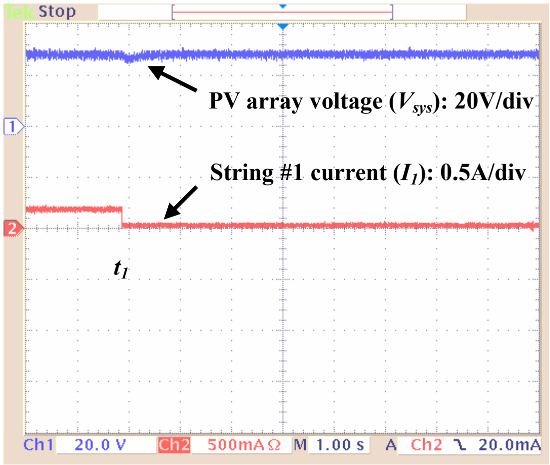

Figure 15. Experiments: V_{sys} and I_1 at line-line fault in the PV system with blocking diodes

VI. CONCLUSION AND FUTURE WORK

This paper presents the challenges to overcurrent protection devices in PV arrays brought by two types of unique fault scenarios. The first one is the fault occurring under low irradiance conditions. In this case, the reverse current into the faulted string will never reach a high value to trip OCPDs, even when high irradiance occurs later in the day. The second fault scenario is the use of blocking diodes in PV arrays. In both US and European countries, blocking diodes are often used to block reverse current flow into PV strings in the PV system with battery storage. When the OCPDs and blocking diodes are both used in PV arrays, the blocking diodes may cut off the reverse current so that the OCPD may not work properly. Therefore, the fault may remain undetected and be hidden in the PV array until the whole system fails.

This paper discusses these two unique fault scenarios in theory and simulation on a grid-connected PV system consisting of 10×10 modules (nominal power level 17.5kW). The simulation results are clearly explained and verified through detailed fault evolution analysis in a small-scale experimental PV system. For “low irradiance” fault, the solution might be to add a PV string-level monitoring system on each PV string. For “blocking diode” protection issue, the solution might be avoiding blocking diodes in PV arrays when OCPDs are required on each string, especially when there is no battery storage. Our future research plan will further confirm our research results on a large-scale experimental PV system.

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