

Review

Reverse Polarity Protection in Photovoltaic Systems: A Review

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ABSTRACT: In photovoltaic (PV) systems, precise wiring connections are critical to ensuring safe operation. Thus, effective reverse polarity protection is the first line of defense against polarity reversal caused by wiring errors. This paper systematically reviews existing methods for protecting PV systems against reverse polarity. First, the operating principles of PV side reverse polarity protection techniques are analyzed, along with their advantages and limitations. Additionally, DC-bus side protection methods are examined, and the effectiveness of different approaches is evaluated. Overall, this review provides researchers with the latest advances in reverse polarity protection for PV systems.

Keywords: PV system; Reverse polarity protection; PV side protection; DC-bus side protection; Power electronics

1. Introduction

PV systems must be safe and reliable [1–4]. Within this context, the proper installation of electrical wiring constitutes one of the critical factors for ensuring system safety. However, during manual installation or maintenance, incorrect polarity connections can occur, resulting in equipment overheating, damage, and even increased fire risk [5–8]. To address this issue, a reverse polarity protection technology has been proposed, that detects polarity connection errors in real time and interrupts abnormal current flow [9–13]. Thus, conducting a thorough investigation into this technology is critical for improving the overall reliability of PV systems [14–16].

In a typical PV system, PV strings are first connected to a DC/DC converter for voltage boosting. The boosted DC is then converted into AC via a DC/AC inverter, which supplies the grid or local loads. This configuration presents two critical connection points that are vulnerable to reverse polarity faults: one at the input, where PV strings are interfaced with the DC/DC converter, and the other at the DC-bus connection, which links the DC/DC and DC/AC converters. Based on this, this paper clearly classifies reverse polarity protection strategies into two categories: PV side protection and DC-bus side protection. Protection on the PV side prevents reverse polarity from the PV strings. Conversely, protection on the DC-bus side safeguards against reverse polarity faults originating from the DC/DC converter's output [16–19].



In recent years, extensive research has been conducted on these two types of reverse polarity protection technologies [20–31]. These studies have employed diverse strategies, utilizing hardware components such as fuses [21,22], semiconductor-based devices including diodes [23,24], metal-oxide-semiconductor field-effect transistors (MOSFETs) [25–27], and intelligent relays [28], among others. In addition, there are protection solutions that use existing system components and are implemented via software-based control. However, existing research has primarily focused on individual devices or localized solutions, with no comprehensive analysis framework. This discrepancy makes systematic comparison and selection guidance between different methods difficult.

To bridge this gap, this paper categorizes and compares existing protection technologies across several key dimensions. These include the location of protection, distinguishing between PV side and DC-bus side implementations; the stage of implementation, which distinguishes between preventive activation prior to fault current formation and reactive activation thereafter; and the means of implementation, classified into hardware-based and software-based solutions. The study establishes a structured, hierarchical classification framework that provides a systematic basis for selecting appropriate protection strategies across a wide range of application scenarios. Furthermore, each approach is evaluated for commercial viability, enabling the optimal selection of a protection strategy across a range of system topologies.

The structure of this article is as follows. Section 2 discusses the fundamental theory of reverse polarity fault in PV systems. Section 3 details PV side protection methods and their operating principles. Section 4 comprehensively examines DC-bus side protection schemes and evaluates their performance. Section 5 concludes the paper and outlines future research directions in reverse polarity protection.

2. Fundamental Theory of Reverse Polarity Fault

Figure 1 depicts current loops with a reverse polarity fault on the PV side and DC-bus side. To facilitate the analysis of reverse polarity faults across different system topologies, two distinct PV connection schemes are incorporated: the input of converter DC/DC #1 is supplied by a single PV string PV₁, whereas the input of converter DC/DC #n is connected to multiple PV strings PV_{n1} to PV_{nm} in parallel. Meanwhile, all DC/DC converters are interconnected to a common DC bus.

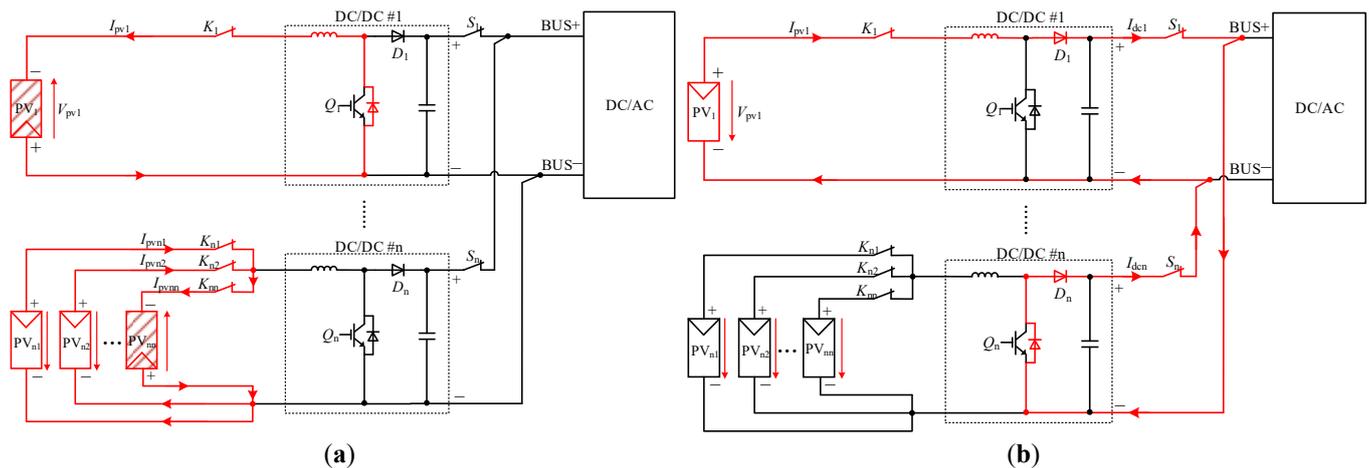


Figure 1. Current loops of PV system when a reverse polarity fault occurs on (a) PV side and (b) DC-bus side. The arrow pointing from the positive to the negative terminal of a PV string indicates the direction of the voltage drop across that string, while the other arrows in the circuit denote the current direction. Additionally, the shaded PV strings represent those with the reverse polarity fault, the red solid lines highlight the current flow paths, and the black dotted box include the components that make up the DC/DC converter circuit.

As shown in Figure 1a, for converter DC/DC #1, when the polarity of PV₁ is reversed and DC switch K₁ is closed, the output voltage polarity of PV₁ is reversed, thereby causing the output current I_{pv1} to flow

in reverse through the body diode of switch Q_1 . This reverse current may damage the body diode, causing the system to malfunction. To prevent this, the reversal of both voltage and current is utilized as the diagnostic signal for implementing reverse polarity protection in this single-PV topology.

For converter DC/DC # n , when the polarity of string PV $_{nn}$ is reversed, and DC switches K_{n1} to K_{nn} are closed, the normal string's currents flow toward PV $_{nn}$ instead of the converter DC/DC # n . The primary reason is that PV $_{nn}$'s output voltage polarity is reversed relative to the normal strings, resulting in a low-impedance short-circuit path between them. According to the principle that current preferentially flows along the path with the lowest impedance, the current generated by the normal strings will be primarily diverted through this fault path, which has a much lower impedance than the input of the converter DC/DC # n . Figure 2 presents the current–voltage (I–V) characteristics of both normal and reversed strings.

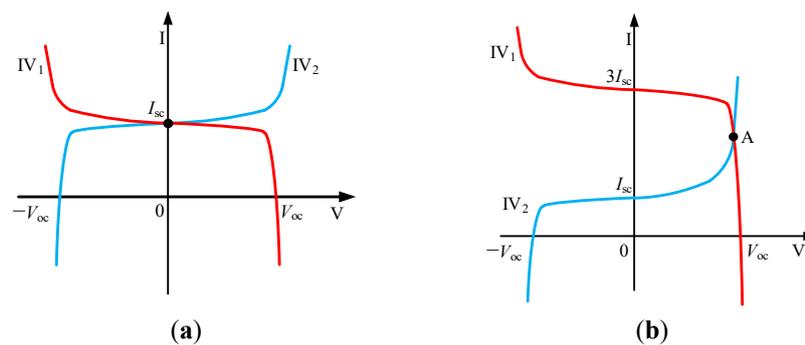


Figure 2. I–V curves of the normal and reversed PV strings, (a) $n = 1$, and (b) $n = 4$.

In Figure 2a, for $n = 2$, the I–V curves of the normal and reversed strings are denoted as IV_1 and IV_2 , respectively. The system operates under short-circuit conditions at $(0, I_{sc})$, where the reversed string remains undamaged. In Figure 2b, for $n = 4$, the combined I–V curve of three normal strings is represented by IV_1 , while IV_2 gives that of the reversed string. The intersection of these curves at operating point A corresponds to an elevated current level, implying that the reversed string will be damaged. Therefore, multi-string parallel PV systems must also include reverse polarity protection. The electrical signatures manifested during the fault are used to design such protection, specifically the reversal of voltage/current polarity in the faulty string and a current magnitude equal to the sum of the currents from all normal strings.

Figure 1b illustrates the current loop with a reverse polarity fault on the DC-bus side. When the polarity of DC/DC # n 's output is reversed, the current I_{dc1} to $I_{dc(n-1)}$ from converters DC/DC #1 to DC/DC # $(n-1)$ flows through the DC bus to the body diode of Q_n in DC/DC # n instead of the inverter DC/AC, due to the lower impedance path. However, this current may cause overcurrent damage to Q_n 's body diode.

It is worth noting that the direction of the current I_{dcn} flowing into or out of the terminals of the faulty converter DC/DC # n remains unchanged from normal operation; only the magnitude increases abnormally. In comparison to a PV side reverse polarity fault, a DC-bus side fault shows fewer electrical signatures, primarily an abnormal current amplitude. As a result, protection must be implemented without interfering with normal system operation, which makes its design more difficult.

Regarding all the aforementioned reverse polarity faults, a variety of reverse polarity protection schemes have been developed. Detailed discussions of these strategies are provided in the following sections.

3. PV Side Reverse Polarity Protection Methods

This section discusses PV side reverse polarity protection methods. The protection methods are divided into two categories based on their activation timing and fundamental goal: reactive activation protection and preventive activation protection.

Reactive activation protection is a post-fault mitigation strategy. It works after the DC switch is turned on, sensing or detecting fault signals such as an abnormally high reverse current or voltage. When such a signal is detected, the protective unit is activated, or the DC switch is controlled to turn off, thereby interrupting the fault path. Its primary goal is to respond to and isolate a previously detected fault.

In contrast, preventive activation protection is a pre-fault prevention strategy. This method actively verifies the polarity connection before turning on the DC switch. Only after the polarity is confirmed to be correct does the DC switch turn on, allowing the system to start up. Thus, the main goal is to prevent the generation of reverse-polarity fault current at the source.

3.1. Reactive Activation Protection

The reactive activation protection schemes are classified into hardware-based and software-based solutions according to the means of implementation. Although both take the “detects and responds” principle, their fault detecting and actuation mechanisms differ. Hardware-based solutions make use of protective units that activate when a fault signal appears, preventing the current from flowing. On the other hand, software-based solutions, once a sensor detects a fault signal, interrupt the fault current by turning off the DC switch.

3.1.1. Hardware-Based Solutions

Hardware-based solutions require adding protection units to the system. Three conventional protection approaches are currently in use: fuse-based protection, diode-based protection, and MOSFET-based protection. The explanations in this subsection are based on the system topologies described in Section 2. Specifically, the fuse-based protection, which is only applicable to multi-string parallel topologies, will be explained using the corresponding topology. In contrast, diode- and MOSFET-based protection, applicable to both single- and multi-string parallel PV systems, will be discussed using the single-string topology for clarity, with their applicability to multi-string configurations explicitly stated.

Fuse-Based Protection

Figure 3 depicts a fuse-based reverse polarity protection circuit suitable for multi-string parallel PV systems, as well as its current path when a reverse polarity fault occurs [21,22,32]. In this circuit, a fuse is connected in series to both the positive and negative conductors of each PV string branch, as shown in Figure 3a.

When one of the paralleled PV strings has its polarity reversed, a low-impedance fault loop forms within that branch, as described in Section 2. Under this condition, the output currents from all other normally operating parallel PV strings converge and flow through the fuses FUSE_{1n} and FUSE_{2n} in the faulty branch PV_n, as shown in Figure 3b. This combined current, which is significantly greater than the current of a single string, is sufficient to quickly blow the fuses FUSE_{1n} and FUSE_{2n}, breaking the fault loop and providing protection [33].

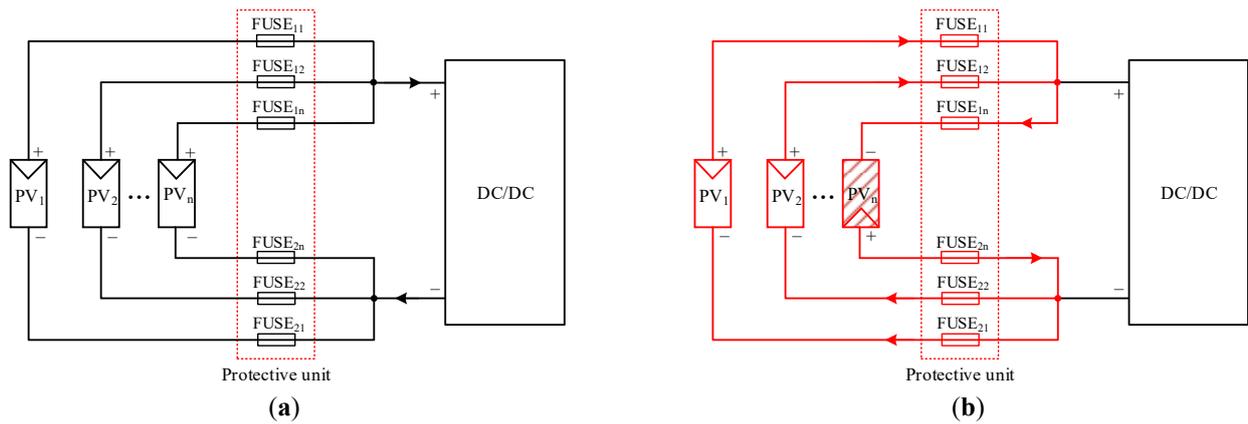


Figure 3. Fuse-based protection circuit for a multi-string parallel PV system under reverse polarity fault: (a) topology and (b) current loop when string PV_n 's polarity is reversed. The arrows, shading, and red solid lines follow the same definitions as in Figure 1, and the red dotted box encloses the components that form the protective unit.

This approach eliminates the need for current sensing and controller intervention. However, there are some inherent limitations [34–36]. (1) The added fuses may need manual replacement, which can raise maintenance costs. (2) The fuse melting process requires a period of time, and short-circuit currents can damage the body diode in switching device Q_1 , reducing system reliability. (3) This method is completely dependent on a multi-PV-string parallel topology. In a single-string PV system, the reverse polarity fault current is limited to the short-circuit current of that specific string. The fuse's rated current is typically set higher than the short-circuit current of a single PV string, so it cannot be blown, rendering the protection scheme ineffective.

From a commercialization perspective, the fuse-based approach requires minimal additional hardware cost, as it can utilize the existing DC fuse module already employed for overcurrent protection in the system. However, its practical commercial adoption is highly limited, especially in medium- to large-scale plants or in scenarios that demand high reliability. This is primarily due to its inherent drawbacks: the need for manual replacement after operation and the inability to automatically distinguish reverse-polarity faults from other overcurrent events. Consequently, this scheme is only found in cost-sensitive, small-scale, or outdated system designs and is strictly applicable to multi-string parallel PV topologies.

Diode-Based Protection

Driven by the limitations of fuse-based protection and facilitated by advances in semiconductor power devices, diode-based schemes have emerged as an alternative for reverse polarity protection. Figure 4 illustrates several diode-based reverse polarity protection circuits for a single PV string system. Figure 4a depicts a conventional circuit that employs a series-connected diode D_1 on the DC side, which uses unidirectional conduction for reverse polarity protection [23,24,37–39].

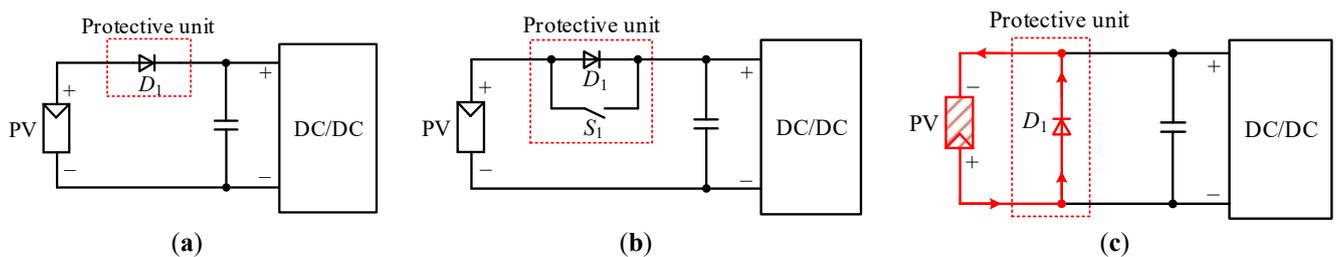


Figure 4. Diode-based reverse polarity protection circuits for a single PV string system: (a) conventional series-diode, (b) optimized series-diode, and (c) shunt-diode topology. The arrows, shading, and red solid lines follow the same definitions as in Figure 1, and the red dotted box follows the same definition as in Figure 3.

When the polarity of the PV string is reversed, diode D_1 cannot conduct, effectively blocking the reverse current path [40–42]. While structurally simple, this method causes power loss due to D_1 's forward voltage drop during normal operation, leading to thermal effects.

A modified approach is proposed in [43,44] by using a parallel-connected switch across the diode. As illustrated in Figure 4b, during normal operation, switch S_1 is turned on to bypass the diode D_1 , thereby eliminating its conduction losses.

Paper [45] proposes an alternative protection method based on a bypass diode. Figure 4c shows the protection circuit of this method and its corresponding current loop when a reverse polarity fault occurs. Diode D_1 is connected in reverse parallel across the PV string. During normal operation, D_1 remains reverse biased. Under reverse polarity, as shown in Figure 4c, D_1 becomes forward-biased, resulting in a short-circuit path that prevents reverse current flows to the DC/DC or DC/AC circuits. For visual polarity indication, the diode can adopt light emitting diodes (LEDs) instead of conventional diodes [46,47]. Overall, this approach has a simple structure, eliminating control circuitry while remaining low-costs [48,49].

It is worth noting that for multi-string parallel PV systems, the aforementioned methods can be expanded by individually configuring the corresponding diode-based protection unit for each PV string branch.

The previously mentioned diode-based schemes differ significantly in terms of commercial viability. The bypass diode configuration has become one of the most common hardware protection methods in small-to-medium-scale PV systems due to its simple structure, low cost, and elimination of control circuitry. In contrast, the series-connected diode method, while simple in concept, introduces persistent conduction loss during normal operation, lowering system efficiency and increasing thermal management costs; this inherent disadvantage severely limits its use in commercial products. The improved series diode scheme, which eliminates conduction loss via a parallel switch, adds control complexity and cost, reducing its commercial viability.

MOSFET-Based Protection

Aiming to mitigate the inherent additional power loss associated with the series-diode method, alternative schemes employing MOSFETs with significantly lower conduction losses have been proposed. Figure 5 illustrates a protection circuit utilizing MOSFET switching characteristics [25–27,50] for a single PV string system. The protection unit is made up of a series-connected MOSFET Q_1 in the PV string path. Under the correct polarity, Q_1 is turned on with the voltage divider network formed by resistors R_1 and R_2 . When the polarity of the PV string is reversed, diode D_1 becomes reverse-biased, disabling the voltage divider and causing Q_1 to turn off, which can effectively block reverse current [51].

Similar to the diode-based protection method, the MOSFET-based protection can be applied to multi-string parallel PV systems by configuring a separate protection unit for each PV string branch.

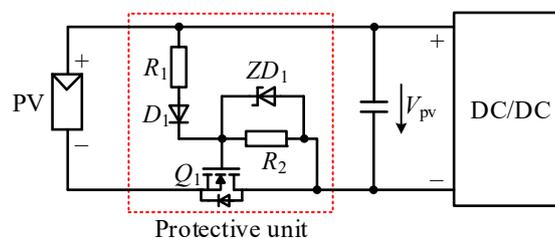


Figure 5. Series-connected MOSFET polarity protection circuit for a single PV string system. The red dotted box follows the same definition as in Figure 3, and the arrow adjacent to the capacitor indicates the direction of the voltage drop across it.

This solution uses PV output voltage to drive MOSFETs without the need for additional control circuits. Compared to conventional series-diode approaches, it offers two main advantages: (1) significantly lower conduction loss due to the MOSFET's low on-resistance, and (2) compact system design using surface-

mount MOSFETs while maintaining thermal performance [52,53]. Nevertheless, it is associated with a higher cost than the series-diode scheme.

The MOSFET-based protection scheme is a viable commercial option for low-loss reverse-polarity protection in PV systems, and it is suitable for a variety of topologies. Notably, patent barriers associated with existing alternative methods have, to some extent, fuelled topology innovation and driven the design of MOSFET-based solutions to circumvent intellectual property restrictions. Nonetheless, the practical application of this scheme requires consideration of inherent challenges such as drive requirements and potential cost increases.

3.1.2. Software-Based Solutions

Unlike hardware-based solutions, software-based solutions do not require additional protection units. The software solutions monitor the system's electrical parameters to determine the polarity of PV strings. When a reverse-polarity fault is detected, the DC switch can be switched off to provide protection.

Given the different current paths in single- and multi-string parallel systems during reverse polarity, the corresponding protection methods for each configuration are different, which are shown as follows.

Reverse Polarity Protection for a Single PV String

This solution achieves reverse polarity identification by monitoring the PV string's output voltage V_{pv} and current I_{pv} . Figure 6 depicts the current loop under three scenarios: normal polarity, reverse polarity condition, and MOSFET activation under reverse polarity. As shown in Figure 6a, during normal operation, V_{pv} remains positive, with I_{pv} flowing to the DC/DC and DC/AC circuits. Under reverse polarity fault as shown in Figure 6b, V_{pv} becomes negative with a reduced magnitude, while I_{pv} reverses through Q_1 's body diode, resulting in a closed loop. When a negative V_{pv} or reversed I_{pv} is detected, the system determines that the PV string is in reverse polarity.

It is noted that prolonged I_{pv} flowing through Q_1 's body diode may cause damage to the switch [54]. Therefore, the controller turns on Q_1 , diverting current through Q_1 's channel rather than its body diode due to Q_1 's lower conduction voltage, which are shown in Figure 6c [55]. Then, the DC switch is turned off, ensuring complete protection.

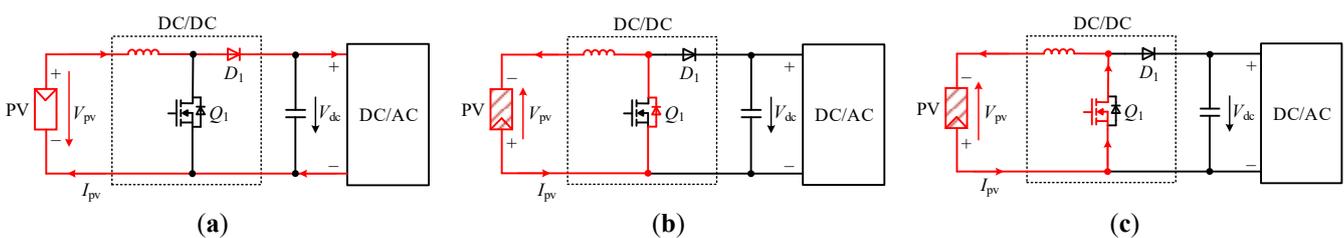


Figure 6. Current loop in single-string PV system, (a) normal polarity, (b) reverse polarity condition, and (c) MOSFET activation under reverse polarity. The arrows, shading, red solid lines and black dotted box follow the same definitions as in Figure 1 and Figure 5.

Software-based solutions provide a cost advantage over hardware methods, but they have a protection delay due to the need to detect faults first. This delay not only increases the danger of device damage but also requires reliability testing and risk assessment within the target system architecture prior to deployment. Consequently, such methods are rarely the chosen choice in safety-critical commercial products.

Reverse Polarity Protection for Parallel PV Strings

In multi-string parallel PV systems, reverse polarity protection can be achieved by monitoring relationships of different PV strings' currents.

Figure 7 presents an example. As shown in Figure 7a, for normal polarity connections, all parallel strings generate currents I_{pv1} to I_{pvn} with consistent direction and magnitude.

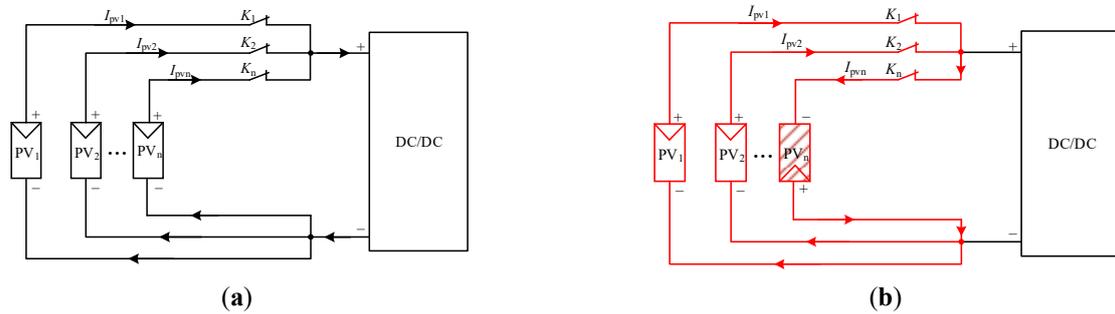


Figure 7. Current loops in multi-string parallel PV system, (a) normal polarity, and (b) string PV_n 's polarity is reversed. The arrows, shading, and red solid lines follow the same definitions as in Figure 1.

Figure 7b shows that when the polarity of string PV_n is reversed, normal string currents are diverted to PV_n rather than the DC/DC converter. As a result, the current I_{pvn} runs in the opposite direction as the other PV strings' output currents, and its value equals the sum of those currents [56].

From above, the system can continuously monitor the direction and magnitude of current in each string. A reverse polarity fault is confirmed when a string exhibits both reversed current direction and abnormally increased magnitude. Then, the corresponding DC switch is switched off for the faulty string.

It is worth mentioning that the voltage across DC switches needs to withstand twice the PV open-circuit voltage. Under these conditions, turning off the switch directly creates a significant arcing risk [57,58]. Therefore, voltage clamping and spike absorption methods are introduced in [59,60] and [61], respectively. Both solutions are illustrated in Figure 8.

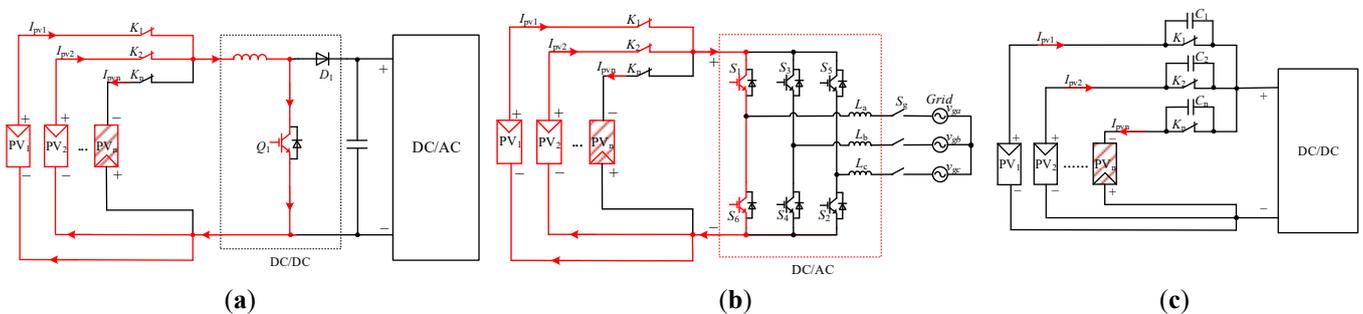


Figure 8. Overvoltage suppression solutions, (a) DC/DC converter switch is turned on, (b) inverter phase-A leg switches are turned on, and (c) voltage spike absorption circuit. The arrows, shading, red solid lines and black dotted box follow the same definitions as in Figure 1, and the red dotted box include the components that make up the DC/AC converter circuit.

As illustrated in Figure 8a,b, when the polarity of a PV string is reversed, either the DC/DC converter's switch Q_1 or all switches S_1 and S_6 in one inverter bridge leg are turned on [59,60]. This action limits the PV voltage to the switch's conduction drop level. Therefore, the voltage difference across the DC switch is significantly reduced, allowing it to be safely turned off. As illustrated in Figure 8c, paper [61] proposes connecting a capacitor in parallel at each DC switch. The capacitors absorb turn-off voltage spikes due to their inherent voltage continuity property, allowing safe switch operation within the rated voltage limits [62].

Furthermore, multiple PV strings can share common switches to reduce costs. Figure 9 uses an example of five parallel-connected PV strings to illustrate various wiring configurations between the strings and the switches.

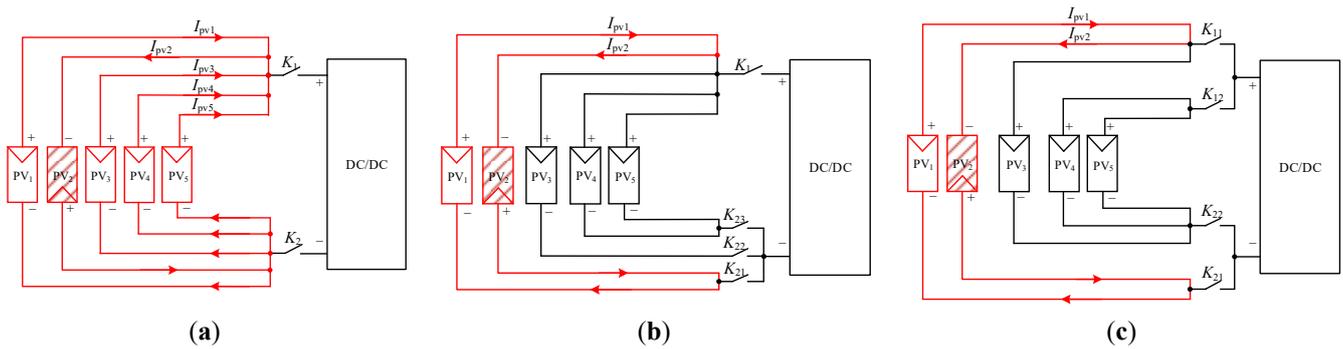


Figure 9. PV string-to-switch connection topologies: (a) shared-positive with common-negative, (b) shared-positive with dual-negative, and (c) flexible cross-connection. The arrows, shading, and red solid lines follow the same definitions as in Figure 1.

As shown in Figure 9a, PV₁ through PV₅ share a common positive switch K_1 and a common negative switch K_2 . When the system detects reverse current from PV₂, it turns off switches K_1 and K_2 . However, the output currents from normal strings PV₁, PV₃, PV₄, and PV₅ continue to flow to PV₂ via parallel paths, resulting in overcurrent damage to PV₂.

To address this issue, Refs. [56,63] and [64–66] proposed two improved solutions that involve optimizing the connection between PV strings and DC switches, as shown in Figure 9b and Figure 9c. These solutions ensure that no more than two strings remain in parallel after DC switches are turned off.

Figure 9b depicts the first solution, which employs a shared positive switch, with negative switches allowing up to two parallel PV strings [56,63]. After switches are turned off, only PV₁ and PV₂ remain parallel, while the other strings are isolated. As a result, current flows from PV₁ to PV₂ while remaining within acceptable limits, preventing overcurrent damage. However, switch K_1 's current-carrying capacity restricts the total number of parallel PV strings.

The second solution, shown in Figure 9c, proposes a flexible connection architecture [64–66] that overcomes the current-carrying limit and allows an unlimited number of parallel PV strings. From it, PV₁ and PV₂ are paralleled, while PV₄ and PV₅ form another group. PV₃ has a unique cross-connection: the positive terminal connects to the PV₁–PV₂ group, while the negative terminal connects to the PV₄–PV₅ group. Although PV₁, PV₂, and PV₃ share a positive switch, the negative switching configuration ensures that only PV₁ and PV₂ are paralleled after switch deactivation, thereby containing the fault current. Meanwhile, because the current through each switch does not exceed the combined output of three PV strings, the design theoretically allows for unlimited parallel expansion.

The above solutions rely on auxiliary power to detect reverse polarity. However, DC-powered auxiliary power fails during string polarity reversal conditions. Therefore, papers [67,68] propose a priority power supply scheme. A protection unit connects between PV_n and the DC/DC circuit. When the PV_n polarity is correct, the unit is activated manually, where the auxiliary detection system can be powered up. Therefore, the proposed unit effectively addresses system power challenges. However, it is noted that if PV_n reverses, the proposed unit cannot be activated.

Similar to a single-string PV system, software-based protection in multi-string parallel configurations is low-cost but has the inherent limitation of response delay. As a result, in commercial applications, such schemes are rarely the preferred choice for high-reliability scenarios; their applicability is often limited to contexts with greater tolerance for cost and greater control flexibility.

3.2. Preventive Activation Protection

Unlike reactive activation protection methods that work on a “detects and responds” basis after the DC switch is turned on, the strategies in this section use preventive activation protection, which works on a “verifies and permits” principle. This entails verifying the polarity of PV strings before the DC switch is

turned on, with energization occurring only after correct polarity is confirmed. The protection schemes are also classified into hardware- and software-based solutions based on their implementation.

3.2.1. Hardware-Based Solutions

The difference between hardware-based solutions is in their DC switching drive mechanisms. Based on this distinction, protection schemes can be classified into two types: independent coil driving protection and hybrid driving protection.

Independent Coil Driving Protection

In this method, each PV string has a DC switch, which is controlled by its own independent coil drive circuit [69–71]. Figure 10 depicts two typical hardware circuit implementations for this approach.

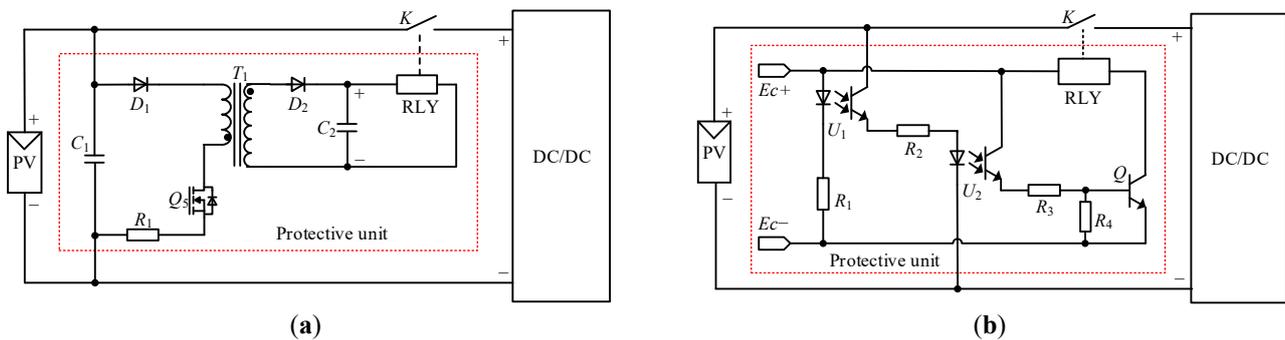


Figure 10. Protection circuits for direct-drive DC switches against reverse polarity: (a) auxiliary-powered, and (b) optically-coupled. The red dotted box follows the same definition as in Figure 3.

Figure 10a shows that the coil drive circuit uses an auxiliary power supply design [69,70]. Its reverse polarity protection function is accomplished by controlling relay operation based on the output state of the auxiliary power supply. When the PV string is connected with the correct polarity, the auxiliary supply is energized, exciting the relay coil and creating a conducting path in the main circuit. Conversely, under reversed polarity conditions, diode D_1 becomes reverse-biased and remains off, preventing the auxiliary power supply from functioning. As a result, the relay coil remains de-energized, thus providing effective fault isolation. However, because the state of the DC switch is determined solely by the PV string, with no involvement from the system controller, this configuration prevents the switch from turning off in response to other types of faults.

An enhanced coil driving circuit implemented with multiple optical couplers is presented in Figure 10b to bring the switch under system control [71]. The operating principle involves the coordinated action of the optical coupler U_1 and U_2 to simultaneously detect both PV string polarity and the relay control signal. The relay closure occurs only when correct polarity is confirmed, and a turn-on signal is received concurrently.

As depicted in Figure 10b, upon receipt of a relay activation signal at terminals $Ec+/Ec-$, the primary side of U_1 conducts. If the PV string exhibits correct polarity, the secondary side of U_1 becomes active, thereby triggering the operation of U_2 . This subsequently drives the relay closure via transistor Q . In contrast, under reverse PV string polarity, the diode on the primary side of U_2 becomes reverse-biased. Consequently, the relay remains de-energized, thereby ensuring reverse polarity protection.

The previous protection schemes require manual intervention to correct polarity after a reversed PV connection is detected. Papers [72,73] present an automatic PV string polarity switching method that eliminates the need for human involvement, thereby ensuring uninterrupted system operation and improved maintenance efficiency.

Figure 11 illustrates the operational principles of the protection unit under correct and reversed PV polarity conditions. Designed to enable automatic polarity switching, the unit comprises primarily a double-pole double-throw relay K_1 , along with a diode D_1 , a current-limiting resistor R_1 , and a Zener diode ZD_1 . Under correct polarity conditions, as shown in Figure 11a, D_1 remains reverse-biased and non-conducting, allowing switch K_1 to connect to the upper terminals and thereby establish the main circuit connection. Conversely, under reversed polarity conditions illustrated in Figure 11b, D_1 becomes forward-biased and conducts, energizing the driving coil. This actuates switch K_1 to commute to the lower contact terminals. Through this autonomous operation, the system achieves reliable self-correction of polarity, maintaining continuous power delivery without interruption [72].

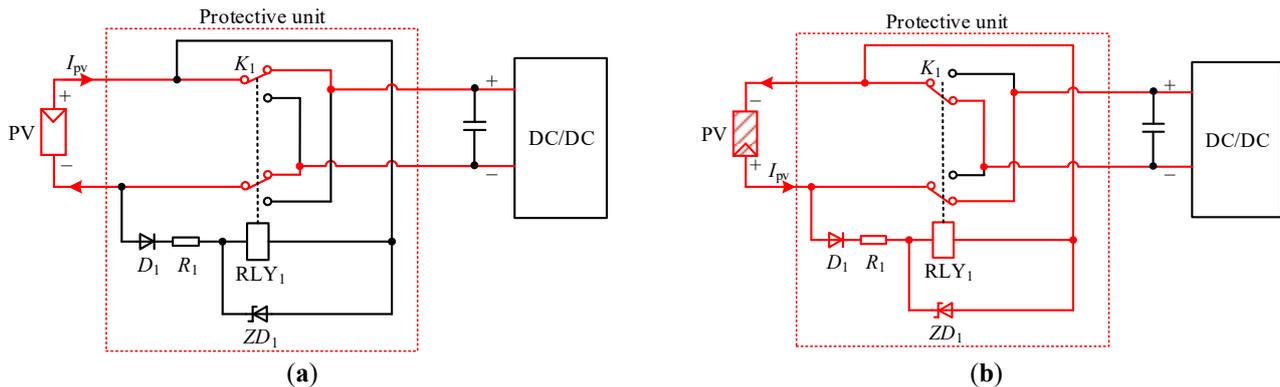


Figure 11. Polarity automatic switching hardware circuit, (a) normal polarity, and (b) reversed polarity. The arrows, shading, and red solid lines follow the same definitions as in Figure 1, and the red dotted box follows the same definition as in Figure 3.

Additionally, a break-before-make switching strategy is introduced in [73]. This method incorporates an additional controllable switch on the PV side. When a reverse current is detected, the controller opens this switch to prevent the current path. Subsequently, switch K_2 is activated to perform the polarity reversal. This zero-current switching strategy effectively prevents arcing, thereby significantly improving system reliability.

All methods described in this section serve as preventive activation protection, ensuring a high level of safety. However, in multi-string parallel PV systems, implementing the protection unit described in this section for each DC switch incurs additional costs. As a result, this solution is better suited for small-scale PV systems, whereas its higher cost may prevent widespread adoption in large-scale installations.

Hybrid Driving Protection

A hybrid driving protection has been developed to reduce the cost of independent coil driving in multi-string PV systems. It relies on a shared protection unit and coordinated driving of the DC switch across multiple strings to provide reverse polarity protection. Figure 12 depicts a typical circuit implementation, which includes a polarity protection circuit with a dual-winding magnetic core structure and illustrates current paths under both normal and reverse polarity fault conditions [74,75].

As shown in Figure 12a, the positive conductors of two PV strings are wound in opposite directions around a common core. Under proper polarity, currents I_{pv1} and I_{pv2} flow in opposite directions through the windings. Their induced electromagnetic forces cancel out in the core, allowing switch K to remain turned on. Figure 12b illustrates that when the polarity of PV₂ is reversed, the direction of the current I_{pv2} reverses correspondingly. The electromagnetic forces of I_{pv1} and I_{pv2} are combined together, which can produce enough magnetic force for switch K to turn off.

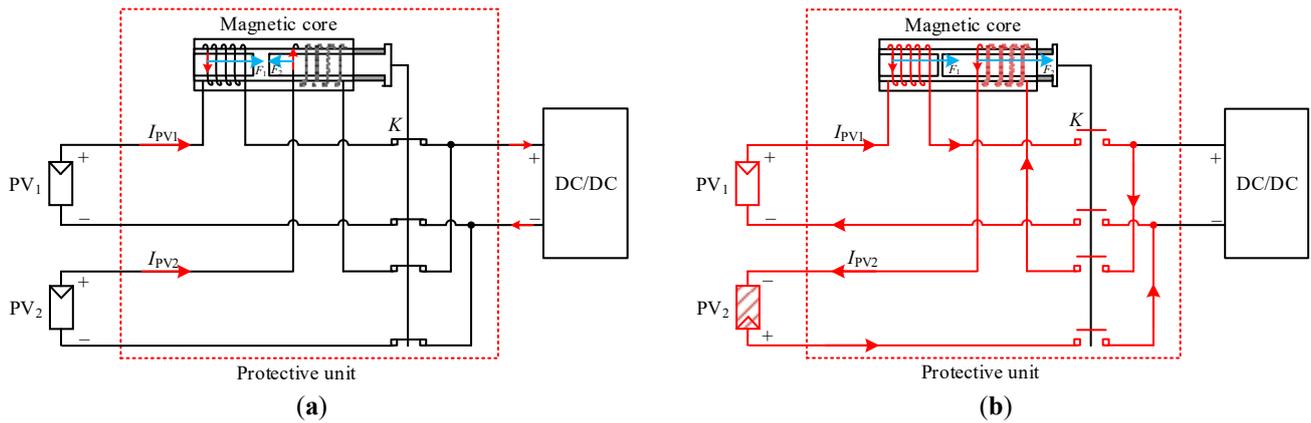


Figure 12. Magnetic core-based polarity protection circuit under reverse polarity fault: (a) topology and (b) current loop when string PV₂'s polarity is reversed. The arrows, shading, and red solid lines follow the same definitions as in Figure 1, and the red dotted box follows the same definition as in Figure 3.

According to the analysis presented above, this method has several significant drawbacks. First, it only applies to multi-string parallel PV systems. Furthermore, a reverse-polarity fault in any single string disables all switches, preventing even normal strings from functioning. Although the shared-drive design reduces cost compared to using individual protection units per switch, common components like a shared magnetic core remain expensive.

Commercially, such hardware solutions are frequently less optimal for large-scale PV systems due to cost considerations. In contrast, for small-scale systems, the independent coil-drive protection scheme is more practical due to its simplified design.

3.2.2. Software-Based Solutions

This method determines the polarity of each PV strings by measuring its open-circuit voltage or a voltage that is proportional to open-circuit voltage, while the DC switch is turned off and no closed circuit loop exists [76–78]. Essentially, it is a voltage-based software protection strategy.

The corresponding hardware circuit and the defined voltage polarity are illustrated in Figure 13, with the open-circuit voltage serving as the example case. From it, the voltage sensors measure the open-circuit voltage of each PV string and send the information to the controller. Based on the detected voltage polarity, the controller makes decisions and outputs switching control signals. Strings PV₁ to PV_(n-1) are connected with correct polarity, resulting in positive measured voltages. As a result, the controller closes the corresponding DC switches K_1 to $K_{(n-1)}$. In contrast, string PV_n is connected with reversed polarity, resulting in a negative voltage measurement, $-V_{pv}$. Consequently, the controller maintains switch K_n in the open state, thereby isolating the faulty string and ensuring protection against reverse polarity.

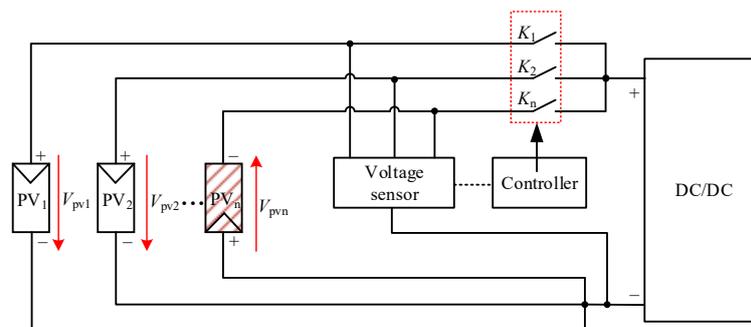


Figure 13. Schematic for implementing reverse polarity protection based on the open-circuit voltage of the PV string. The red dotted box encloses the DC switch that is inherently part of the system, while the arrows and shading follow the same definitions as in Figure 1.

This method is commonly used because it takes advantage of existing voltage sensors in PV systems. By only adding control logic, it provides a secure and straightforward implementation. It is also topology-independent, which ensures wide applicability. However, as with all software solutions, response times are slower than those of hardware protection. Nonetheless, unlike reactive activation protection, the slower response does not jeopardize system safety because the protection action occurs before the main power path is activated. Given these trade-offs, software-based preventive activation protection is widely used in commercial systems, particularly large-scale PV plants.

3.3. Protection Methods Evaluation on the PV Side

Table 1 presents a systematic summary of reverse polarity protection strategies on the PV side in PV systems, which are divided into reactive activation protection and preventive activation protection based on the implementation stage.

Table 1. Evaluation of different methods.

Stage of Implementation	Means of Implementation	Method	Advantages	Limitations	Commercialization
Reactive activation protection	Hardware-based solutions	Fuse-based protection	Simple structure	High maintenance, slow response, and unsuitable for single PV string systems	Low
		Diode-based protection	Simple structure and low cost	Requires optimization to reduce conduction loss	High(bypass topology)/Low(series topology)
		MOSFET-based protection	Low Conduction Loss	Requires drive network and higher cost than diode-based protection	High
	Software-based solutions	Voltage/current detection protection	No additional hardware required, and direct fault identification	Slower response than hardware-based solutions and potential for arc faults in multi-string systems	Low
Preventive activation protection	Hardware-based solutions	Independent coil driving protection	Higher safety and increased system reliability compared to reactive activation protection	Higher hardware cost and larger size than reactive activation protection	Medium
		Hybrid driving protection		Higher cost and larger size; not for single PV string systems; simultaneous switching	Low
	Software-based solutions	Voltage detection protection		Slower response than hardware-based solutions	High

Reactive activation protection is used after a fault occurs and can be classified as hardware-based or software-based depending on how it is implemented. Hardware-based solutions include fuse-based protection, which has a simple structure but requires high maintenance, exhibits slow response, and is not suitable for single PV string systems; diode-based protection, which has a simple structure and is inexpensive but requires optimized design to reduce conduction losses; and MOSFET-based protection, which offers low conduction loss but necessitates additional drive circuits and is more expensive than diodes. At this stage, the software-based solution is voltage/current detection protection, which has the advantage of not requiring additional hardware and enabling direct fault identification. However, its response time is slower than hardware solutions, and it may introduce arc faults in multi-string systems.

Preventive activation protection is intended to prevent faults, thereby increasing system safety and reliability. Its hardware-based solutions are primarily comprised of independent coil driving protection and hybrid driving protection, both of which have the disadvantages of higher hardware costs and larger size compared to reactive activation protection, which is unsuitable for single PV string systems and requires simultaneous operation of all switches. At this stage, the software-based approach is voltage detection protection, which responds more slowly than hardware-based solutions.

Choosing reverse polarity protection methods for PV systems requires balancing cost, reliability, efficiency, and other considerations for commercial viability. Among reactive activation protection, the diode-bypass method is frequently used due to its simplicity and inexpensive cost. MOSFET-based protection is also a popular commercial option due to its low loss. Other techniques, on the other hand, have low commercial acceptance due to intrinsic disadvantages such as maintenance requirements, power losses, or reliability concerns.

Within preventive activation protection, software-based solutions are widely used due to their cost-effectiveness and scalability. Independent coil driving protection is suitable for small-scale systems due to its simplicity, but hybrid driving protection are not widely used due to its limitations.

4. DC-Bus Side Reverse Polarity Protection Methods

Reverse-polarity faults on the DC-bus side primarily originate from miswiring between DC/DC converter outputs and bus bars during on-site installation. Fully integrated and factory-prewired small-scale systems require minimal field wiring, reducing the risk and need for protection. In contrast, manual wiring poses a substantial danger of reverse polarity connection for medium- to large-scale systems requiring on-site installation. Therefore, this section focuses on reverse polarity protection solutions for the DC bus side.

The protection strategies can be classified into hardware-based and software-based solutions. It is important to note that all methods require a current path to be established between at least one PV string and the bus in order to achieve reverse-polarity protection. This implies that the protection at the DC-bus is inherently a reactive activation mechanism.

4.1. Hardware-Based Solutions

Considering the characteristics of reverse polarity fault signals on the DC-bus side and the design constraint of not interfering with normal operation, the number of viable hardware solutions is less than on the PV side. Hardware solutions used on the PV side, such as fuses and series-connected diodes/MOSFETs, are no longer suitable for the DC-bus side due to high conduction losses or disruption of normal system operation. As a result, practically feasible methods can be divided into two categories: diode bypass protection and additional capacitor voltage polarity detection method.

4.1.1. Diode Bypass Method

As described in Section 2, if the output of a DC/DC converter is reversed and connected to the DC-bus, a low-impedance fault loop forms. As shown in Figure 14a, the output currents from all other normally operating parallel converters, DC/DC #1 to DC/DC #(n-1), converge and flow through the body diode of the Q_n in the reversed converter DC/DC #n, subjecting it to severe overcurrent stress and potential damage.

To address this issue, Paper [79] proposes a diode bypass-based hardware protection method. As shown in Figure 14b, the diodes D_{t1} to D_{tn} , each with a lower forward voltage drop and higher current capability than the body diodes Q_1 to Q_n , are installed antiparallel to the outputs of each DC/DC converter.

When the output of DC/DC #n is reversed, the combined output currents from the other converters flow preferentially through the parallel diode D_{tn} rather than through the body diode of Q_n . This is because

D_{tn} 's lower forward voltage drop allows for a more easily conductive path. As a result, the fault current is redirected, protecting the switch from damage due to overcurrent.

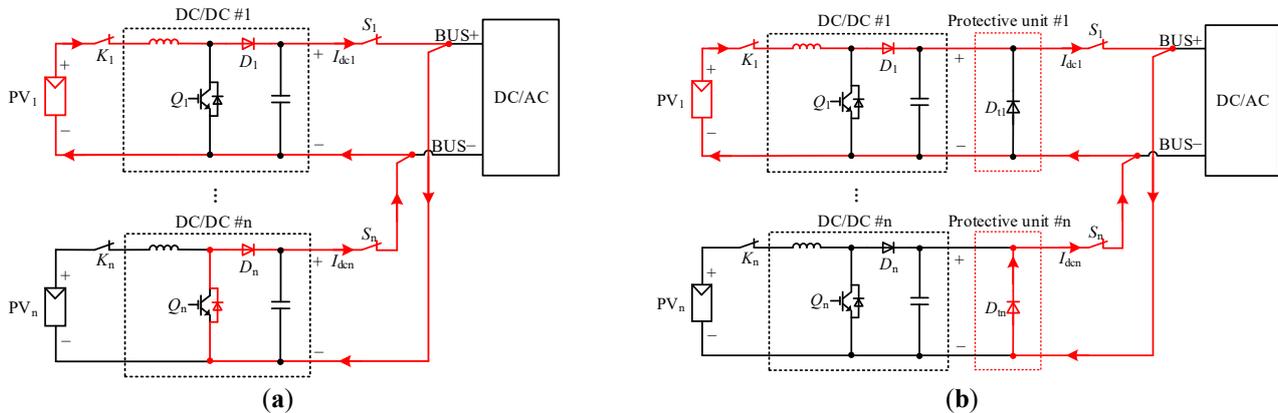


Figure 14. Fault current paths (a) with output of DC/DC #n reversed, and (b) with diode bypass protection. The arrows, red solid lines, and the black dotted box follow the same definitions as in Figure 1, and the red dotted box follows the same definition as in Figure 3.

According to this configuration, reverse protection can be achieved by monitoring the current in the parallel diode branch: if current is detected in this branch, it can be determined that the corresponding DC/DC converter has reversed output polarity. To achieve rapid protection and fault isolation, the converter's output switch can be turned off immediately.

This method is characterized by its low incremental cost and simple circuitry, which only requires the addition of diodes. However, the diodes in the protection unit must have a lower forward voltage drop than the switching transistor's body diode in order to provide a low-impedance path for fault current. The number of parallel DC/DC converters is limited by the diode's transient current capability, since the bypass diode in the reverse DC/DC converter must carry the full current from all other DC/DC converters. Commercially, its low-cost advantage makes it suited for residential and small-scale PV systems, while its restricted scalability prevents adoption in large-scale applications.

4.1.2. Additional Capacitor Voltage Polarity Detection Method

A method proposed in [80] addresses the limitation on the number of parallel DC/DC converters in reverse polarity protection by incorporating an additional capacitor as a protection unit, with protection enabled by voltage detection. Figure 15 depicts the additional protection circuit utilized in the proposed method, along with the current paths under both correct and reverse polarity conditions. From it, the protection unit consists of capacitors C_1 to C_n , connected in parallel between the DC/DC converter output and the DC-bus.

The protection procedure begins with the operation of one DC/DC converter, such as DC/DC #1, which must be selected to power the DC-bus. At this stage, the switches K_1 and S_1 are turned on, allowing the string PV_1 to supply power to the DC-bus via this converter. Since the other converters have not yet started, the DC-bus charges all capacitors C_2 to C_n connected in parallel across it.

As shown in Figure 15a, when all DC/DC converters are properly connected, the polarity of each capacitor aligns with that of the DC-bus, resulting in a positive voltage. When a converter, such as DC/DC #n, is reversely connected to the DC-bus, as illustrated in Figure 15b, its corresponding capacitor C_n charges to a negative voltage due to the reversed polarity, while the remaining capacitors maintain positive voltages. If the first activated converter DC/DC #1 is reversely connected, as shown in Figure 15c, its capacitor C_1 is forward-charged by DC/DC #1 and develops a positive voltage, while all other capacitors are reversely charged through the DC-bus and exhibit negative voltages.

In summary, the detection mechanism is based on the voltage polarity of each protection unit after the initial charging phase. When the voltage polarity of one branch differs from that of the others, it indicates a reverse polarity defect in that branch, and the related switch is switched off to provide system safety.

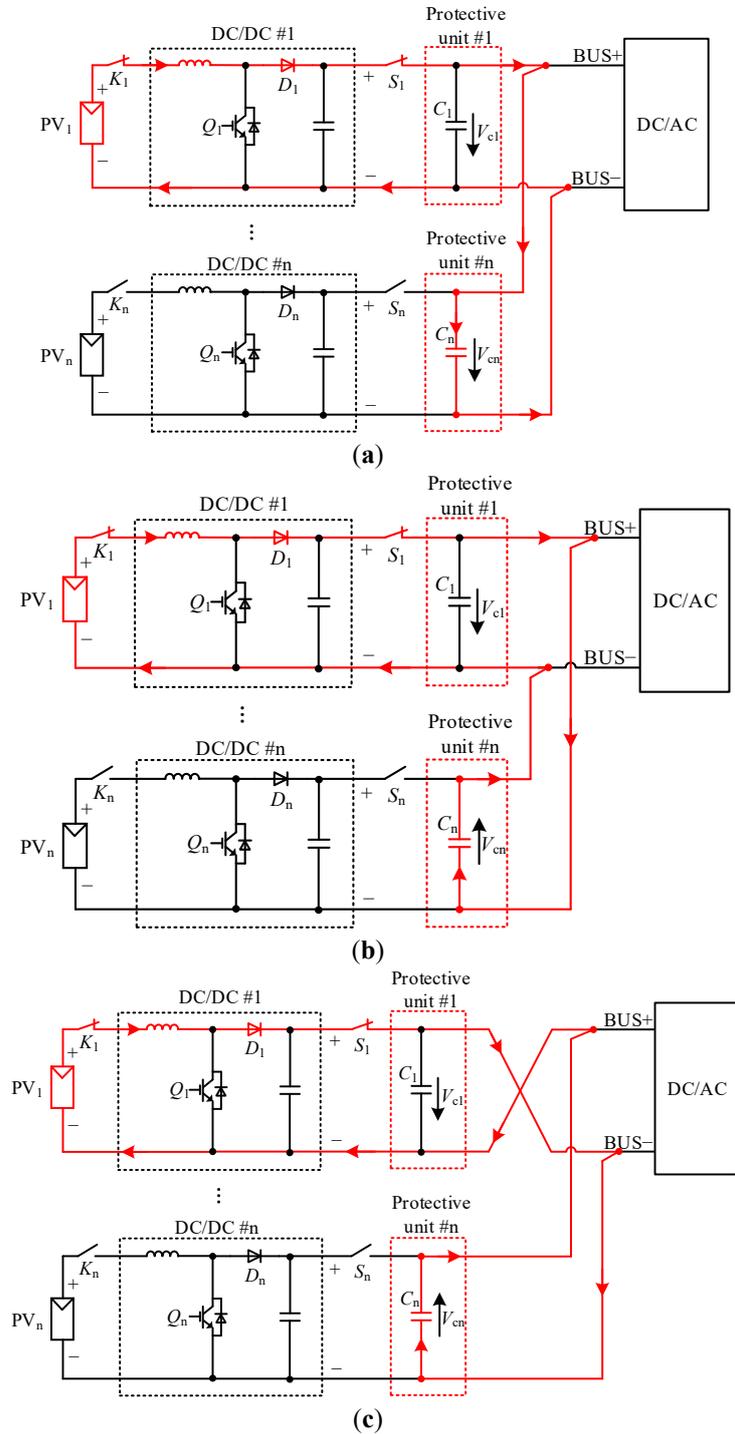


Figure 15. Detection circuit with K_1 and S_1 are turned on, (a) normal polarity, (b) DC/DC #n reverse polarity, (c) DC/DC #1 reverse polarity. The arrows, red solid lines, and the black dotted box follow the same definitions as in Figure 1 and Figure 5, and the red dotted box follows the same definition as in Figure 3.

As previously discussed, the scalability of the diode bypass method is limited by the transient current capability of the diode. In contrast, the proposed solution activates one DC/DC converter to supply a controlled charging current to the DC-bus and all capacitors, thereby preventing capacitor overvoltage. This

makes the method independent of the number of parallel DC/DC converters and thus offers higher scalability compared to the diode bypass approach. However, because the protection action relies on the capacitor charging process, the response time for protection is longer than that of the diode bypass method.

Because of its superior scalability, this approach has interesting commercial applications for medium/large-scale PV systems or scenarios needing flexible extension, particularly in systems with several parallel units. However, due to the higher hardware cost and accompanying control circuitry required, it is best suited for medium-power PV systems with a focus on great scalability and low cost sensitivity.

4.2. Software-Based Solutions

From the above solutions, additional protection units are required. Therefore, paper [81] proposes a software-based algorithm for DC-bus side reverse polarity protection.

As depicted in Figure 1, a reverse-polarity connection in DC/DC # n results in a substantial increase in the current flowing through the corresponding switch, S_n . This method identifies such faults by continuously monitoring the currents of all DC switches. A large divergence, specifically a current that significantly exceeds that of the other branches, indicates a reversed fault in the corresponding DC/DC converter.

Upon fault detection, all switches (Q_1 to Q_n) are simultaneously activated, as shown in Figure 16. This action effectively short-circuits the PV strings, diverting current away from the DC/DC converters. Consequently, the current through the DC switches (S_1 to S_n) drops to zero, allowing them to be safely opened, thereby preventing electrical stress or arcing.

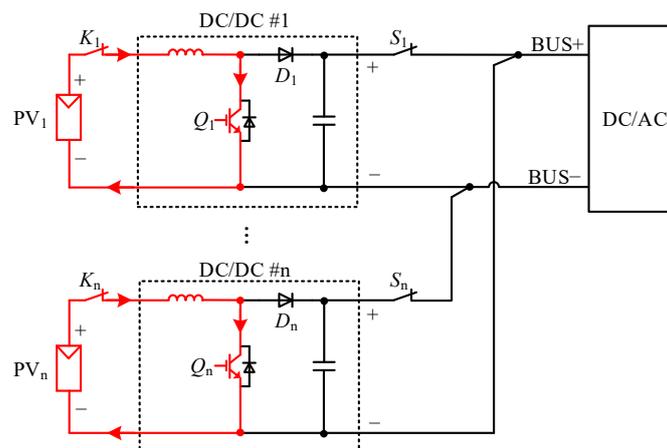


Figure 16. Current loop while Q_1 to Q_n are turned on in the DC/DC circuit. The arrows, red solid lines, and the black dotted box follow the same definitions as in Figure 1.

This software-based protection eliminates the need for extra hardware, resulting in cost savings. However, within the detection-to-actuation interval, the fault current remains present in the original circuit, exposing sensitive components to electrical stress. As a result, the necessity to evaluate its reaction delay prior to deployment limits the commercial application of this technology.

4.3. Protection Methods Evaluation on the DC-Bus Side

Table 2 provides a systematic summary of reverse polarity protection strategies on the DC-bus side of PV systems. The methods described all fall under the category of reactive activation protection and are classified as hardware-based or software-based solutions based on their implementation means.

Hardware-based solutions primarily include the diode bypass method and the additional capacitor voltage polarity detection method. The diode bypass method consists of connecting diodes in reverse parallel within each DC/DC branch. This approach is simple to implement, inexpensive, and provides a

quick response. However, it must have a lower forward voltage drop than the switching transistor's body diode in order to provide a low-impedance path for fault current. And the limited current-carrying capacity of diodes restricts the scalability of the number of DC/DC converters that can be connected in parallel. The additional capacitor voltage polarity detection method necessitates the activation of one DC/DC circuit during the system startup phase to charge the DC-bus and the extra parallel capacitors. The polarity of the capacitor voltage is then used to identify a reverse connection fault. While this method is not restricted by the number of the DC/DC converters, it has a relatively slow response time due to the capacitor charging time.

The software-based solution is primarily based on monitoring the current values in each DC/DC branch, which eliminates the need for additional hardware. However, its protection mechanism reacts slowly, posing a safety risk because the fault current continues to flow along the original path until the protective polarity response is engaged.

Based on the above analysis, the selection of reverse polarity protection solutions on the DC-bus side necessitates a comprehensive evaluation of the advantages and limitations of all candidate methods to identify the optimal approach. The additional capacitor voltage polarity detection method has been the most extensively commercialized option due to its scalability and safety. The diode bypass method has economic potential in residential and small-scale PV systems due to its inexpensive implementation costs. While software-based solutions are cost-effective, their commercialization is limited due to safety concerns about reaction times.

Table 2. Evaluation of different methods.

Stage of Implementation	Means of Implementation	Method	Advantages	Limitations	Commercialization
Reactive activationsolutions protection	Hardware-based	Diode bypass method	Simple structure, low cost and quick response	Critical diode selection (the forward voltage must be lower than the body diode of the switch Q) and low scalability	Medium
		Additional capacitor voltage polarity detection method	High scalability	Limited response speed (capacitor charging delay)	High
	Software-based solution	Current detection protection	No additional hardware required	Safety risk due to slow response	Low

5. Conclusions

This paper has presented a comprehensive review of reverse polarity protection technologies in PV systems. A multidimensional framework is proposed to categorize and compare existing methods. This framework is organized around three key criteria: protection location, which determines whether it is implemented on the PV or DC-bus side; implementation stage, which distinguishes between preventive and reactive activation; and implementation means, which categorize approaches as hardware-based or software-based. In addition, each method is evaluated in terms of commercial viability.

Based on this framework, this paper begins by providing a comprehensive review of PV side protection schemes. These are divided into two categories: reactive activation methods and preventive activation methods. Reactive activation schemes respond after fault occurrence. Hardware-based solutions among these, the diode-bypass approach is widely used in small-to-medium-scale systems due to its low cost and simplicity. MOSFET-based protection reduces loss, though it increases complexity and cost. Fuse-based methods are simple and inexpensive but suffer from slow response and maintenance needs, and are unsuitable for single-string systems. Software-based reactive protection avoids extra hardware but is slower than hardware alternatives and may pose security risks. Preventive-activation schemes enhance safety by

verifying polarity before startup. Among these, hardware-based solutions are reliable but costly, whereas software-based solutions add minimal hardware at the expense of slower response time. In commercial applications, solutions based on diode bypass and MOSFETs dominate in the reactive activation field, while software-based solutions are more widely used in preventive activation.

Subsequently, the paper focuses on analyzing protection schemes for the DC bus side; all practical schemes are reactive. The diode-bypass hardware solution is cost-effective and fast, but has limited scalability because each diode must withstand the cumulative failure current from all healthy parallel converters. This method is appropriate for smaller-scale systems. The additional capacitor voltage polarity detection method is commonly employed in medium-scale systems, however, its response may be delayed due to capacitor charging. Although software-based current monitoring eliminates the need for additional hardware, it is slower and permits fault current to remain until protection is engaged, making it less suited for safety-critical applications.

In practice, the optimal solution varies depending on the specific situations. The system scale, cost sensitivity, and reliability needs should all be considered during the selection process. Future research should concentrate on components with reduced loss and faster switching, as well as integrated designs that make installation easier while maintaining high dependability at different system scales.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

Generative AI was used solely for English grammar polishing.

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Author Contributions

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Informed Consent Statement

Not applicable.

Data Availability Statement

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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Declaration of Competing Interest

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