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Impact of Blocking Diodes on Fault Current Behaviour in Photovoltaic Arrays under Line-Ground and Line- Line Faults

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Abstract

The maximum power output from a photovoltaic (PV) array is reduced by abnormal situations like faults and partial shading. In order to improve reliability, efficiency and safety in PV systems, fault analysis in solar photovoltaic (PV) arrays is crucial. Blocking diodes play a crucial role in photovoltaic (PV) arrays by preventing reverse current flow and improving system reliability under fault conditions. This paper investigates the impact of blocking diodes on fault current behavior in PV arrays subjected **to** Line-to-Ground (L-G) and Line-to-Line (L-L) faults. A comparative analysis is conducted between PV arrays with and without blocking diodes to evaluate their effect on fault current magnitude, and power loss**.** Results indicate that blocking diodes significantly limit reverse fault currents, thereby reducing system damage and enhancing fault isolation.The presence of blocking diodes modifies the I-V characteristics of the PV array, influencing fault detection methodologies. The performance results of 25 kW PV array system are revealed by using a Matlab/Simulink model of 10×5 size of solar array.

A. Introduction

Power generation based on PV sources has been steadily increasing over the last few decades. Photovoltaic systems play a crucial role in reducing greenhouse gas emissions and mitigating climate change[1]. A large-scale PV (Photovoltaic) system typically includes a variety of components and infrastructure to generate electricity from sunlight efficiently. In large photovoltaic (PV) systems, PV modules are usually connected in series or parallel to form a PV string or array in order to generate sufficient power. If one of them fails, it could impact the system's overall performance [3].

PV arrays are susceptible to various electrical faults, including Line-to-Ground (L-G) and Line-to-Line (L-L) faults, which can significantly impact system performance, safety, and longevity. These faults may arise due to insulation failures, environmental conditions, poor wiring, or degradation of PV modules, leading to potential hazards such as excessive fault currents, thermal runaway, and reduced energy output.

Fault detection and timely troubleshooting are essential for the optimum performance in any power generation system, including photovoltaic PV system [4]. Therefore, for increased system reliability and efficiency, partial shadowing and faults in a PV array must be detected. Conventional protection systems for PV arrays consist of overcurrent protection devices (OCPD), arc fault circuit interrupters, and ground fault protection devices (GFPD) [12]. Conventional protection devices are unable to detect faults under cloudy and low irradiance conditions, which can result in safety problems and fire threats in the photovoltaic field [11][12].

One of the key protective components used in PV arrays to mitigate such issues is the blocking diode. Blocking diodes are typically placed in series with PV strings to prevent reverse current flow, which can otherwise lead to power loss and overheating of modules. Under normal operating conditions, these diodes ensure unidirectional power flow from the PV modules to the load or inverter. However, under fault conditions, the behavior of fault currents in the presence of blocking diodes is significantly altered. Understanding this impact is crucial for designing effective fault detection and protection mechanisms in PV systems.

This study investigates the influence of blocking diodes on fault current behavior under L-G and L-L fault conditions. Specifically, the research aims to analyze how blocking diodes affect fault current magnitude, power loss, and fault propagation within the PV array. A comparative analysis between PV arrays with and without blocking diodes is performed to highlight their role in limiting fault currents and preventing system-wide damage. Furthermore, the effect of blocking diodes on the I-V characteristics of the PV array is examined, providing insights into their implications for fault diagnosis and system protection strategies[8].

The remainder of this paper is structured as follows: Section II presents a literature review on PV fault analysis and the role of blocking diodes. Section III describes the system model and methodology used for analyzing fault behavior. Section IV discusses the results and their implications on fault detection and system protection. Finally, Section V concludes the paper with key findings and recommendations for future work.

B. Fault Analysis in Photovoltaic (PV) Systems

Photovoltaic (PV) systems are susceptible to various electrical faults that can affect their performance, safety, and longevity. Line-to-Ground (L-G) and Line-to-Line (L-L) faults are among the most critical types of faults, causing excessive current flow, power losses, and even fire hazards [9]. Studies have explored the behavior of these faults in different PV configurations, highlighting their impact on power output, voltage profiles, and thermal characteristics of modules.

Several researchers have investigated the impact of L-G faults in PV arrays. It has been observed that L-G faults create leakage currents, leading to potential grounding issues and safety concerns. According to [11], L-G faults can cause significant voltage imbalance, affecting the overall performance of the system. Furthermore, [4] noted that these faults are often difficult to detect due to their low fault current magnitudes in ungrounded PV systems.

On the other hand, L-L faults result in high short-circuit currents, posing severe risks to the PV array. Research in [5] demonstrated that L-L faults could lead to localized heating and thermal runaway, which may permanently damage PV modules. String-to-string faults have also been analyzed in [10], where it was shown that uncontrolled current flow between strings could disrupt power generation and lead to system-wide failures.

To mitigate the risks associated with L-G and L-L faults, various fault detection techniques have been proposed in the literature. These methods include: Voltage and Current Monitoring: Identifying abnormal variations in I-V characteristics [5]. Machine Learning-Based Fault Detection: Utilizing AI techniques for anomaly detection in PV arrays [2,3]. Wavelet Transform and Signal Processing Methods: Detecting transient behavior in faulty PV systems [7]. However, conventional protection mechanisms, such as circuit breakers and fuses, often fail to provide adequate fault isolation due to the unique characteristics of PV faults, such as low fault current magnitudes and intermittent fault conditions [8].

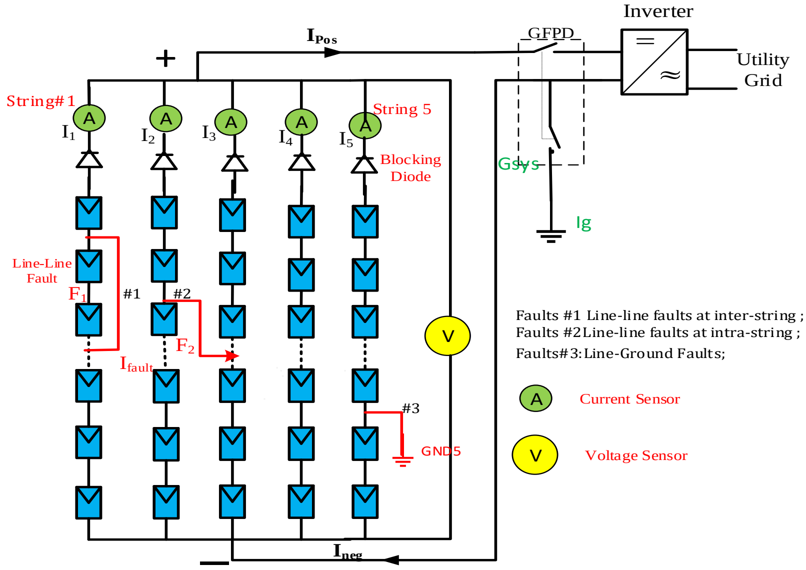


Figure 1. Schematic Diagram of a PV System under Various Fault

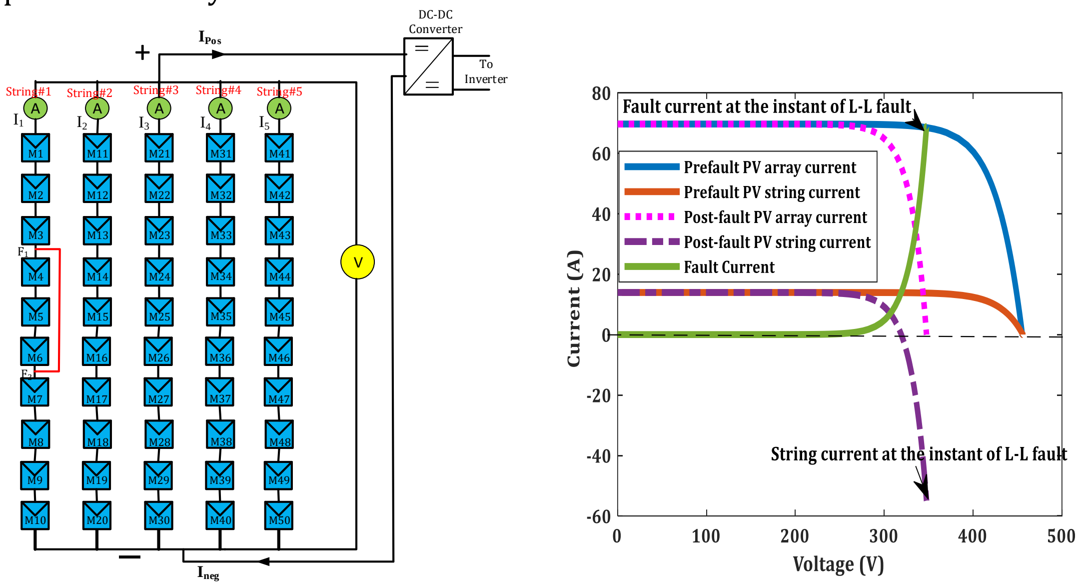
The levels of PV monitoring consist of array level, combiner level and string level. PV string monitoring is best suited to understand the working status of each PV string in real time . The output voltage and current of each PV array; output power and energy of each PV array; ambient temperature and PV module temperature are measured by using voltmeter, current, irradiance and temperature sensors and I-V Tester etc.

Figure 1 depicts the schematic diagram of a grid-connected PV system PV system with different types of faults. A PV array, an inverter, a DC–DC converter with MPPT, blocking diodes, and current sensors make up a typical PV system [9]. The array is made up of modules coupled in series and parallel to provide the required output power. If the PV strings are all electrically identical and have the same environmental working condition [10].

Fault analysis with and without blocking diodes

PV system faults occur at various locations, including the utility grid, power converter, and PV array. As seen in Figure 2(a), the PV array faults, such as L-L faults, happen between fault point (M_5 and M_7) at inter string strings of the PV system.

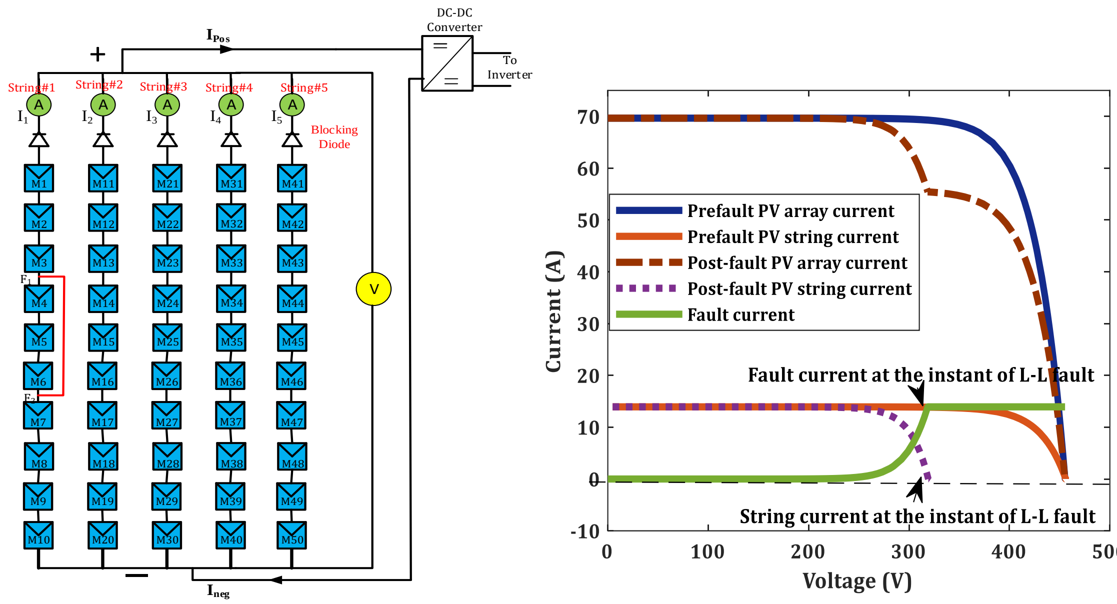
Figure 2(b) displays the PV system's current versus voltage (I-V) characteristic curve without blocking diodes under L-L fault conditions at inter string, as well as the fault current (I_F) and string current under prefault and postfault situations. It has been noted that an L-L fault causes the current to flow through the faulted string in reverse. A back or reverse current (I_{REV}) flows into the faulted string from the other healthy string, while the faulted string creates an I_F between points F_1 and F_2. As seen in figure 2(b), the I_F at the moment of fault is nearly twice the string's short-circuit current at prefault conditions, making it simple for the PV system's OCPDs to detect.



(a) (b)

Figure2.(a) PV Array System without Blocking Diodes under Fault.(b) I-V Characteristics Curves without Blocking Diode under Fault

The PV array system with blocking diodes under fault condition is shown in figure 3(a).Figure 3(b). displays the PV system's I-V characteristic curve under prefault and postfault situations with blocking diodes and string current in addition to the I_F. The blocking diode prevents the back or I_{REV} produced by the other healthy string from flowing into the faulty string, while the string creates an I_F between points F_1 and F_2. Since the I_{REV} is blocked by the blocking diodes, the instant I_F is nearly identical to the string's short-circuit current in the prefault state, as seen in figure 3(b). As a result, the PV system fault remains undetected since the I_F does not reach the OCPD threshold current. Furthermore, the power converter's MPPT function frequently shifts the operating point to a new location on the I-V characteristic curve, causing the I_F magnitude to drop with time. The I_F through the impacted strings is determined to be insufficiently large to reach the threshold limit of the OCPDs if the L-L and L-G fault occurs during low irradiation conditions, such as dawn or sunset, and the fault goes unnoticed.



(a) (b)

Figure.3 (a) PV Array System with Blocking Diodes under Fault.(b) I-V Characteristics Curves with Blocking Diode under Fault

Blocking diodes have been widely used in PV arrays to prevent reverse current flow and protect modules from damage. By restricting the fault current to the affected module or string, blocking diodes reduce the risk of overheating and module degradation.

C. Case Study

The photovoltaic (PV) system under study consists of a series-parallel configuration of PV modules, representative of a typical grid-connected solar array. The system is modeled to analyze the impact of blocking diodes on fault current behavior under Line-to-Ground (L-G) and Line-to-Line (L-L) faults.

In this paper, a typical solar PV array system considered that has five strings with ten series modules in each of them. figure 4 depicts the voltage-current and voltage-power curve of a 25 kW solar PV array under normal condition. According to figure, the maximum power is approximately 25 kW and maximum voltage and maximum current for the whole array system are about 383.4 V and 65.3 A respectively. The parameters of each panel under Standard Testing Conditions (STC-temperature of 25°C and irradiance-1000 W/m²) is shown in Table 1.

Table 1. PV Module Specifications at STC

Module Type	JASolarJAM66S30-500MR
Rated Power	500 W
Open-circuit voltage, V_{oc}	45.59 V
Short-circuit current, Isc	13.93 A
Voltage at P_{max}, V_{mp}	38.35 V
Current at P_{max}, I_{mp}	13.04 A

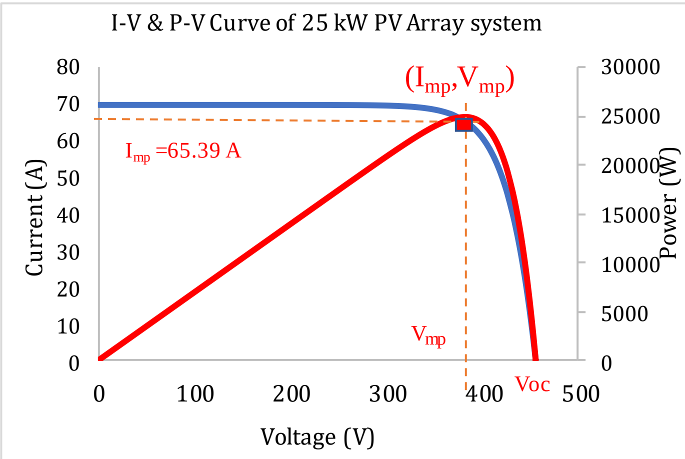


Figure. 4. P-V and I-V Characteristic Curve of PV Array System

Figure 5 shows the P-V and I-V (current-voltage) characteristics for a PV array system under varying irradiance levels, represented (W/m^2). Each curve shows the maximum power point (MPP) for different irradiance conditions: 1000 W/m^2, 800 W/m^2, 500 W/m^2, and 200 W/m^2. According to figure 5, the irradiance level is directly proportional to the short-circuit current. As irradiance decreases, both the current and power output of the PV system reduce significantly. However, the voltage of the PV system does not change significantly when the solar irradiance changes.

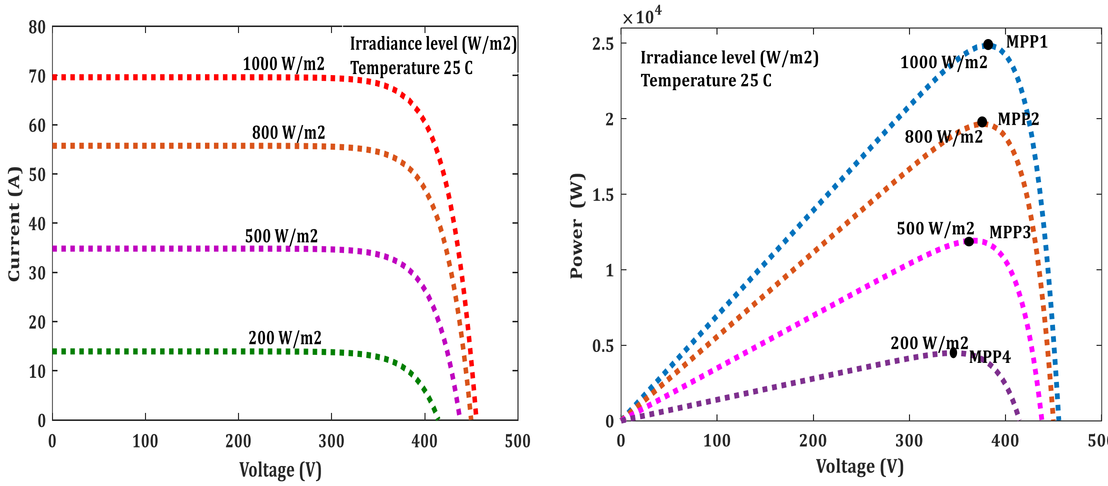
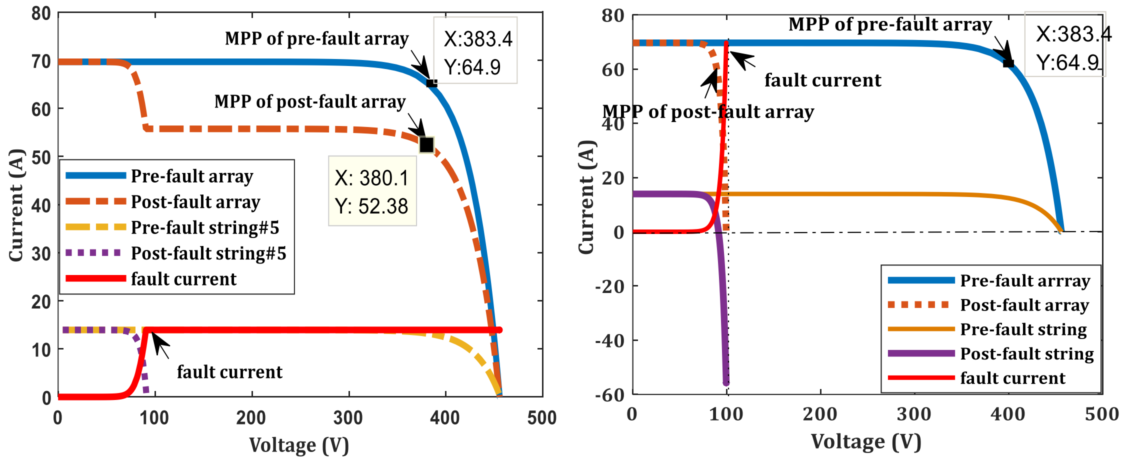


Figure. 5. P-V and I-V Characteristics Curves under Normal Condition at Different Irradiation Levels

Line to Ground Fault

A line-ground fault occurred at upper position between the 2nd and 3rd two modules at the string (#5) of PV array is created. A current sensor is connected to each string in order to measure the currents in the strings. The voltage sensor is connected across the PV array output terminals to measure the V_{pv}.

Figure 6 displays the I-V characteristic curve of the PV system with and without blocking diodes and string current under prefault and postfault conditions in addition to the I_F. As a figure 6(a), the other healthy string's back or I_{REV} is prevented from flowing into the faulted string by the blocking diode, while the string creates an I_F between points F_1 and F_2. It is found that the post-fault array's voltage is lower than the pre-fault array's. The open-circuit voltage drops and the string current I_5 decreases when ground faults at a higher position occurs in the string#5.



(a) (b)

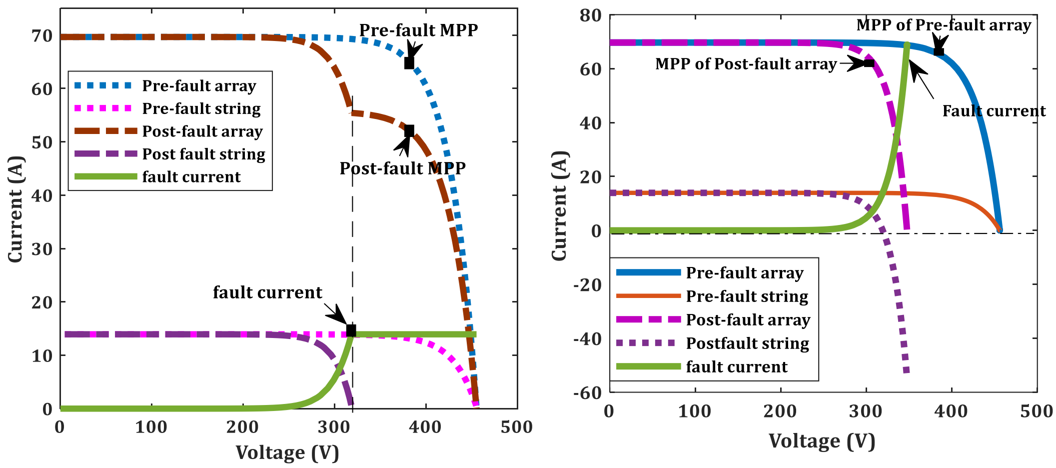
Figure.6. I-V Characteristics Curves under Line to Ground Fault at STC (a) with Blocking Diode (b) without Blocking Diode

When ground faults at a higher position occurs at the string #5 of PV array without blocking diodes, the maximum magnitude of ground fault current I_{fault} is 68.73 A (4.9 Isc). Then, a large amount of backfed current -55.58 A (-4Isc) from other normal strings enters string #5 as shown in figure 6(b). Power loss is more severe in the absence of a blocking diode**,** which can lead to further mismatches and inefficiencies in the PV system.

Line to Line Fault at Inter String

The first string (#1) creates the L-L fault with the mismatch of many modules. The L-L fault is created from the beginning point F_1 to the finishing point F_2 (M_5 and M_7). The current passing through the first string drops to 0 A when it is open-circuited. The voltage of the PV array doesn't change. Each string has current sensors that are used to measure the string currents.

The I-V characteristics under normal and abnormal circumstances are shown in figure 7. It is found that under faulty conditions, the maximum PV power and PV current are lower than under normal conditions. The reverse-biased blocking diode, on the other hand, keeps the maximum PV voltage constant and isolates the faulted string in this situation.The open-circuit voltage drops to 319 V and the string current I_1 decreases when three module failure occurs in the first string.



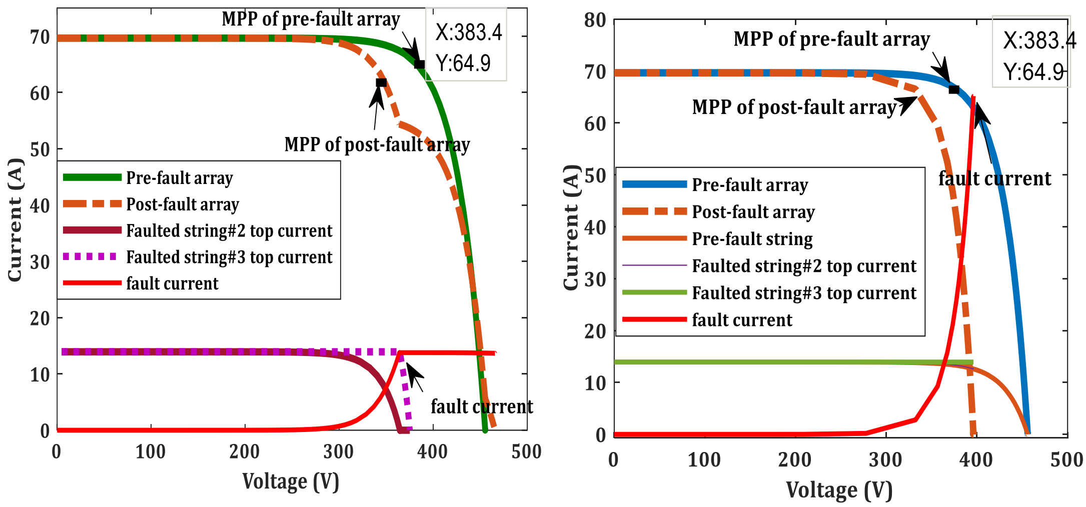
(a) (b)

Figure.7. I-V Characteristics Curves under Line- Line Fault at Inter String at STC (a) with Blocking Diode (b) without Blocking Diode

As seen in figure 7(b), the I_F at the moment of fault is nearly twice the string's short-circuit current at prefault conditions when line-line faults at inter string #1 of PV array without blocking diodes.

Line to Line Fault at Intra String

The line-line faults with large voltage difference occurs between fault point at string #2 and fault point at string #3 of PV array is created as shown in figure 1 . It means that there is a line-line fault with two module level difference between string #2 and string #3. The I-V characteristics curves of this condition is shown in figure.8.



(a) (b)

Figure.8. I-V Characteristics Curves under Line- Line Fault at Intra String at STC (a) with Blocking Diode (b) without Blocking Diode

The intra string fault between the second and third strings is formed. As seen in figure 8(b), the I_F at the moment of fault is nearly twice the string's short-circuit current at prefault conditions when line-line faults at intra string #1 of PV array without blocking diodes.In this condition, the blocking diode is forward biased for the PV parameters. Furthermore, the power converter's MPPT function frequently shifts the operating point to a new location on the I-V characteristic curve, causing the I_F magnitude to decrease over time. The I-V characteristics with blocking diodes under normal and abnormal circumstances are shown in figure 8(a). It is found that under faulty conditions, the maximum PV power and PV current are lower than under normal conditions. The open-circuit voltage drops to 363.3 V decreases when three module failure occurs in the first string. As a result, the top current I_2 of faulted string #2 is lower than the top current I_3 of faulted string#3 and the other string currents are equal.

D. Simulation Result and Discussion

This section presents the analysis of fault current behavior, and power loss for a 25 kW PV array system consisting of five strings, each with ten series-connected 500 W modules. The results compare system performance with and without blocking diodes under Line-Ground (L-G) and Line-Line (L-L) faults, highlighting their implications for fault detection and system protection.

The typical solar PV (25 kW) photovoltaic array system that has five strings with ten series modules in series-parallel connections by using MATLAB/Simulink simulation is shown in figure 9. The output voltage, current and power of PV system under pre-faults condition are 383.4 V, 65.2 A and 25 kW respectively. Similarly, the output voltage, current and power of each PV string are 383.4 V, 12.91 A and 5 kW respectively.

The breaker switches are used to connect lines between the strings and modules in order to produce the necessary faults in MATLAB/Simulink simulations. For every type of fault taken into consideration in this work, the faults are generated in Simulink at 0.1s by flipping switches ON and OFF. Line-line and line-ground fault conditions in solar PV system with and without blocking diodes are studied in this paper.

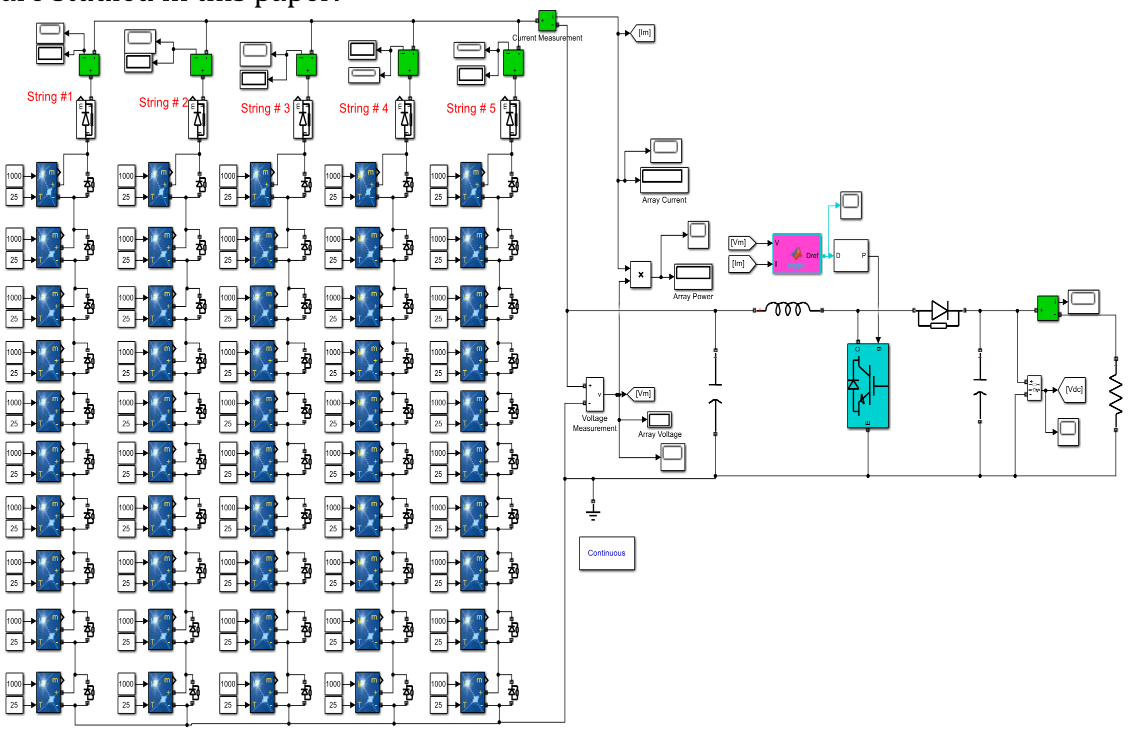


Figure 9. Matlab /Simulink Model of a PV Array System with 10 x 5 Modules

The PV array voltage, current, power for the possible conditions of the PV array, are described individually in figure for irradiance level 1000w/m^2. . Each of these conditions is discussed below:

Case I- Line to Ground Fault

In this case, the line-ground fault at upper position occurs between the 2nd and 3rd two modules at the string (#5) of PV array as shown in figure 1. The designed PV array system is simulated in MATLAB/Simulink for analysing the effects of L-G fault. In normal condition, the breaker switch is created at OFF switch condition. And then, the L-G faults are created in Simulink by turning ON switches after 0.1s normal operating condition. Unbalanced currents and voltage variations between the faulted string and other regular strings are frequently caused by the instantaneous fault.

From the figure 10(a), it is found that the ground-fault current I_{fault} reaches its maximum magnitude of 8.4A (0.58Isc) when the ground fault occurs at t=0.1s. Faulted string current is less than 13.93 A and the other four string currents are same.No backfed current enters the faulted string in this upper ground fault scenario because of blocking diodes. In this case, there is no backfed current into the faulted string, and no overcurrent is larger than the fuse rated current 1.56 Isc. The simulated fault current (I_{fault}) and top String#5 current (I_5) is plotted in figure 10(a).

Figure 10 (b) shows the simulation results of string parameter under L-G fault in PV array without blocking diodes. From the figure, the maximum magnitude of ground fault current I_{fault} is 58 A (4.1 Isc).Then, a large amount of backfed current -48 A (-3.5Isc) from other normal strings enters string #5. Depending on the type of fault and fault location in the PV array, the fault current (I_{fault}) varies.

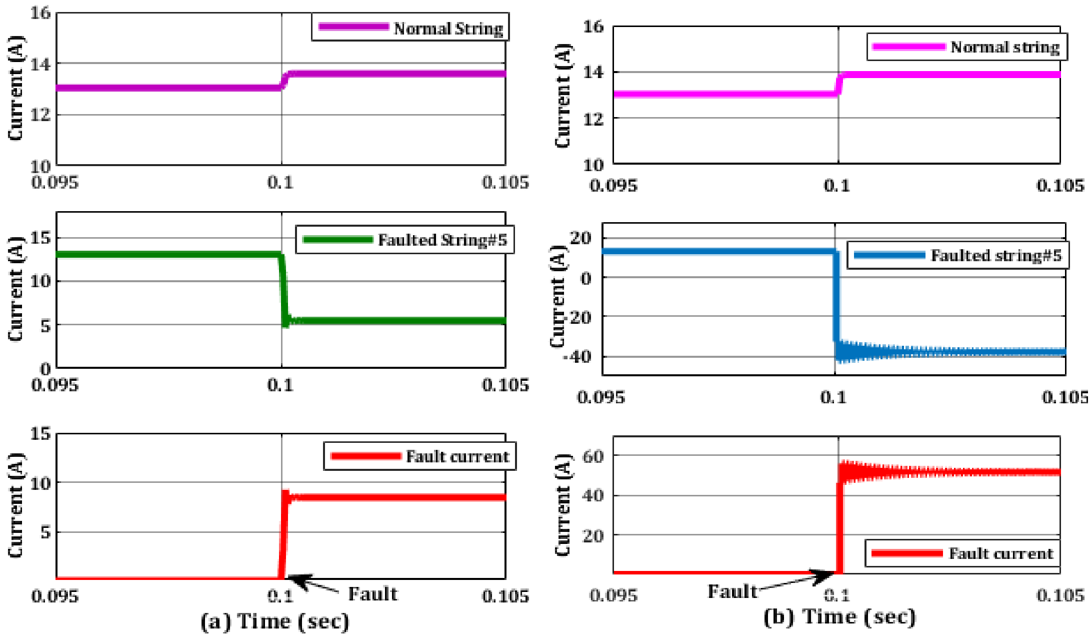


Figure 10. Simulated Results of String Current of L-G Fault in PV Array (a) with Blocking Diodes (b) without Blocking Diodes

The output voltage (V_{sys}), current (I_{sys}) and power (P_{sys}) of the entire PV array are shown in Figure. 11. With blocking diodes, the output power of PV system is reduced from 25 kW to 21.6 kW when ground faults at a higher position occurs at 0.1s. The output voltage, current of PV array system under faults condition are 350.6 V, 61.2 A respectively. Without blocking diodes, the output power of PV system is reduced from 25 kW to 8407.8 W. The output voltage, current of PV array system under faults condition are 200 V, 38.5 A respectively. The impact of faults on power output is reduced with blocking diodes, ensuring early-stage fault identification based on power variations.

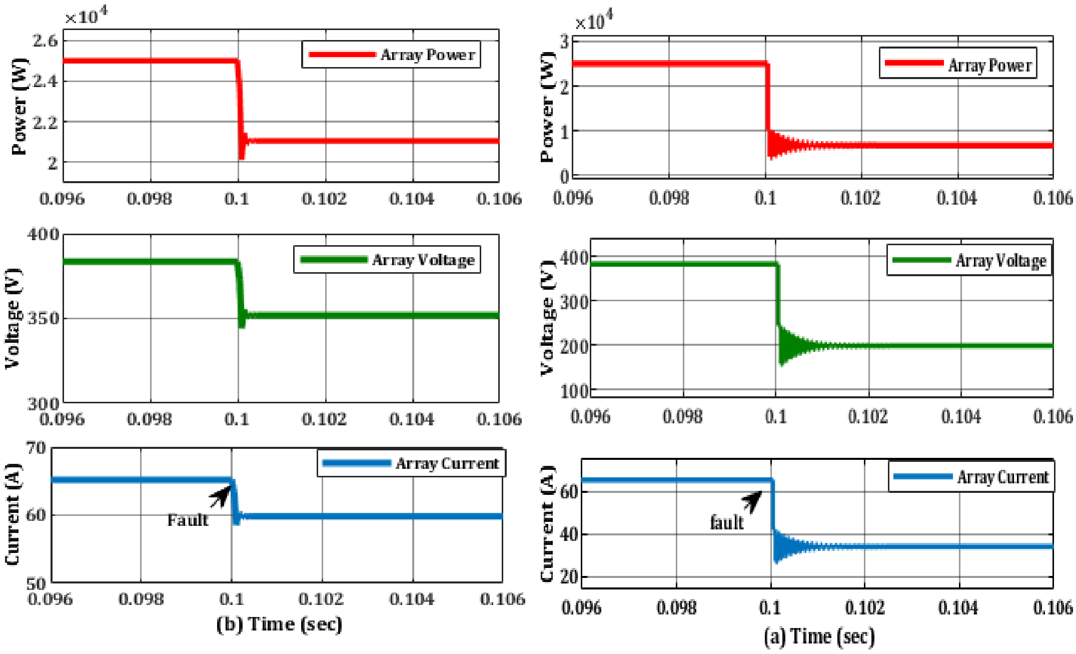


Figure 11. Simulated Results of L-G Fault of Array Parameters in PV array (a) with Blocking Diodes (b) without Blocking Diodes

Case II. Line to Line Fault with inter string

In this case, the line-line faults with inter string occurs fault point at string #1 and three modules are short-circuit. As seen in figure 9, an L-L fault is introduced in the first string at 0.1 s. The current sensors in each string are used to detect the three-module mismatch. The fault current and other string currents under L-L fault in the first string are displayed in figure 12. The array voltage remains constant under these faults because the blocking diode in the first string is reverse biased, meaning it is open circuited and isolated from the PV array.

When the line to line fault occurs, the fault current I_{fault} has the maximum magnitude 14.39 A (0.54 Isc) and the faulted string #1's top current reaches its minimum 0.445 A. The other four string currents are same.In this case, there is no backfed current into the faulted string, and no overcurrent is larger than the fuse rated current 1.56 Isc. Therefore, traditional protection devices cannot trip a line-line fault with a small voltage difference.

Figure 12 (b) shows the simulation results of string parameter under L-L fault at inter string in PV array without blocking diodes. From the figure, the maximum magnitude of fault current I_{fault} is 38 A (2.7 Isc). Then, a large amount of backfed current -25 A (-1.7Isc) from other normal strings enters string #1.

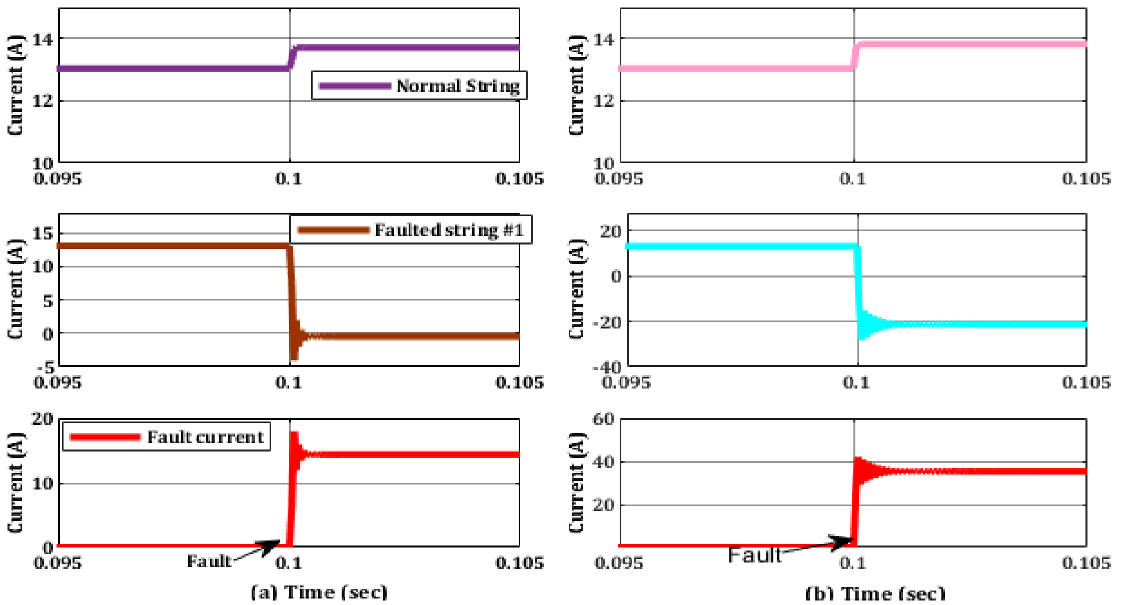


Figure 12. Simulated Results of L-L Fault at Inter String in PV Array (a) with Blocking Diodes (b) without Blocking Diodes

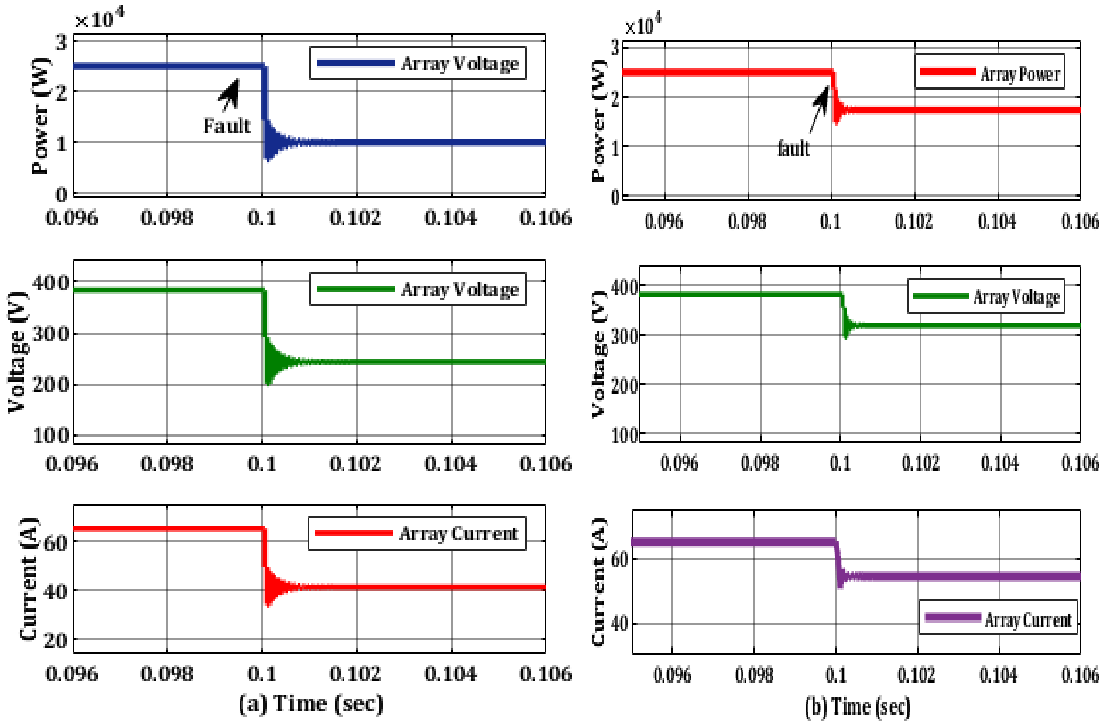


Figure 13. Simulated Results of Array Parameter of L-L fault at Inter String in PV Array (a) without Blocking Diodes (b) with Blocking Diodes

The output voltage (V_{sys}), current (I_{sys}) and power (P_{sys}) of the entire PV array are shown in figure 13. With blocking diodes, the output power of PV system is reduced from 25 kW to 18.5 kW when L-L faults at inter string occurs at 0.1s. The output voltage, current of PV array system under faults condition are 340.6 V, 56 A respectively. Without blocking diodes, the output power of PV system is reduced from 25 kW to 10000 W. The output voltage, current of PV array system under faults condition are 250 V, 40 A respectively.

Case III. Line to Line Fault with intra string

In this case, the line to line faults with large voltage difference occurs between fault point at string #2 and fault point at string #3 of PV array is presented. The string current in the second string is 5.367 A and the defective third string is 13.77 A when a multiple string fault occurs between the second and third strings. The string currents under line to line fault with intra string are displayed in Figure 14.The third string current is higher than the other three string currents, and the second string current is clearly lower than the others, according to this figure 14(a).

Figure 14 (b) shows the simulation results of string parameter under L-L fault at intra string in PV array without blocking diodes. From the figure, the maximum magnitude of fault current I_{fault} is 28 A (2Isc).

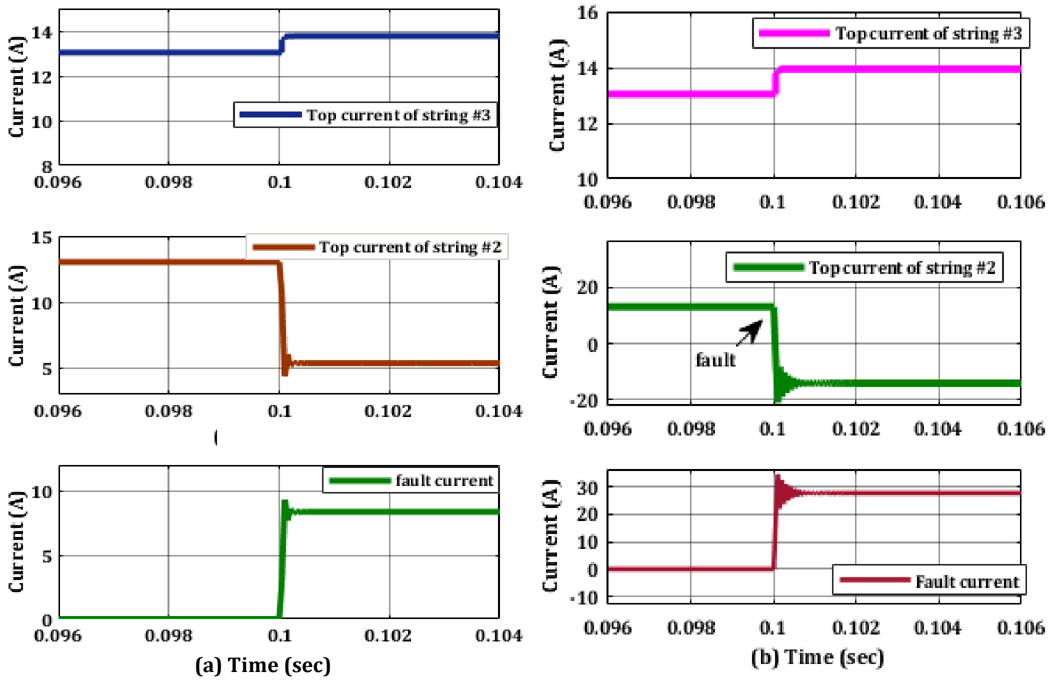


Figure 14. Simulated Results of L-L fault at Inter String in PV array (a) with Blocking Diodes (b) without Blocking Diodes

The output voltage (V_{sys}), current (I_{sys}) and power (P_{sys}) of the entire PV array are shown in figure. 15. With blocking diodes, the output power of PV system is reduced from 25 kW to 2.1 kW when L-L faults at intra string occurs at 0.1s. The output voltage, current of PV array system under faults condition are 350.6 V, 60 A respectively. Without blocking diodes, the output power of PV system is reduced from 25 kW to 13000 W. The output voltage, current of PV array system under faults condition are 290 V, 49 A respectively.

The fault that has a greater voltage difference between two fault points will produce a greater fault current. One-module voltage differences, or L-L faults with a small voltage difference, may not cause any backfed current to enter the faulted string. As a result, The efficiency and reliability of the system could be threatened by this L-L fault, which could be concealed in the PV array. As a result, existing protection mechanisms may face difficulties when dealing with L-L faults with a small voltage difference. A large backfed current into the faulted string and a large fault current in the fault path will result from L-L faults with a large voltage difference—that is, a voltage difference greater than one module. L-L faults typically have a reduced array voltage (Vsys) but a much smaller reduction in array current (Isys) if the fault can develop uninterruptedly.

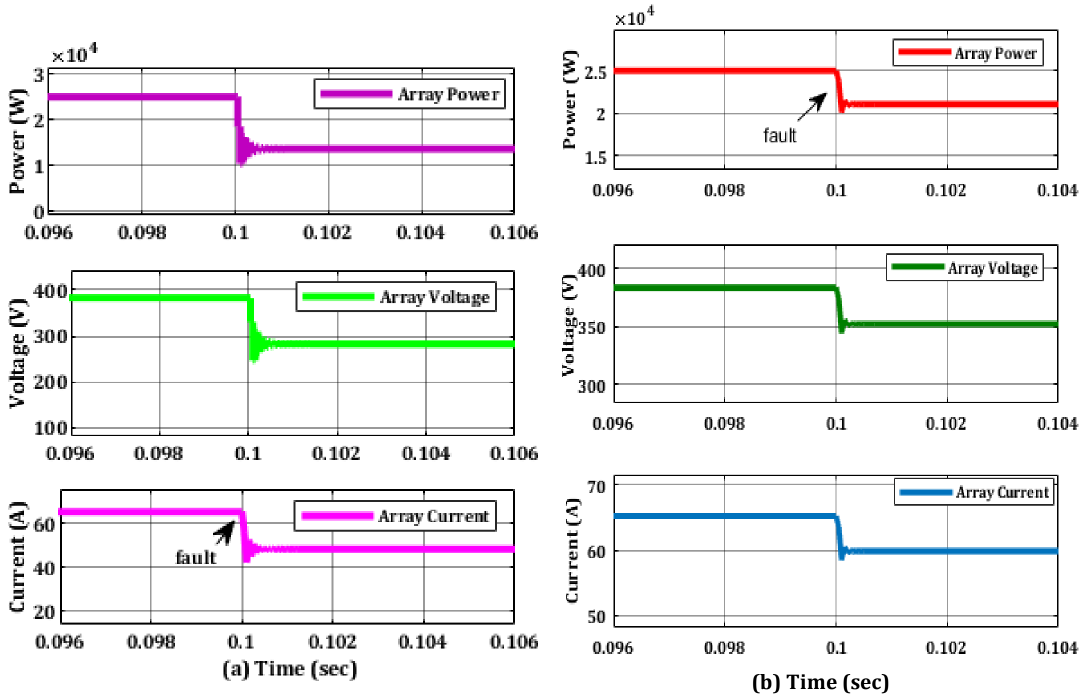


Figure 15. Simulated Results of Array Parameters of L-L fault at Inter string in PV Array (a) without Blocking Diodes (b) with Blocking Diodes

F. Conclusion

This study analyzed the impact of blocking diodes on fault current behavior, power loss, and fault detection strategies in a 25 kW photovoltaic (PV) array system under Line-to-Ground (L-G) faults and Line-to-Line (L-L) faults. The results show that a significant backfed current enter into the faulted string under upper line to ground fault and line to line faults with large voltage difference in PV arrays without blocking diodes and overcurrent is larger than the fuse rated current 1.56 Isc. Therefore, traditional protection devices will effectively clear the line to line fault with a large voltage difference. But, the blocking diode prevents the back or I_{REV} produced by the other healthy string from flowing into the faulty string in PV arrays with blocking diodes. As a result ,lower ground fault and line-line fault with small voltage difference does not cause large enough overcurrent to trigger the fuses. Blocking diodes significantly influence fault current behavior in PV arrays by limiting reverse current flow, reducing system damage, and improving fault isolation**.** Blocking diodes effectively reduce fault current magnitudes in both L-G and L-L fault conditions, preventing excessive current leakage and overheating. Power loss is significantly lower when blocking diodes are used, improving system efficiency.Understanding their impact is essential for effective fault diagnosis and mitigation in PV systems**.** The use of blocking diodes in PV arrays is a cost-effective and efficient solution to enhance fault detection, reduce power losses, and improve overall system safety**.** By integrating intelligent monitoring techniques and optimized protection strategies**,** future PV systems can achieve greater reliability and resilience against electrical faults**,** ensuring long-term performance and sustainability**.**

G. Acknowledgment

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